# PROCEEDINGS

OF THE

# American Philosophical Society

HELD AT PHILADELPHIA

FOR

PROMOTING USEFUL KNOWLEDGE

VOLUME XLVII

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PHILADELPHIA
THE AMERICAN PHILOSOPHICAL SOCIETY
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VOL. XLVII JANUARY–APRIL, 1908. No. 188.

## *Stated Meeting January 3, 1908.*

Treasurer JAYNE in the Chair.

The decease of the following members was announced:

Dr. Coleman Sellers, at Philadelphia, on December 28, 1907, æt. 80.

Prof. Thomas Day Seymour, at New Haven, on December 31, 1907, æt. 59.

The judges of the annual election of officers and councillors held on this day, between the hours of two and five in the afternoon, reported that the following named persons were elected, according to the laws, regulations and ordinances of the Society, to be the officers for the ensuing year.

*President:*

William W. Keen.

*Vice-Presidents:*

George F. Barker, William B. Scott, Simon Newcomb.

*Secretaries:*

I. Minis Hays, James W. Holland,
Arthur W. Goodspeed, Amos P. Brown.

*Curators:*

Charles L. Doolittle, William P. Wilson, Leslie W. Miller.

*Treasurer:*

Henry La Barre Jayne.

*Councillors:*

(*To serve for three years.*)

Hampton L. Carson, Harry F. Keller,
Talcott Williams, Francis B. Gummere.

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*Stated Meeting January 17, 1908.*

Councillor ROSENGARTEN in the Chair.

A letter was received from the American Institute of Electrical Engineers, inviting the Society to be represented at the Memorial Exercises in honor of Lord Kelvin, to be held on January 12, at 3 P. M.; and from Vice-President Scott announcing the appointment of Mr. Andrew Carnegie and Professor Michael I. Pupin to represent the Society on the occasion.

A letter was received from the Committee of Organization of the First Congress of Chemistry and Physics in memory of the celebrated Russian Chemist, Mendéléeff, announcing that the Congress will be held at the University of St. Petersburg on the second to the twelfth of January, 1908.

The decease was announced of Professor Charles Augustus Young, at Hanover, N. H., on January 3, 1908, æt. 78.

PROFESSOR LEO LOEB read a paper on "Tumor Growth and Tissue Growth." (See page 3.)

# TUMOR GROWTH AND TISSUE GROWTH.

By LEO LOEB.

(*Read January 17, 1908.*)

In the course of the last five years, partly through the aid of their respective governments and partly through private initiative, institutions have been founded in the majority of civilized countries for the investigation of the causes and the conditions of growth of malignant tumors; or, as briefly named, for the investigation of cancer. This fact proves more clearly than anything else could do the widespread interest that has recently been aroused in this part of pathological research. Pathological investigations share with those of other sciences a double nature. On the one hand, their problems are of a practical character. Pathology wants to find the causes of diseases and the conditions that favor and inhibit their progress, in order to lay a firm and scientific basis for their cure. In this respect, pathology is an applied, a technical science. On the other hand, pathology desires to analyze the conditions that ultimately lead to death, in order to recognize some of the phenomena of life. In that sense, pathology is a pure science; its aim is philosophical.

Tempting as it might be to relate something of the first attempts of pathology to find the cause and the cure of cancer, I shall here, rather, turn to the purely theoretical aspects of these investigations and indicate some of the results of tumor investigations that have some bearing upon one of the fundamental characteristics of living matter—the ability to grow. Before entering, however, upon a necessarily very limited discussion of some of the relations between tissue and tumor-growth, it might be well to indicate what a tumor is; and, especially, what a cancer is.

Perhaps I can best approach this delicate task by stating some varieties of growth that are not included under the term tumors.

Our bodies consist of cells (that is small parts of protoplasm with nuclear material), of products of cells of different kinds, of decomposition products of cells and of material used for the building up of cells. Here we are concerned with the two former only, namely, with the cells and their direct products. Now growth is based upon an increase in the number or the size of cells in the locality, where growth takes place. The increase in the number of cells can be brought about in two ways: either through the multiplication of preexisting cells, or through a wandering in of new cells. Cell-growth can take place under various conditions. If toxic substances—the products of bacteria for instance—or even if inert substances foreign to the body are introduced into the organism, a certain proliferation of the neighboring cells and immigration of cells from the blood- and lymph-vessels take place. After a certain period, such reactions come to a standstill, and scar tissue develops. Such a cell-proliferation we do not call a true tumor; but we class it among the inflammatory reactions.

There are other conditions in which an unusual cell-proliferation takes place in the adult organism; in cases of wound healing. If, for instance, a wound is made in the skin, the cells of the epidermis proliferate until the wound is closed; then the additional proliferation ceases. We call this regenerative growth. It lasts only as long as the continuity of the epidermis is interrupted. This is not tumor-growth.

We now come to a third variety of cell-proliferation, distinct from the two former varieties. If a follicle of the ovary ruptures at the time of menstruation, the follicle cells enlarge, and proliferate much more extensively than would be necessary in order to insure wound-healing. There is formed a new growth, which exists for a limited period and then disappears. A still more striking example of this new formation was found in our laboratory in the course of the past year. If, at a certain period after copulation has taken place, or at the period of heat, the inner surface of the uterus is sufficiently exposed and cuts are made in the wall of the uterus, we find that, instead of the ordinary wound-healing, another process takes place, namely: the development of nodules of new tissue, which resembles closely the maternal part of the placenta—without, however, an ovum being in this case responsible for the new formation; but also in this case the experimentally new-formed decidua, as we call this tissue, dies.

The latter variety of growth resembles much more closely the real tumor-growth than do the former; but in this case also the cell-proliferation, and even the life of the newly formed cells, cease, when the cause for the proliferation has disappeared. The cause for the development of an artificial decidua is probably two-fold: in the first place, a general chemical condition exists in the body at that period; and, under these predisposing conditions, a local stimulus suffices to produce the tumor-like growth. These new formations might be called transitory tumors, because they have a definite life-cycle; they grow for some time, and then they disappear.

In real tumors we find a similar but still more marked cell-proliferation; and they do not have such a definite life-cycle. Real tumors do not retrograde usually, and may even grow, more or less, during the lifetime of the bearer. Furthermore, we do not know the cause of their origin, as we do in the case of the transitory tumor. They grow, and we do not know why. If such tumors grow more rapidly, and especially if they grow deep into the surrounding tissue, digesting it, if parts penetrate into the blood- or lymph-vessels and are carried away to distant parts of the body, and here start a new growth, a so-called metastasis, then we call the tumor malignant, or a cancer.

We distinguish different varieties of cancer, according to the tissue or variety of cells from which these cancers originate. The malignant tumors derived from epithelial surfaces or gland cells, we call carcinomata and the malignant tumors derived from the connective-tissue cells, which unite the functionally more highly developed cells, we call sarcomata. But from whatever tissue these malignant tumors are derived, their main characteristics are identical.

During the second half of the last century, pathologists studied very carefully the microscopical character of the different tumors; and they determined quite accurately the genesis of these tumors from normal tissues. They observed how cells began to grow down into the adjoining tissues in cancer; they described the general spreading out of the new formation, and the character of the secondary growth; they also determined that a certain number of tumors apparently originate in tissue that has been misplaced during embryonic development. In other cases, long irritation, and occasionally a traumatism, may be held responsible for the origin of cancer. Apparently, however, no further progress could be made by these means of observation. The investigations seemed to have arrived at a dead point.

After a few isolated previous attempts, mainly since the year 1899, the attention of the investigators was directed to the occurrence of tumors in animals; to the fact that cancer in animals frequently occurs endemically. This means that a number of animals are affected with cancer simultaneously in a certain locality. Furthermore, they observed that certain kinds of tumors are characteristic for certain species of animals; and that the tumors occurring endemically in a species of animals are all of the same type.

The most important fact, however, which was fully developed only within the last eight years, is that it is possible to transplant a certain number of cancers into other animals of the same species. Many attempts have been made to transplant cancers into animals of other species and make them grow in these animals, but without any success. A certain kind of cancer found in the dog can be made to grow in some related species, as, for instance, in the fox. Other tumors found in white rats may be transplanted into hybrids between white and gray rats, and the cancer of white mice can occasionally be made to grow in gray mice. The cancer of a Japanese mouse could not be successfully transplanted into white mice, however, but only into the Japanese mice. No such tumors can be transplanted into more distantly related animals, nor can the cancer of man be transplanted into lower animals. A very malignant tumor from a mouse can occasionally be made to grow for a few days in a rat, but the growth soon stops. In a similar way, normal tissues of the body, for instance the epithelium, may be transplanted into other animals of the same species, and kept there alive after an initial growth; but if transplanted into an animal of another species, it grows for a short period and then it dies.

Some tumors, and probably the majority of them, can be transplanted only into the same animal in which they have originated.

Here they live, and even grow; while in other animals of the same species, they die very soon after transplantation. This probably applies to most of human tumors. The same holds good of certain animal tissues and organs; as, for instance, the ovary. They can much more easily be transplanted into the animal of which they have formed an integral part, than into other animals of the same species.

There exists another point of similarity between the transplantation of normal tissues and organs, on the one hand, and of tumors, on the other: in both cases, after transplantation, only the peripheral parts of the transplanted piece usually remain alive; the central part, which is not well supplied with lymph or blood from the host, soon dying. This similarity between the behavior of normal tissues and of tumors after transplantation can be easily explained, if we consider that in both cases we have equally to deal with the inoculation of cells or tissues from an animal organism; and that the transplanted tumor, as can be readily shown by microscopic examination, grows merely from the transferred tumor-cells themselves, and not from the tissues of the receiving host-animal.

On the other hand, however, there exist also some very interesting differences between the growth of normal tissues and of tumor-tissues after transplantation, the former always growing only very slowly for a time, and then ceasing to grow, or merely remaining alive after transplantation; and the latter continuing to grow rapidly, and sometimes continuing to infiltrate the surrounding host-tissue and to make metastases. Their character is not markedly modified through transplantation. Eight years ago I transplanted a sarcoma of a white rat into more than forty generations, without an appreciable decrease in the energy of growth of the tumor cells. The fact that it is possible to propagate tissues of the animal body through years and years in other animals of the same species, without any loss of vitality and power of propagation of the tumor-cells, while they would long since have died if they had remained in the animal to which they originally belonged—suggests, it seems to me, a consideration of great biological significance, namely, the question whether our own body-cells are all equally mortal, or whether their death does depend upon their accidental connection with other cells and with an organism that dies, and because a certain number of cells, especially of nervous character, cannot survive.

The inevitable fate of all metazoan organisms is death; and this conception deeply influenced all our valuations and directions of thought, as Metchnikoff only recently pointed out in his book on the "Nature of Man." Weismann added one consoling idea: not all of our cells must necessarily die, but only the so-called somatic cells; the germ-cells, ova and the sperm-cells, of each individual may propagate forever, may be immortal. The results of the tumor investigations just mentioned may, perhaps, enlarge the number of cells that may remain alive for so long a period that we cannot see the end at present; ordinary somatic cells may propagate through many generations, long after their brother cells that remained in the original organism have been transformed into simple chemical substances, and who can at present deny the possibility that they may have the potentiality of immortality, as well as the germ cells? Thus the work on tumors leads us into different realms of general biology, and opens up new fields that are not without interest.

The experimental work on tumors has given some other results of an unexpected nature. One of the great achievements of the last century was the development of bacteriological technique by which it is possible for us not only to cultivate bacteria on artificial culture-media, but also to influence markedly their behavior, functions, vitality, and virulence. It has been found to be possible to raise the virulence of certain bacteria by inoculating them into animals through several generations; on the other hand, it is possible to decrease their virulence by subjecting them to certain injurious chemical or physical agencies. Such a bacterial culture with artificially decreased virulence has been used as a vaccine; that means, as a substance that, when inoculated into human beings or animals, without causing the disease, confers immunity against the virulent bacilli.

In experimenting with tumor cells, the surprising result was obtained that, through successive transplantations, by cutting out pieces of tumor, an artificial stimulus is given to the tumor cells, so that they begin to grow more rapidly and more extensively. In other words, their virulence has been increased. This is due to a direct stimulating action upon the tumor cells, and not to secondary conditions. This explains a fact very familiar to surgeons; namely, that after an operation a recurrent tumor is frequently more malignant than the original tumor.

But it is also possible to decrease the power of propagation of tumor cells without killing them by exposing the cells to chemical and physical injurious influences, in a way similar to that pursued in the case of bacteria. Here, also, we may, not without some hope, look forward to the preparation of some vaccine that may, some day in the future, help us to combat the dreaded disease. Even in this case, however, tumor tissue probably differs only in degree, and not in principle, from normal tissue. At least, this conclusion is indicated by the fact that such an organ as the normal thyroid gland may, without being entirely destroyed, be markedly weakened in its power of growth through a short exposure to the air before transplantation.

There exist, however, some interesting differences of another kind between tumor tissue and normal tissues or organs. Normal organs have a specific metabolism and, in connection with or as a part of this metabolism, they exert distinct specific functions. We understand by functions those physical and chemical processes which attract our attention by their real or apparent significance for the organism as a whole. The normal female mammary gland, for instance, secretes milk under the influence of certain chemical stimuli which are present in the circulation at the end of pregnancy; and it also grows during pregnancy, under the influence of similar stimuli. If we now transplant the mammary gland of a nonpregnant animal into a pregnant animal, the foreign transplanted gland may secrete milk at the end of pregnancy in a similar way to that of the animal's own gland. The circulating chemical substance exerts the same stimulus upon the transplanted as upon the autochthonous gland, and the transplanted gland responds to the stimulus in the normal way.

There exist certain conditions in which a tumor-like hypertrophy of the mammary gland is found in the white rat. The structure of the gland is slightly modified, but the tumor is not infiltrating. We do not call it a cancer, but a benign tumor—an adenoma. If we transplant such a tumor to another place in the original animal, it heals, and if the animal becomes pregnant, it begins to grow in the same way as the normal gland, but is no longer able to produce milk. It responds, therefore, only to certain stimuli, but not to others.

If we persist still further and transplant a malignant tumor, a cancer, of the mammary gland, we find that it no longer responds to the stimuli of pregnancy. Such tumors do not seem to assume a more rapid growth, nor do they ever secrete milk. The metabolism of tumors differs, however, only in a greater or less degree from that of the corresponding normal tissues; and the tumor tissue can even still continue to secrete certain substances in a similar way to the normal tissues. This has been observed, for instance, in the case of the tumors of the liver and of the thyroid gland, which latter provides a so-called internal secretion, without which widespread changes would take place in our body. It seems, therefore, in the case of the tumor tissues that there exists a parallelism between its loss of function and its capability to respond to chemical stimuli in the body that normally excite and regulate function and growth.

These observations bring us also nearer to an understanding of tissue growth and tumor growth in general. Just now we mentioned substances of various kinds circulating in the body that regulate the growth of normal tissues and of tumors; but there probably exist a number of such substances. How else could we explain the fact that the majority of tumors may be successfully transplanted into the organism in which the tumor had originated, but not into other individuals of the same species? Evidently there must exist some difference between the chemical composition of the blood and lymph of each individual of one species; and each tissue of one individual is more or less adapted to its own body fluid. Furthermore, we have seen that tissues do not grow in animals belonging to different species; there must, therefore, exist substances regulating growth, which are the same in the same species, but differ in different species. Sometimes, however, certain families of white mice differ among one another to a higher degree than the white mice differ from gray mice.

Such substances, however, can merely regulate the growth of normal tissue and of tumor tissue; they are not able to transform normal tissue into tumor tissue. How the latter transformation is brought about, we do not yet know; and this is one of the problems that remain before us. Of one fact we may be reasonably certain; namely, that the growth-regulating substances to which we referred just now are, in all likelihood, not the primary factors in the production of tumors. We draw this conclusion because the action of such substances has so far not been shown to be hereditary. They influence the growth as long as they are present. If we liberate tissues or tumors from their influence these substances lose their effect at once or relatively soon. If, however, we are able to transplant certain tumors through forty generations of animals and if the tumors preserve their character as tumors, notwithstanding the individual differences of the different animals into which they are transplanted, then there must be present some factor in or near the tumor cells themselves that constantly stimulates their growth and stirs them restlessly to new activity, until through their activity they destroy their host, and thus prepare their own end. What the character of this local stimulus is, we do not yet know. All the discoveries of organisms that have been announced from time to time were found to be based upon erroneous observations; but that does not exclude the possibility that, after all, a microörganism in intimate relation with the tumor cell is the local stimulus acting on the tumor cell.

There are two discoveries that, in themselves of interest, promise to give us a foothold from which to attack successfully this problem: In the first place the endemic occurrence of tumors among animals, to which we alluded above. Here we can determine whether it is caused by hereditary conditions, or whether it is due to microörganisms or environmental factors. Secondly, the surprising fact we learned three years ago, that if we inoculate one kind of tumor, an epithelial tumor, a carcinoma, into animals, the carcinoma, in a certain number of cases, causes the surrounding connective tissue to assume, likewise, a cancerous growth. We have here, therefore, actually succeeded in producing a new tumor, a sarcoma. Such a fact was entirely unforeseen. It could be discovered only through the experimental method of investigation. The more unexpected a new fact, the more welcome it is; the more it promises to change existing conceptions and to open up new roads, where before no way out could be seen.

Lastly, the first steps have already been taken to find a rational way of curing cancer by procuring immunity in a similar way to that by which we are able to cure a certain number of infectious diseases. Protective sera can not only be prepared against bacteria, against toxins, but also against cells; and probably also against tumor cells. The beginning has been made. Certain tumors in animals have been made to disappear in such a way. Let us hope that the future holds still better results, and that we shall be able to alleviate suffering and to gain a deeper insight into conditions that determine the fate of living matter.

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### *Stated Meeting February 7, 1908.*

Councillor ROSENGARTEN in the Chair.

A letter was read from the Fourth International Congress of Mathematics, announcing that the Congress will be held at Rome, April 6–11, 1908.

PROFESSOR EDGAR ODELL LOVETT presented a report on the "Leçon sur l'intégration des Equations différentielles aux dérivées partielles professées, a Stockholm (Février-Mars 1906) Sur l'invitation de S. M. le Roi de Suède par M. V. Volterra, Senateur du Royaume d'Italie, Professeur de Physique Mathématique à l'Université de Rome." He also presented a paper on "Integrable Oases of the Problem of those Bodies in which the Force Function is a Function only of the Mutual Distances."

PROFESSOR HORACE C. RICHARDS and PROFESSOR ARTHUR W. GOODSPEED read a paper on "Recent Advances in Color Photography."

Photographs by the Lumière process were exhibited by Dr. Hartzell and Dr. W. P. Wilson.

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### *Stated Meeting February 21, 1908.*

Treasurer JAYNE in the Chair.

DR. J. H. HART read a paper on "Artificial Refrigeration."

### *Stated Meeting March 6, 1908.*

Secretary Holland in the Chair.

Letters were read from the Secretary of the Committee of Organization of the Fourth International Congress of Mathematics, to be held at Rome, Italy, April 6–11, 1908, inviting the Society to be represented at the congress, and Vice-President Simon Newcomb was appointed as the Society's delegate.

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### *Stated Meeting March 20, 1908.*

Curator Miller in the Chair.

The death was announced of Sir Samuel Davenport, of Adelaide, Australia.

Dr. George Byron Gordon read a paper on "Some of the Results of the University of Pennsylvania Expedition to Alaska, 1907."

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### *Stated Meeting April 3, 1908.*

Councillor Rosengarten in the Chair.

Letters were received from the Secretary of the Smithsonian Institution informing the Society that the Institution has learned through the Department of State that the Second International Archæological Congress will be held at Cairo, Egypt, on the date of the Latin Easter, 1909, and requesting that the Institution be apprised of the names of scholars likely to attend the Congress.

Dr. Leonard Pearson read a paper on "Some Aspects of the Production and Distribution of Milk."

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### *General Meeting, April 23, 24 and 25, 1908.*

Vice-President Scott in the Chair.

*April 23, Afternoon Session.*

A letter was received from the College of Physicians, of Philadelphia, inviting the President to be present on April 29, 1908, at the laying of the corner-stone of the new building of the College. Owing to the absence of the President in Europe, Secretary James W. Holland, M.D., was appointed to represent the Society at the ceremony.

The following papers were read:

"The Law of Oresme, Copernicus and Gresham," by THOMAS WILLING BALCH, of Philadelphia.

"The Dramatic Function of Cassandre in the Oresteia of Æschylus," by PROFESSOR WILLIAM A. LAMBERTON, of Philadelphia.

"Goethe's Private Library as an Index of his Literary Interests," by PROFESSOR WATERMAN T. HEWETT, of Ithaca, N. Y.

"Art and Ethnology," by EDWIN SWIFT BALCH, of Philadelphia.

"Cytomorphosis, A Study of the Law of Cellular Change," by PROFESSOR CHARLES SEDGWICK MINOT, of Cambridge.

"Preliminary Report on the Brains of the Natives of the Andaman and Nicobar Islands," by PROFESSOR E. A. SPITZKA, of Philadelphia (introduced by Professor J. W. Holland).

"Observations regarding the Infliction of the Death Penalty by Electricity," by PROFESSOR E. A. SPITZKA, of Philadelphia (introduced by Professor J. W. Holland).

"The Brain of Rhinochimaera," by PROFESSOR BURT G. WILDER, of Ithaca, N. Y.

*April 24, Morning Session.*

The following papers were read:

"A Comparison of the Albino Rat with Man in Respect to the Growth of the Brain and of the Spinal Cord," by PROFESSOR HENRY H. DONALDSON, of Philadelphia. (See *Journal of Comparative Neurology and Psychology,* Vol. XVIII, No. 4, 1908.)

"Preliminary Report upon a Crystallographic Study of the Hemoglobins: A Contribution to the Specificity of Vital Substances in Different Vertebrates," by PROFESSORS EDWARD T. REICHERT and AMOS P. BROWN, of Philadelphia.

"Recent Discoveries in the Pathology of Rabies," by MAZYCK P. RAVENEL, M.D., of Madison, Wis.

"The Explosion of the Saratoga Septic Tank," by PROFESSOR WILLIAM PITT MASON, of Troy, N. Y.

"Determination of Dominance in Mendelian Inheritance," by CHARLES B. DAVENPORT, Ph.D., of Cold Spring Harbor, N. Y.

"Inheritance in Protozoa," by PROFESSOR HERBERT SPENCER JENNINGS, of Baltimore.

"The Excretory Organs of the Metazoa: A Critical Review," by PROFESSOR THOMAS H. MONTGOMERY, JR., of Austin, Texas.

"The Classification of the Cetacea," by DR. F. W. TRUE, of Washington.

"Additional Notes on the Santa Cruz Typotheria," by W. J. SINCLAIR, Ph.D., of Princeton, N. J. (introduced by Professor W. B. Scott).

*Afternoon Session.*

The following papers were read:

"Further Researches on the Physics of the Earth, and especially on the Folding of Mountain Ranges and the uplift of Plateaus and Continents produced by movements of Lava beneath the Crust arising from Secular Leakage of the Ocean Bottom," by DR. T. J. J. SEE, of U. S. Naval Observatory, Mare Island, Cal.

"Stratigraphic Observations in the Vicinity of Susquehanna Gap, North of Harrisburg, Pa., by GILBERT VAN INGEN, of Princeton, N. J. (introduced by Professor W. B. Scott).

"Some Chilean Copper Minerals," by PROFESSOR HARRY F. KELLER, of Philadelphia.

"Progress of Demarcation of the Boundary between Alaska and Canada," by PROFESSOR O. H. TITTMANN, of Washington.

"The Leaf Structures of the Bermuda Sand Strand Plants," by PROFESSOR JOHN W. HARSHBERGER, of Philadelphia.

"The Influence of Heat and Chemicals on the Starch Grain," by PROFESSOR HENRY KRAEMER, of Philadelphia.

"A Contribution to a Knowledge of the Fungi of Pennsylvania; Gasteromycetes," by D. R. SUMSTINE, of Wilkinsburg, Pa. (introduced by Dr. A. E. Ortmann).

*April 25, Executive Session.*

The pending nominations for membership were read and the Society proceeded to an election, and the teller of election reported that the following candidates had been elected to membership:

*Residents of the United States:*

Martin Grove Burmbaugh, Ph.D., Philadelphia.
Walter Bradford Cannon, A.M., M.D., Boston, Mass.
James Christie, Philadelphia.
William Hallock, Ph.D., New York City.
Edward Washburn Hopkins, Ph.D., LL.D., New Haven, Conn.
Leonard Pearson, B.S., V.M.D., M.D., Philadelphia.
Josiah Royce, Ph.D., LL.D., Cambridge, Mass.
Jacob G. Schurman, Ph.D., Ithaca, N. Y.
Charles Henry Smyth, Ph.D., Princeton, N. J.
Herbert Weir Smyth, Ph.D. (Göttingen), Cambridge, Mass.
Henry Wilson Spangler, M.S., Sc.D., Philadelphia.
Edward Anthony Spitzka, M.D., Philadelphia.
John Robert Sitlington Sterrett, Ph.D. (Munich), Ithaca, New York.
Richard Hawley Tucker, Mt. Hamilton, California.
Robert Williams Wood, Ph.D., Baltimore.

*Foreign Residents:*

Ernest Nys, Brussels.
Albrecht F. K. Penck, Ph.D., Berlin.

*Morning Session, 10.30 o'clock.*

The following papers were read:

"The Solution of Algebraic Equations in Infinite Series," by PROFESSOR PRESTON A. LAMBERT, of Bethlehem, Pa.

"The Investigation of the Personal Error in Double Star Measures which depend on the Position Angle," by MR. ERIC DOOLITTLE, of Philadelphia.

"Some Results of the Ocean Magnetic Work of the Carnegie Institution of Washington," by DR. L. A. BAUER, Director of the Department of Terrestrial Magnetism, Washington (introduced by President Robert S. Woodward).

"Photographs of Daniel's Comet," by PROFESSOR E. E. BARNARD, of Yerkes Observatory, Williams Bay, Wis.

"Astronomical Photography," by DR. JOHN A. BRASHEAR, of Allegheny, Pa.

"The Completion of the Lunar Theory and the Tables of the Moon's Motion to be made therefrom," by Professor Ernest W. Brown, of New Haven.

"The Relative Advantages of Various Forms of Telescopes for Solar Research," by Professor George E. Hale, of Solar Observatory, Pasadena, Cal.

"Problems of Three Bodies on Surfaces," by Professor Edgar Odell Lovett, of Princeton, N. J.

"A Living Representative of the Most Primitive Ancestors of the Plant Kingdom," by George T. Moore, Ph.D., head of the Department of Botany, Marine Biological Laboratory, Wood's Hole, Mass.

*Afternoon Session.*

The following papers were read:

"The Effect of an Angle in a Wire Conductor on Spark Discharge," by Professor Francis E. Nipher, of St. Louis.

"Absorption Spectra of Solutions," by Professor H. C. Jones, of Baltimore (introduced by Professor Ira Remsen).

"The Effect of Certain Preservatives upon Metabolism," by Harvey W. Wiley, M.D., of Washington.

"A Vedic Concordance," by Professor Maurice Bloomfield, of Baltimore.

"On the Lost Tribes of Israel and the Aryan Ancestry of Jesus and His First Disciples," by Professor Paul Haupt, of Baltimore.

"The Sign and Name for Planet in Babylonia," by Professor Morris Jastrow, Jr., of Philadelphia.

"Mediæval German Sculpture in the Germanic Museum of Harvard University," by Professor Kuno Francke, of Cambridge.

"Notes on Greek Vases in the Museum of Science and Art of the University of Pennsylvania," by Professor William N. Bates, of Philadelphia (introduced by Professor Wm. A. Lamberton).

# THE LAW OF ORESME, COPERNICUS AND GRESHAM.

By THOMAS WILLING BALCH.

(*Read April 23, 1908.*)

Among the most certain laws known to economic science is the one that, when two moneys of unequal value are placed in circulation at the same time side by side as currency of the realm, the poorer or cheaper will drive the better or dearer from circulation. This law, though fought over most strenuously in this country within recent years, as if its immutable operation had not been thoroughly demonstrated in past ages of humanity, was known in part at least to the Ancients. Of this there is ample proof in the "Frogs" of Aristophanes. In that play, the foremost comic poet dramatist of Greece places in the mouth of the chorus these lines:

"Oftentimes have we reflected on a similar abuse
In the choice of men for office, and of coins for common use;
For your old and standard pieces, valued and approved and tried
Here among the Grecian nations, and in all the world beside,
Recognized in every realm for trusty stamp and pure assay,
Are rejected and abandoned for the trash of yesterday;
For vile, adulterate issue, drossy, counterfeit and base,
Which the traffic of the city passes current in their place."[1]

In Bohn's Classical Library this passage is thus rendered: "The freedom of the city has often appeared to us to be similarly circumstanced with regard to the good and honorable citizens as to the old coin and the new gold. For neither do we employ these at all, which are not adulterated, but the most excellent, as it appears, of all coins, and alone correctly struck and proved by ringing everywhere, both among the Greeks and the barbarians, but this vile copper coin, struck but yesterday and latterly with the vilest stamps."

In the above quotation it is distinctly shown that the better coins that had been current were driven out and replaced by pieces of inferior value. And as a poetic mind like that of Aristophanes could hardly have understood, much less have discovered such a subtle unwritten law of money, had not some knowledge of it been

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[1] Frere's translation.

the common possession of the intellectuals of Greece in the epoch in which he lived, we can infer from Aristophanes's statement of it, that the Grecian states passed through the ups and downs of a change in the standard of value caused by a debasement of the currency.

The same state of affairs existed among the Romans, and the amount of benefits and evils that obtained in the reign of each Roman emperor can in a measure be judged by the greater or less purity of the coinage issued in their respective reigns.

The experiences of the ancient world with money as the mechanism of exchange were largely known to the peoples of the Middle Ages, and they had to discover for themselves at a great and bitter cost that any attempt to debase the currency only results in the good money disappearing from circulation to the ruin of the commonwealth and of its inhabitants, especially of the poorer members.

Three men, exercising three different callings, but all three profound students, and two of them ranking among the scholars of the world, in three different countries, in three distinct periods of time, discovered independently of one another and explained to their respective sovereigns that when into the currency of a country a poorer or cheaper money is injected by the side of a better which is the standard of value, the certain and immutable result will be that the currency of the realm will be debased to the standard of the poorer money. For as it will then be possible to pay debts in either money, people will naturally pay them in the cheaper currency, selling the better money by weight at the premium that it will command in the standard of the poorer currency.

These three men were Nicole Oresme, Bishop of Lisieux in Normandy, who stated this subtle unwritten law of money for Charles the Fifth of France, surnamed the Wise; Nicolaus Copernicus of Thorn in Prussia, the discoverer of the Copernican theory of astronomy, who expounded this same law of the currency for Sigismund the First of Poland; and Sir Thomas Gresham, a noted English merchant, who explained it to Elizabeth of England. It is proper, then, that in honor of these three discoverers of an economic truth that is a precious thing for humanity to know, that this law should be called the Law of Oresme, Copernicus and Gresham.

Oresme and Copernicus each prepared a learned and comprehensive treatise for their respective sovereigns on the practical functions and workings of money, and Gresham wrote a letter to his Queen in which he pointed out to her that good and bad coin could not circulate together. No branch of science arises all developed at one bound from the brain of a single man as Minerva sprang all armed from the head of Jove. It advances by successive degrees, as one scholar after another, armed with the knowledge acquired by his predecessors, develops further what the human race knows of the laws of the universe. And as Hugo Grotius, who assembled from all points of the compass the rules and usages that princes and cities observed in his day in their relations one with another in his monumental work, "De Jure Belli ac Pacis," and gave them a further advance in the trend of a humane and civilized development, has justly been called ever since the father of the science of International Law, so Nicole Oresme and, a greater man than he, Nicolaus Copernicus, for their pioneer work in the exposition of the true rules that govern money as the medium of commercial exchange, have just as truly been described by MacLeod as the Castor and Pollux of monetary science. They both delved into the past experiences in the matter of money of their respective countries, and probably made use of much of what the Greek and the Roman publicists had said on the subject. The work of Grotius first redounded to the advantage of humanity by the application of many of the humane principles that he advocated by their practical adoption by Gustavus Adolphus of Sweden in the terrible Thirty Years War. The light shed by Oresme and Copernicus on the functions of currency first helped to lighten the burdens of humanity through their application by Charles the Fifth of France and Sigismund the First of Poland. And a generation after the true expounder of our solar and planetary system had prepared his treatise on money, Sir Thomas Gresham likewise, through Elizabeth of England, aided the human race to derive the advantages that are conferred upon society by an honestly maintained measure of value.

The importance of the economic work of Nicole Oresme was first revealed to the world at large in 1862 by William Roscher, professor of political economy in the University of Leipzig. Oresme's master work, "Tractatus De Origine, Natura, Jure et Mutationibus Monetarum," was often referred to before that time. But in every case before Roscher saw Oresme's work in manuscript, the examiners of Oresme's learned and lucid treatise failed to grasp its real importance. When, however, it came under the eye of Roscher, a trained economist, he saw at once the profound significance of the work. Under the title of "A Great French Economist of the Fourteenth Century," Roscher called the attention of the world to Oresme's treatise on money. Two years later the French naturalized Pole, Louis Wolowski, also signalized to his adopted country the work of the fourteenth century economist.[2]

Nicole Oresme, who may be looked upon as the first scholar, so far as we now know, to expound comprehensively money as the mechanism of exchange, was by birth a Norman. He studied at the University of Paris, where he was classed in the Norman nation. At the university, Oresme was reputed to be the most able and learned in his knowledge of the sciences and the fine arts. He translated at the request of Charles the Fifth the "Ethics," "Politics," and other works of Aristotle. He delivered at Avignon on December 24, 1363, before Pope Urban the Fifth and the members of the sacred college a sermon in which he censured the high clergy of France. Charles also commissioned him to translate the Bible, in order that this vernacular version might be opposed to that of the Waldensians.

When Charles the Fifth succeeded to the throne of his ancestors, the French, crushed by what was for those times an enormous debt, were groaning under the weight of the accumulated mismanagement of previous rulers, and the "*royaume des lys*" had shrunk to small proportions before the English invasion, and was fast disappearing in misery and anarchy. Owing to the capture of Charles's father, King John, by the English, Charles was called upon to act as regent. During those years he learnt much which later as king he put to valuable practical use. Reigning from 1364 to 1380 under the title of Charles the Fifth, he was, for his able management of the affairs

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[2] "Traictie de la première invention des Monnoies de Nicole Oresme" textes français et latin d'après les manuscrits de la Bibliothèque Impériale et "Traité de la Monnoie de Copernic," texte latin et traduction française publiés et annotés par M. L. Wolowski, membre de l'Institut. Paris, Guillaumin et Cie., 1864.

of his kingdom, justly surnamed the Wise. This honorary title, Charles the Fifth, who was a capable and sagacious man, was entitled for in great measure to the fact that he surrounded himself and relied upon the services of men of first rate ability who had strengthened their natural capacities by hard work, such generals as the Breton, Bertrand du Guesclin, such scholars as the Norman, Nicole Oresme. It was Charles the Wise, too, who, in beginning the first collection of manuscripts in the Louvre, that afterwards became the Bibliothèque Royale, then the Bibliothèque Imperiale, and to-day is known as the Bibliothèque Nationale, was the founder of what is to-day the largest depository of learning in the world.

The chief cause of the unhappy state in which the French people found themselves when Duc Charles became king in 1364 was in large measure due to the tampering by their rulers with the weight of the value of the coins of the realm. Many of the French kings had thought to raise revenue by forcing their people to accept a debased coinage. Of these royal false coiners, Dante flays Philip the Fair (1285–1314) in the *Paradiso* in these words:

> "La si vedra il duol che sopra Senna
> Induce, falseggiando la moneta."[3]

In addition to debasing the coinage, the French sovereigns again and again changed the mint price of gold and silver. In the reign of King John the Second, the value of the *livre tournois* was changed between 1351 and 1360 no less than seventy-one times.[4] And what made the resulting confusion from this unjustified and foolish meddling with the measure of commerce still worse was that sometimes the value of the *livre tournois* was raised and sometimes it was lowered. As a result, far from filling the coffers of the king, this policy prostrated commerce, and the wealth in the realm of France shrank. When Charles the Fifth, upon his father's death, ascended the throne, he called upon Nicole Oresme, in order that he might reform the coinage of France, to shed light upon the confused currency of the kingdom. And thus it was that Oresme prepared his most important work, already referred to, the first comprehensive

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[3] "There shall be seen the woe that he shall pour
Along the Seine by debasing the coinage."

[4] Wolowski.

treatise upon money, entitled "Tractatus De Origine, Natura, Jure et Mutationibus Monetarum."

Of this work many manuscript copies of the Latin original were made, and also of a French translation by the author himself under the title "Traictie de la premiere invention des monnoies." This translation was placed as early as 1373 at least in the library collected by the direction of King Charles in the Louvre.

Oresme, in stating the various workings of money as the mechanism of exchange, explained in precious words to his sovereign that, whenever the public currency was altered or tampered with in such a way as to bring into circulation two moneys, bearing the same designation but in reality having two different values, the money of lower value inevitably drove the money of higher value out of circulation. For the merchants found it to their advantage either to melt down the pieces of money that contained the higher amount of metal and to sell the bullion by weight or else to export the high weight coins to other lands. Thus Oresme says: "The rate of exchange and the price of the moneys must be for the kingdom as a law and a firm ordinance which in no way must alter or change." And further in speaking of the ratio of exchange between gold and silver, Oresme points out that the value or proportion in which those metals are exchanged in their natural state, is the rate of exchange that must be maintained between gold and silver currency. For if a given amount of gold is worth twenty times as much silver, then a *livre* of gold would be worth twenty *livres* of silver, a *mark* of gold twenty *marks* of silver. "But always this proportion," he says, "must follow the natural habit or rate of gold to silver, in value." The mutations of the currency are of great peril to the national welfare "for the injury which comes by it," he says, "is not so soon felt nor seen by the people, as it would be by another tax, and nevertheless no such nor similar can be more grievous or greater; and, in addition, gold and silver, by such mutations and changes, shrink and diminish in a kingdom, and in spite of all vigilance and prohibition that may be taken, they go abroad where they are accorded a higher value for, by adventure, men carry more voluntarily their moneys to the places where they know these have a greater value."

The luminous treatise of Oresme on money opened the eyes of King Charles to the disastrous results to a country whose government attempted to alter the basic value of its currency. As regent of France during the captivity by the English of his father, King John the Second, who was captured at Poitiers in 1356, Charles had not escaped the prevailing custom among rulers of that epoch to fill the royal purse by debasing the coins of the realm. In the previous century the great ordinance of 1255, which the States Generals of France, assembled at Paris, obtained from the king, Louis the Ninth, promised sound and stable money for the whole kingdom of France, so that the mark of silver should never produce more than six *livre tournois.* This royal promise was broken again and again by the French sovereigns, and Duc Charles, as regent for his captive father, said the value of the mark should be worth twelve *livre tournois.* This cutting in half of the measure of value was the signal for the great rising at Paris in 1357 under Etienne Marcel, the Prevost of the Paris merchants, and it was with difficulty that the regent reasserted the royal authority in the city.[5] The distracted and poverty-stricken state of the people and the low ebb of the kingly power, reënforced by his practical experiences as regent, caused Charles the Wise, though of a physique so frail that he could not march at the head of his army in those years of strife and peril, yet endowed with a superior mind and seeking the advice of sage advisers, to set himself to reorganize the finances of France. The luminous thoughts expressed in the treatise of Oresme he made his own, and during his reign the weight of the gold currency remained a fixed and unchanged quantity, and that of silver was but very triflingly altered. The resulting stability in the value of money, the measure of commercial exchange, reëstablished the regularity of commercial transactions, and furnished an important element to public prosperity. The resources of the realm augmented and with them the power of King Charles grew. To honor the scholar who had made plain the confusion that resulted from tampering with the standard of value, the money of the realm, King Charles had Oresme elected in 1377 Count Bishop of Lisieux in Normandy. And it was there, two years after the king's death in 1380, that the great

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[5] Wolowski.

economist died on July 11, 1382, regretted especially by the scholars of his day.

The economic truths that Oresme so well stated in his treatise on money did not become widely known, for his work was written for his king's information, and Gutenberg had not yet made it possible through printing to give them a wide circulation. The truths that Oresme taught and upon which Charles the Wise acted, to the profit of his kingdom and therefore of himself, became in great measure forgotten. A century and a half after Oresme's death they were rediscovered and restated a second time. In the year 1526, in a Latin treatise entitled "Monete Cudende Ratio," written at the request of Sigismund the First, King of Poland, and his Chancellor, Szydlowiecki, Nicolas Copernicus of Thorn in Prussia, who had elucidated for mankind some of the celestial harmonies, gave to the world an exposition of some of the economic truths. Independently of the work of Oresme, of which the Prusso-Polish scholar knew nothing, Copernicus made clear for his sovereign that two moneys of unequal value could not be kept in circulation at the same time. "Gold or silver," he writes, "marked with an imprint, constitutes the money which serves to determine the price of things that are bought and sold, according to the laws established by the State or the Prince. Money is therefore in some sort a common measure of estimating values; but this measure must always be fixed and must conform to the established rule. Otherwise, there would be, necessarily, disorder in the State: buyers and sellers would at all times be misled, as if the ell, the bushel or the weights did not maintain constant quantity.

. . . . . . . . . . . .

> "The establishment of money has necessity for cause. Though in weighing only gold and silver it would have been possible to practice exchanges, those metals, from the unanimous consent of men, being considered everywhere as precious things, nevertheless there would be numerous inconveniences to have to carry always weights along, and, all the world not being apt to recognize at the first glance the purity of gold and silver, it is agreed everywhere to have money marked by government with a stamp designed to show how much each coin contains of gold and silver and to serve as a guaranty to public faith."

Then he explains how the value of metal pieces is changed and depreciated.

> "The value of money is depreciated by various causes, either by the change of the name, while the same weight of metal contains a mixture of copper which exceeds the measure desired; or because the weight is wanting, although the mixture has been accomplished in the right proportion; or, what is the worst, because the two vices meet together at the same time. The value of money diminishes of itself by reason of a long service that uses the metal and diminishes its quantity and this reason suffices to cause to be placed in circulation a new money. This necessity is recognized by an infallible sign, when the money weighs notably less than the money intended to be acquired. It is understood that there results a deterioration of the money."

At the time Copernicus prepared his treatise on the money of the realm for his sovereign liege, King Sigismund, the Polish Kingdom included Thorn, Danzig, and a large part of Prussia. But a portion of Prussia, including Konigsberg, had been erected by the treaty of Cracow, concluded in 1525 between Sigismund, King of Poland, and Albert, Margraf of Brandenburg, into a hereditary fief for the benefit of the latter and his male descendants, which the margraf was to hold of King Sigismund. As by this feudal tenure by Margraf Albert of part of Prussia, subject to the overlordship of the Polish king, the two countries were in a sense one, Copernicus, in his treatise on the money of the realm, expounded to his king what measures were necessary in order to restore stability to the much depreciated Prussian money and then maintain the value of the new money on a parity so that it could circulate both in Poland and Prussia. After pointing out how useless it was to attempt to introduce into circulation by the side of a depreciated currency one of greater value, he then explained how the introduction of a cheaper measure of value by the side of a higher one would drive the former from circulation.

> "If it does not do to introduce a new and good money, while the old is bad and continues to circulate, a much greater error is committed by introducing alongside of an old currency, a new currency of less value; this latter does not merely depreciate the old, it drives it away, so to speak, by main force."

Then in answer to the argument that a depreciated currency helps the poor, he says:

> "We see flourish the countries that possess a good currency, while those that only have a depreciated one, fall into decadence and decline. . . .

"It is incontestable that the countries that make use of good currency shine in all the arts, have better workmen, and have of everything in abundance. On the contrary, in the States which make use of a degraded money, reigns cowardice, laziness and indolence."

In order to remedy the distress to which Prussia had been brought by the falsification and debasement of the currency, and to draw Prussia and Poland closer together by developing their commercial relations, it was necessary to coin two moneys of equal intrinsic value, so that they would circulate concurrently in the two lands. One should bear one one side the royal arms of Poland and on the other those of the Prussian land. The other money should likewise have on one side the royal arms of Poland, but on the other the imprint of the prince, that is, the effigy of the king.

"For the first condition to maintain, is that one and the other currency remain under the royal authority, and that they be current and accepted in the whole kingdom by virtue of the prescription of His Majesty; which would be not of a mediocre importance for the conciliation of public opinion and for reciprocal transactions.

"It would be necessary that these two currencies should be of the same degree of fineness, having a similar real value and a similar nominal value, so that, by vigilant care, the State succeeds to maintan perpetually the regulation which it is now question to establish; it does not belong to princes to obtain any profit from the money that they shall coin; they shall add only so much alloy as may be necessary for the difference between the real value and the nominal value to cover the cost of minting, which will avoid the principal attraction to remelt it.

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"It would be necessary, at the time of the emission of the new money, to demonetise the old and forbid entirely its use, allowing it to be exchanged at the mints, in the just proposition of the intrinsic value. Otherwise it would be labor lost to wish to reestablish good money; the confusion that would ensue would be perhaps even worse than the actual state of affairs. The old money would crush all the advantages of the new."

Then Copernicus explained that gold and silver were the base upon which rested the value of money; and went on to show that in order to maintain them both in circulation the ratio between them must agree with the commercial ratio that existed between them.

"It remains," he went on, "for us to expound the manner of the mutual exchange of gold and silver. In order to pass from the class to the kind and from the simple to the composite, it is necessary first to know the price of pure gold to pure silver. It is known that the same exists between pure gold and silver, as between gold and silver minted under the same stamp; as also that the same ratio applies to gold coins and gold bars as to silver coins and silver bars, provided that they have the same proportion of alloy and that they represent the same weight."

As Oresme and Copernicus explained to their royal masters that by either debasing or raising the coins of the realm disaster and confusion would follow, so also, at the beginning of Queen Elizabeth's reign, one of her merchants, Sir Thomas Gresham, pointed out to his royal mistress this inflexible unwritten law of money.

Of a Norfolk family, the son of Sir Richard Gresham, who was Lord Mayor of London, Sir Thomas Gresham was born in that city probably in 1519, and died there on November 21, 1579. He was educated at Cambridge University, was a Protestant, and all his life took an active part in commercial affairs, often representing in the Low Countries the commercial interests of England. In 1566 and 1567 he built the Royal Exchange in London. He founded also Gresham College, and provided that the science of astronomy should be taught there.

In a letter to Queen Elizabeth, which is headed "information of Sir Thomas Gresham, Mercer, touching the fall of the exchange, MDLVIII," and which begins, "To the Quenes most excellent maiestye," Gresham says:

> "Ytt may pleasse your majesty to understande, thatt the firste occasion off the fall of the exhainge did growe by the Kinges majesty, your latte ffather, in abasinge his quoyne ffrome vi ounces fine to iii ounces fine. Whereuppon the exchainge fell ffrome xxvis. viiid to xiiis. ivd. which was the occasion thatt all your ffine goold was convayd ought of this your realme."

The works on money of these three men, who, independently of one another, expounded to their respective sovereigns the evils resulting to the State from any attempt to debase the coinage, did not become generally known to their contemporaries. However, their discoveries through the influence of their royal rulers gradually made some impress upon mankind, and by the end of the seventeenth century it had become common knowledge among the intellectuals of that day. In a pamphlet published in London in 1696, the Law of Oresme, Copernicus and Gresham, though doubtless the writer did not know directly of their works, is thus stated:

> "When two sorts of Coin are current in the same nation of like value by denomination but not intrinsically [that is in commercial value], that which has the least value will be current, and the other as much as possible will be hoarded."

In 1858 the British economist, Henry Dunning MacLeod, called attention to Gresham's statement of this unwritten law of coinage, and suggested that it should be known as Gresham's Law. At the time he did not know of the more elaborate treatises of Oresme and Copernicus on coinage. But when the works on money of those two master economists were revealed through the efforts of Roscher and Wolowski in 1862 and 1864 to the world at large, MacLeod, like a true scholar who wishes to give credit to whom honor is due, suggested that this economic law, a law more powerful than the statutes enacted by the strongest Parliamentary bodies, should be known after all three of its discoverers as the Law of Oresme, Copernicus and Gresham.

During the centuries, many nations in various parts of the world have had abundant experience to learn the futility of attempting to maintain in circulation as currency two moneys at a ratio different from the market or commercial ratio existing at that time between those two kinds of money. In every case where such an effort has been made, the money that is underrated gradually drives that which is overrated from the country. And this nation has had several experiences with this law. Without touching here upon the works of other economic scholars, such as Petty, Locke, Wolowski, Jevons, Leon Say, Horton, Bamberger, Laughlin, White and others, who have added to our knowledge of the unwritten laws that govern money as the medium of exchange, it can be safely said that the more the economic experience of the human race is studied, the more does it become clear that any attempt to tamper with the currency of a nation by injecting a debased money into its measure of value is certain to end in disaster through the working of that natural law of finance, the Law of Oresme, Copernicus and Gresham.

# ART AND ETHNOLOGY.

By EDWIN SWIFT BALCH.

(*Read April 23, 1908.*)

Man has been studied in many ways and from many directions: history, language, archeology, anatomy, natural history, geography and other sciences have been called upon in the elucidation of the problems of his history, descent, evolution and origin. The evidence which has been gathered from these many different sources about man and his history may be divided into two classes: that which can be obtained from his own personality or his own remains, a class I do not need to mention again in this paper; and that which can be obtained from what man has produced, and this class of evidence may be subdivided into three sub-classes, namely, written records, implements and art.

The most primarily available evidence in tracing the story of the human race is, of course, written records, and whenever we find written records which we can interpret we speak of history; but when, as in the case of savages, there are no written records, or when, as in the case of Old Mexico, we cannot read the records, the subject changes from history into ethnology and pre-history.

When there are no written records, another class of evidence, that obtained from implements, is largely resorted to by ethnologists. The term "implements," as used in this paper, should perhaps be defined as an abbreviated name for the products of the mechanical arts, without some of which at least no man can live. All modern implements have evolved from primitive beginnings, as, for instance, the twelve-inch shell, which is really the most modern form of the flint arrowhead. Much light has been shed already and more will be shed on the story of man by a comparison of the various implements used in different places and at different times.

The other great class of evidence is art, under which term must be understood the fine arts of sculpture, drawing and painting.

Some use has been made of this class of evidence; nevertheless, it is far below what it should be and usually it is only local in its deductions. There are plenty of treatises relating to the art of the white races, of the modern Europeans, of the Romans, of the Greeks; some on Egyptian art; others on Kaldean art and Assyrian art; some on Old Mexican art and Peruvian art, and so forth. But so little is the subject worked out even locally, that there is practically no special publication about African art or Brazilian art, and it is only within the twentieth century that we find the first serious attempt to trace back the wonderful art of China. As a subject of study, either from an artistic or an ethnological standpoint, the art of the world as a whole is so far almost untouched. Even in such an excellent recent art history as Mr. S. Reinach's "Art Throughout the Ages," one finds that by art he means European art alone and that Hindu art or Chinese art or Mexican art are left out in the cold. Whether art comes from only one center or whether there are several foci of dispersion; what relations, what resemblances, and what differences there are in the art of the world as a whole, is as yet an almost virgin field. If I am not mistaken, only one attempt has been made (by the writer himself) to study and classify art in every district of the globe.

Probably the main reason why art in totality is still so largely unstudied is that it is only recently that art specimens from everywhere have been collected, placed in museums, and made accessible. But, connected with this placing of art specimens in museums, there is a curious fact which shows that the art of the world, at present, appears to hang in a sort of borderland between art and science. The specimens are divided. Some are placed in art museums, others in ethnological museums. For instance, in Philadelphia, art specimens are divided between the Pennsylvania Academy of the Fine Arts and the University Archeological Museum; in Washington, between the Corcoran Gallery and the United States National Museum; in New York, between the Metropolitan Museum and the American Museum of Natural History; in Boston, between the Museum of Fine Arts and the Cambridge Peabody Museum. There is no place where anyone can go and get a comprehensive view of art from all over the world.

The art of at least half the races of the world has thus found its way into ethnological museums. There it is not yet culled out as art, but the specimens are looked on rather as belonging to the class which can be most briefly called implements. This is not to be wondered at. Ethnologists, as a rule, have not had any special art training. Among artists it is a pretty thoroughly understood thing—and this can be stated only as a dictum and not discussed in this paper—that only a trained artist can criticize art seriously; in fact, the present most prevalent opinions about art are largely the consensus of opinion of the many artist art critics of modern times. Whilst possibly unconscious of this fact, ethnologists are usually aware of their inability to discuss the esthetic qualities of art specimens, and hence, while they frequently study the decorative art of savages, its patterns and its origins they are apt to leave the esthetic qualities of art alone.

Whilst scientists, therefore, generally do not give much thought to the esthetic points of the art specimens in ethnological museums, on the other hand, artists and art critics so far have paid no attention to such arts as African or Australian art. In the overwhelming majority of cases, they are doubtless unaware of the existence of such arts, and if they did know of them they would in many cases despise them, because these arts do not have the qualities of Greek art or Japanese art or French art. Art critics also usually know nothing of ethnology, and certainly care less. It takes a good deal of time and thought and study to learn something of ethnology, and any scientist knows that only a specialist can really give an opinion about it. The result of these somewhat complex conditions is that both ethnologists and art critics have neglected the esthetic arts of perhaps half the races of the world.

It seems as if it should be recognized that the present state of things leaves a gap in knowledge. It is time that this gap should be filled in and that the art of the entire world should be worked out as a whole into its proper divisions and its relations. Practically this will amount to forming a new branch of science, a science which might well be termed comparative art, and it seems just as necessary that there should be a science of comparative art as a science of comparative philology or a science of comparative anatomy. It will be a science in which art critics and ethnologists will have to work hand in hand; it will either have to be worked out by trained artists and also by ethnologists, or better still, comparative art must be handled by men who are something of specialists in both fields.

Comparative art should not be confounded with comparative archeology. Although there are points of contact, the fields are different. Comparative archeology is mainly based on the results of digging with the pick and the spade. It includes studies of certain phases of art and architecture, of inscriptions, of implements, and some other things. It does not deal with the work of the Eskimo, or the Australian, or the Ashantee of to-day. It is a study of past things.

Comparative art, on the contrary, must deal, not only with the past, but also with the present. It will not be a study of written inscriptions, nor of implements, but it will be a study of art, and architecture so far as this is a form of the fine arts, and it must be applied to every district of the globe, not only to the remotest past in which there was art, but to the actual present of to-day and to the future. It will deal not only with the art of the Pleistokenes and the Assyrians, of the Chinese and the Aztecs, but also with the art of the tribes now living in the Amazon and Kongo forests, in the islands of the Pacific, and on the shores of the Arctic.

Now I do not wish to claim that the study of art specimens is going to clear up all the problems of ethnology, or do away with other methods of studying man and his history, or anything else of that kind. I only want to say that here is a field still mainly untilled, in which there is much work to be done, and from which, when it is properly plowed up, a valuable crop of scientific data may be expected.

That comparative art will bring up new problems and perhaps alter some theories of the present seems probable. For instance, it was formerly generally accepted that there are five races of men: a white, a yellow, a brown, a red and a black. Then other theories were started: one that there are only three races, a white, a yellow and a black; and another that there are four races, a white, a yellow, a red and a black. A study of the art of the world, however, tends to make one revert to the older theory of five main races, if indeed it does not point to more than five. For it seems as if there were sufficiently numerous distinct arts, with sufficiently individual racial characteristics, as to necessitate the classifying them provisionally into at least five and possibly more main classes, corresponding to the five or more races of man from which these arts spring.

Let me now give you some concrete examples of how art can help clear up ethnology. Take the Pleistokene men of western central Europe, usually mistakenly called the Cave men. We have no written records from the Pleistokenes, but we have implements and art. Their implements show that they must have lived near the edge of a great ice sheet and that their habits must have been not unlike those of the Eskimo of to-day. But their art tells us a great deal of which the implements give no hint. In the first place Pleistokent arts tells us the fauna amongst which these men lived. It takes us back to a past geological epoch, when the mammoth and the woolly rhinoceros tichorinus roamed over western Europe. It proves and is the only proof that they had domesticated the horse and possibly the dog and that they lived sometimes in habitations not unlike the teepees of the Red Amerinds. In the next place Pleistokene art reveals the fact that these earliest positively known men were unquestionably advanced in some mental characteristics. They had certainly stopped hanging on by their tails. No one who was not distinctly intelligent could possibly have made their sculptures, their drawings and their paintings. Another fact their art shows is that in all probability they were not a Negroid race. Ordinary Bantu art, and also the art of Great Benin, is too unlike Pleistokene art to warrant the belief that its makers could have been blood relations of the Pleistokenes. Certain qualities of Pleistokene art suggest early Greek art, but there are more resemblances which suggest Chinese or Eskimo work, so that the evidence of art, and it is the strongest evidence on the subject, is that the earliest known race was a yellow race.

Take the case of the eastern United States. Mr. Henry C. Mercer, I believe, and many other ethnologists claim that there is no civilization preceding that of the Amerinds or American Indians on this continent. Dr. Charles C. Abbott *per contra* claims that there is an earlier geological horizon whose argillite implements show there was an earlier race. Unfortunately, there are apparently no art specimens known from the same horizon as these argillite implements. But the lucky finding of a few, only a few, works of art, in undisturbed strata, would tell us positively whether those argillite implements belonged to the Amerinds or whether there really was a previous race. In other words, art would tell us what the implements do not.

Take now the case of the people who inhabit the oceanic fringe of Alaska and British Columbia. I believe ethnologists consider that they are members of the red race of America. But their art raises doubts. Whilst it has certainly some resemblances to the art of Old Mexico and of the United States, it has many more to the art of the brown races of the Pacific. It is more nearly in touch with New Zealand art, with New Guinea art, and so forth, than it is with the art of the rest of America. It shows pretty definitely that, even if these northwestern tribes are not primarily a Pacific island race, yet there must have been some intercourse and some immigration, else they could not produce works of art so similar to those of some of the tribes in the southern Pacific.

Let me give you one more instance. The present art of Japan is an intrusive art which came over from China some fifteen hundred years ago, as is shown by written records. Art critics are only just beginning to find out that it has never risen to the heights reached by its parent art of China. But digging has revealed the fact that there was some more elementary art in Japan which was probably earlier than the Chinese influence. This and some of their own more recent work, their discarded suits of lacquered armor are notable examples, have art qualities which are not Chinese. They are much more in touch with some South Sea art, with that of New Ireland, for instance. The evidence of their art would tend to show that the Japanese were a brown race, who adopted much of Chinese civilization.

To sum up now briefly the gist of this paper, I would submit the following main points:

1. Art is found in every part of the world.

2. Art as a whole has not been studied and examined enough as yet.

3. The art of the whole world should be studied from an esthetic point of view not only locally and individually, but in its broadest relations, in its resemblances and its differences. This branch of science might well be called comparative art.

4. Comparative art, that is the study of the relations in the art of the world, must be done from the esthetic standpoint by persons who are trained art critics.

5. Comparative art, properly worked out, may be expected to throw much light on the story of man.

# THE BRAIN OF RHINOCHIMAERA.

By BURT G. WILDER.

*(Read April 23, 1908.)*

Four years ago, to the small but very peculiar and ancient group of shark-like fishes known as Chimeroids, Holocephala and Chismopnea, Garman added a Japanese species, *Rhinochimaera pacifica.* His description of the brain was brief and the figures represented only the general form from the dorsum, venter and side. A well-preserved example recently obtained from Alan Owston of Yokohama enables me to confirm Garman's account as to the general Chimeroid character of the brain, especially the cerebellum and adjoining segments, and as to the extraordinary—probably unique—slenderness of the other regions, due not merely, as in Chimaera, to the elongation of the cerebral crura, but also to the pedunculate condition of the olfactory bulbs, whose tracts or crura equal the cerebral in length. The partial dissection of this brain discloses additional features, as shown upon the colored crayon diagram, viz., (1) The cerebral and olfactory cavities. (2) The complete circumscription of these cavities by walls of moderate thickness at the olfactory bulbs and parts of the cerebral hemispheres, but mostly thin and largely membranous. (3) The olfactory crura have thinner walls than in any brain known to me, and the proper nervous substance seems to be confined to their outer or lateral sides. (4) The roof of the undivided cerebral cavity is wholly membranous; likewise a narrow mesal zone of the floor, but the floors of the hemispheres are connected by a terma ("lamina terminalis") as described by me in *Chimaera* in 1877. (5) Each substantial wall of the cerebral cavity begins as a single broad band which divides into a ventral and a lateral portion as it approaches the hemisphere; this condition has not been observed by me in any other brain. (6) There was found no trace of the *Nervus terminalis* of Locy; nor has it been recognized in any other member of the group.

Even were our knowledge of structure, development and geologic records more complete, and even were there more substantial agreement as to the bearing of the facts upon the affinities, rank and succession of the forms concerned, a detailed description of this brain and a full discussion of the significance of its resemblances and peculiarities would be profitable before a comprehensive society like this only when, as urged by me in this hall three years ago, the concrete foundations of neurology are laid in the primary schools, and when no child reaches the age of ten without exposing for himself, drawing, dissecting and describing the brain of a shark.

CORNELL UNIVERSITY, April 20, 1908.

# OBSERVATIONS REGARDING THE INFLICTION OF THE DEATH PENALTY BY ELECTRICITY.

By EDW. ANTHONY SPITZKA, M.D.

(*Read April 23, 1908.*)

A great variety of methods of inflicting the death penalty has been devised by the inventive mind of man. The earlier forms are chiefly characterized by cruelty, by an intense and passionate desire to wreak vengeance and inflict pain upon the condemned and to instill terror into the minds of onlookers. I will not review the ancient methods in detail. There is the *burning at the stake* by the Romans, Jews, ancient Britons, Chinese and by the Spanish Inquisition; *beating with clubs* in Greece and many African countries; *beheading* by axe and block, the sword and the guillotine; *blowing from a cannon,* either by lashing the condemned to the muzzle or by thrusting him into it as a part of the charge; *boiling* in water, oil, melted sulphur, melted lead; *breaking on the wheel; burial alive; crucifixion,* a lingering method in which death was sometimes hastened by the thrust of a spear or a blow with a club; *crucifrangium,* inflicted on Roman slaves and Christian martyrs by laying the legs of the condemned upon an anvil and fracturing the bones with a heavy hammer; *decimation,* used upon mutinous regiments by shooting every tenth man; *dichotomy* or bisecting the body with a saw; *dismemberment; drawing and quartering; drowning; exposure to wild beasts; flaying alive; flogging; knouting; garroting; impalement;* the "*Iron Maiden*"; "*peine forte et dure*"; *poisoning; pounding in a mortar; precipitation* from a great height; the *rack; running the gauntlet; shooting; stabbing; stoning; strangling; suffocating*—in short, men have exercised their utmost ingenuity in devising means for inflicting cruel torture and horrible mutilation upon their victims.

As is well known, more than two hundred offenses were punishable with death in England not so very long ago. In modern times the penalty is now universally limited to murder, treason, piracy and military offenses. To the credit of William Penn and his companions it may be recorded that in 1675, when they founded Pennsylvania, the statutes prescribing death for all sorts of offenses, grave and trivial, were left behind in darkest England with its Newgate and London Tower, and the only one retained was that of death for aggravated cases of murder.

## ELECTROCUTION.

In the childhood of the human race lightning and thunder played an important part in the religion and the mental life of the various peoples. Jupiter ruled the world by his thunderbolts. The Norse god Thor with mighty arm wielded the hammer of lightning in combat with the enemies of the gods. Every ancient race and tribe has been awed into humble submission before the powerful divinities imagined to preside among the clouds by this fascinating phenomenon of nature. It is even yet feared by man, for is not its deadliness and its destructiveness demonstrated on every hand?

It is now more than a century and a half ago that Benjamin Franklin, accompanied by his son, went to a field in the neighborhood of Philadelphia as a thunder-storm was approaching and by his famous kite experiment discovered that lightning was, as he shrewdly had surmised, in all respects similar to the frictional electricity which man had produced artificially. In 1760 Franklin erected the first lightning rod upon the house of a merchant named West. Although more than five hundred persons are killed and over eight hundred are injured annually in the United States, Franklin's invention, wherever used, has saved countless lives and vast amounts of property. That the sage Franklin ever foresaw the likelihood of employing this death-dealing and mysterious force in the infliction of capital punishment is apparently not on record.

*Electrocution* (more properly electrothanasia), compounded from "electro-execution," is the popular name for the infliction of the death penalty by passing through the body of the condemned a current of electricity of sufficient intensity to cause death. The method was first adopted by New York State in 1888 by a law which became effective on January 1, 1889, and which provides how many persons may witness the execution, that a post-mortem examination of the body of the convict be performed and that the body, unless claimed by relatives, be interred in the prison cemetery with a sufficient quantity of quicklime to consume it.

The first criminal to be executed by electricity was William Kemmler, on August 6, 1890, at Auburn Prison. Since that time over one hundred murderers have been executed in New York State and the method has been adopted by Ohio (1896), Massachusetts (1898), New Jersey (1907), and Virginia (1907–8).

Reports on the earlier cases have been published by Drs. Carlos F. MacDonald, E. C. Spitzka, E. W. Holmes, and with reference to nerve-cell changes, by P. A. Fish.

My own observations are based upon thirty-one electrocutions (in the last six and one half years) at Sing Sing Prison, Auburn Prison, Dannemora Prison and Trenton (State Penitentiary). Of these twenty-five came to autopsy at my hands.

The apparatus consists of a stationary engine, an alternating dynamo capable of generating 2,000 volts, a "death-chair" with adjustable head-rest, binding straps and adjustable electrodes. [At Trenton a 2,400-volt current is taken from the public service wire and lowered to the desired tension by a rheostat.]

The voltmeter, ammeter and switchboard controlling the current is located in the execution-room; the dynamo-room is communicated with by electric signals. Before each execution the apparatus is thoroughly tested. When everything is in readiness the criminal is brought in unfettered and usually unassisted, and seats himself in the chair. His head, chest, arms and legs are secured by broad straps, an electrode thoroughly moistened with saturated salt-solution is affixed to the head, another to the calf of one leg, both electrodes being molded so as to assure good contact. The head is not shaved as is popularly thought.

The application of the current is usually as follows: The contact is made with a high potential (1,800 volts) for 5–7 seconds, reduced to 200–250 volts until a half minute has elapsed; raised to high voltage for 3–5 seconds, again reduced to low voltage until one minute has elapsed, when it is again raised to the high voltage for a few seconds and the contact is broken. The ammeter usually shows that from seven to ten ampères have passed through the criminal's body.

A second or even a third brief contact is sometimes made, partly as a precautionary measure, but more to completely abolish reflexes in the dead body.

The time consumed by the strapping-in process is usually about forty-five seconds and the first contact is made a few seconds later. In all about 60–70 seconds elapse from the moment the convict leaves his cell until he is shocked to death.

The convicts that I have seen thus dealt with have usually slept soundly the night before, they have entered the room calmly and stolidly, often with a half smile on their lips, some without uttering a word, others repeating a brief prayer, still others with a cheerful good-bye to those present. They usually seated themselves without betraying any signs of fear or trembling, curiously watching the strapping-in process for a while, then sitting erect, looking straight ahead at nothing in particular.

The physician in charge observes the respiratory movements of the prisoner and signals to the electrician at a moment when the lungs contain the minimum quantity of air. At the moment that the contact is made the criminal's body stiffens in a state of tonic muscular spasm, restrained by the straps. This spasm abates somewhat as the voltage is reduced, to again attain its maximum with each raise of voltage. When the current is interrupted the body collapses completely. An examination by the physicians usually fails to elicit any signs of life. Occasionally, there is heard a turbulent, incoördinate, accelerated heart-beat, but apparently limited to the auricular chambers of the heart. In only two cases was there any respiratory effort and this was limited to a single contraction of the thoracic respiratory muscles. An additional brief contact or two regularly abolished these reflex phenomena.

The reason for making the contact at the moment that the convict has expired air from his lungs in the natural course of his breathing is this—and it will explain why certain witnesses of the first electrocution thought that life still existed in Kemmler's body. It must be recalled that there is created a terrifically powerful spasmodic contraction of all muscles, including the sphincters and the glottis.

The closure of the glottis confines whatever air may be in the lungs; upon interrupting the current the body becomes entirely limp, the glottis partly relaxes, the thorax collapses and the contained air rushes through the partly closed glottis. A sound resembling a sigh or half groan may be thus produced upon the body of any dead animal; a little mucus present augments the sound into a gurgle. It is no wonder that inexperienced persons then believe life to be still present.

The death is undoubtedly painless and instantaneous. The vital mechanisms of life, *circulation* and *respiration,* cease with the first contact. Consciousness is blotted out instantly and the prolonged application of the current as it is usually practised by Mr. E. F. Davis, the state electrician of New York, ensures the permanent derangement of the vital functions so that there could be no recovery of these. Occasionally, the drying of the sponges through undue generation of heat causes desquamation or superficial blistering of the skin at the site of the electrodes, but not often. Post-mortem discoloration, or lividity, often appears during the first contact. The pupils of the eyes dilate instantly and remain dilated in death.

The post-mortem examination of "electrocuted" criminals reveals a number of interesting phenomena.

The temperature of the body rises promptly and reaches as high as 120° F. to 129½° F. within twenty minutes in many cases. After the removal of the brain the temperature recorded in the vertebral canal was often over 120° F. The development of this high temperature is to be regarded as resulting from the active metabolism of tissues not (somatically) dead within a body where all vital mechanisms have been abolished, there being no circulation to carry off the generated heat. The maximum heat is generated at the site of the leg-electrodes, where muscle (myosin) coagulation is most extensive. Furthermore, the release of from ten to twenty horsepower of energy within the body must contribute materially to the caloric increase.

The heart, at first flaccid when exposed after death, soon contracts and assumes a tetanized condition. This is particularly marked in the left ventricle; on the whole the organ assumes the form of a heart *in systole.* In one case (Koenig) the right ventricular wall of the heart had ruptured in several places. In one case I was able to elicit slight fibrillar contractions, limited to the small area stimulated, by touching the wall of the heart with a cold instrument. In several cases mechanical irritation of the *atrio-ventricular bundle* elicited slight contractions limited to the columnæ carneæ and the papillary muscles of the left ventricle. In experiments conducted with Professor Coplin upon one of these bodies, this mode of contraction could be called forth by faradaic stimulation, although no response was elicited by direct stimulation. In the same individual it was impossible to elicit any response *via* the nerve system, either through stimulation of the cortex (exposed within about ten minutes), the spinal cord or peripheral nerves, although muscular reflexes could always be called forth by directly stimulating the muscle.

The lungs are usually devoid of blood and weigh only seven or eight ounces avoirdupois each.

The blood is profoundly altered bio-chemically. It is of a very dark, brownish hue, and it rarely coagulates. Either the fibrinogen, or the fibrin-ferment, or both, are destroyed.

The maximum damage is undoubtedly wrought in the nerve system though this is not always manifest. Regarding the histologic changes, reports from various sources vary. There is a general agreement as to the frequent occurrence of capillary hemorrhages, disruptive and destructive for adjacent tissues. In the nerve-cells themselves there appears to be no apparent change, although there must have resulted terrific molecular change. P. A. Fish found vacuoles in one case, but no visible changes in another. Aside from the capillary hemorrhages and the arterial anemia with venous congestion, the brain shows no gross changes of appearance. In a case of accidental death from contact with an alternating current of 1,000 volts for about one half minute, Jellinek found extensive streaks of capillary hemorrhages in the gray substance of brain and spinal cord together with more or less destruction of the nerve cells, extrusion of the cell nucleus, etc.

In the case of Strollo, I have had sections made of the pons, oblongata and spinal cord by my colleague, Dr. Radasch, and these have revealed curious circular areas with a peripheral zone of condensation which fades off into the surrounding unaffected areas. The bulk of the central rarified portion shows a delicate network of loose fibrillæ which in all probability are glia fibers. The cellular elements in the rarefied area are few in number though apparently free nuclei are scattered in this portion. These areas follow more or less closely the course of the finer vessels. Many of them contain an unruptured vessel centrally located, while others contain longitudinal sections with the areas arranged in a bead-like manner along such vessel. These areas are larger and more numerous in the pons than in the oblongata and spinal cord and apparently distributed in the longitudinal directions more frequently than in other directions. They seem to resemble gaseous emphysema and are possibly due to the electrolytic liberation of gas in the peri-vascular spaces. One is reminded of the punctures in a piece of paper interposed in the path of the sparks of a static machine.

Through the courtesy of Mr. Wilson H. Brown, Sheriff of Philadelphia, I was permitted to witness a number of hangings and thus was enabled to compare the new method with the old.

The preparations for the execution were always swiftly conducted. Upon this point comparison favors neither method. But after the drop through the trap-door the ensuing seconds and even minutes bear a different tale. In nearly all cases the heart beats for about thirteen minutes. In no case could fracture of a cervical vertebra or rupture of ligaments be determined in the ordinary examination.

In one case only was there no movement of the body after the drop, although the heart beat the usual length of time. This prisoner, a Chinaman, apparently died in syncope or of apoplexy. In others the unconsciousness produced by the first shock of the drop appeared to abate and in several instances there were conscious—or at least semi-conscious—efforts at respiration, efforts to reach the neck where the choking sensation was unbearable, efforts at reaching for a support for the feet manifested by such vigorous efforts that several witnesses fainted at the sight.

They veritably "danced upon the air" until the asphyxia (apnea) became so profound as to blot out consciousness, apparently after one or one and one half minutes in some cases.

The anatomy of hanging has been frequently discussed. A recent publication[1] by Dr. Frederic Wood Jones gives the results of the examination of the bodies of one hundred men executed in Nubia in Roman and Byzantine times. Sixty-two were in one trench, forty in another. They were all adult males, with cords binding the legs and arms trussed to the sides. The hanging rope was still *in situ* on one.

Not a single case of damage to the cervical vertebræ was found. The most commonly found lesion was an oblique opening of the sutures of the skull, so that one portion of the skull, represented by the occipital and temporal bones becomes pulled aside from the other portion, represented by the facial part of the skull and the other temporal bone. The basilar suture in most cases was also disunited. The skulls all gave evidence of blood staining.

This remarkable finding of evidence dating about 2,000 years back, prompted me to examine the head and neck bones of five individuals executed by hanging and sent to the Jefferson Medical College for dissection. In not a single instance could I find a fractured cervical vertebra or a separation of any cranial suture. Death had ensued through strangulation.

The Newgate Calendar and other criminal records are full of instances in which the rope broke and the condemned had to be rehanged and even cases where the head was severed from the body. Furthermore, there are not a few authentic cases of resuscitation and total recovery after hanging.

Compared with hanging as well as other methods, electrocution is the most humane, decent and scientific method of inflicting the death penalty because of its efficiency, quickness and painlessness, and it should be adopted by Pennsylvania as well as every state in the Union. The executions should take place in a building remote from the penitentiaries where other convicts, more or less susceptible to reformation, are confined. The erection of scaffolds in prison corridors or the knowledge on the part of other convicts that an electrocution is in progress has a bad, even brutalizing, effect upon them.

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[1] *British Medical Journal,* March 28, 1908.

At the time when objections to the hangman's bungling were most strongly urged in favor of some better method, poisoning by prussic acid as well as chloroform were suggested. With regard to the injection of prussic acid by means of the hypodermic syringe, the Gerry Commission report says:

> "This is open to the very serious objection that the use of that instrument is so associated with the practice of medicine, and as a legitimate means of alleviating human suffering, that it is hardly advisable to urge its application for the purposes of legal executions against the almost unanimous protest of the medical profession."

It seems to me that the use of chloroform, first suggested by Wilder in 1870, cheap and efficient as it would be, is open to the same objection. There should be a lively sense of violence, of mysteriously overwhelming power, of potent force and destructive energy attached to the means employed in putting the murderous ruffian out of existence. If any sentimentality is to obtain in relation with capital punishment methods it should not be in favor of the "plug ugly" wielders of the stiletto, black-jack and the ever-ready revolver.

Capital punishment has been abolished in Rhode Island, Maine, Michigan and Wisconsin. Kansas had abolished it but restored it after a negro was burned at the stake for an outrage upon a woman. The states of New York, Colorado and Iowa deemed it wise to reënact the death penalty after it had once been abolished, owing to the increase of crime. (The same experience was met with in Switzerland where the penalty was abolished in 1874 and again established in several cantons in 1879.)

In Louisiana the death penalty is inflicted for assault with intent to kill, arson, burglary and administering poison.

In Delaware and North Carolina arson and burglary are capital crimes.

In Missouri seven crimes are punishable by death; among them are murder, train robbery, arson, perjury in a capital case and mayhem.

In Connecticut the law prescribes the death penalty for placing obstructions on a railroad track.

In Utah the law provides that the condemned may choose between hanging and shooting.

The question "Is capital punishment justifiable"? has agitated the minds of men ever since the dawn of civilization. Public opinion is never so fickle with regard to any problem of life as this one. My own opinion is a firm conviction in favor of it for those who commit premeditated murder, arson, train-wrecking and bomb-throwing. Society needs this penalty for its own protection and it is authorized to use it. The Mosaic law "Thou shalt not kill" refers to murder and not to legal execution. The fear of death is in most men and it is therefore the most powerful means of intimidation. Optimists may hope to see society organized upon such an enlightened plane that the penalty need not be resorted to—but that time is not yet at hand. In nearly every county or state which abolished the penalty, the subsequent increase in crime aroused a clamor for its reëstablishment.

The opinion is held by some that the penalty fails to act as a deterrent for others. The argument is puerile, for this country at least, inasmuch as only 1.3 per cent. of homicides are convicted. In Germany 95 per cent. are convicted, or, proportionately, thirteen times as many. Were the penalty as rigorously enforced in the case of murder as the whipping-post is used in Delaware for various crimes, its deterrent effects would soon become manifest. It is idle to talk of anything but prompt punishment as a deterrent of crime.

Thus, in New York City, in 1904, there were 147 first degree murders; but there were only 27 convictions and only two were executed. In the same year, in Philadelphia, 48 murder trials resulted in only 7 verdicts of murder in the first degree and several of these, on re-trial, received minor sentences. London, with 6,000,000 inhabitants, had 24 murders; 9 were hanged therefor. Chicago, with 2,000,000 inhabitants, had 128 murders; only 1 was hanged.

The tardy justice meted out to murderers is the most deplorable feature of our legal machinery to-day. There are too many loopholes for escape—long delays, endless appeals, lots of slush about the "unwritten law," numerous legal technicalities and sentimental juries. By the pettifogging of criminal law the great majority of cases are granted new trials in the United States; in Great Britain only 3.5 per cent. Nearly always the appeal is based upon points of pleading and practice and many years elapse before the final settlement of the case. Our administration of justice has degenerated into a sort of "rose-water penology." Its demoralizing effect upon the community is manifested by the rapid increase of crimes of violence among juveniles, so ready to imitate and emulate their seniors in crime. We have become too much accustomed to failure of justice in murder cases. This blot upon our civilization is largely the outcome of our indifference to the way many criminal courts are conducted. Certain magistrates make a farce out of serious business, lawyers wrangle with each other unchecked, witnesses are brow-beaten and bribery and corruption of political complexion degrade the proceedings to the level of a saloon or gambling-den or a policy-shop rather than a court of law.

The explanation is sometimes given that "hard times" influence this appalling increase of crime. That this is not so can be readily shown by reference to statistics. I would rather point to the moral deterioration indicated by the manner in which large sums of money are stolen or used for bribery and corruption and the luxury and reckless extravagance with which some wealthy persons (who ought to be in the penitentiary) offend the decent class of our population. Add to this the manner in which the newspapers set forth the details of brutal crimes and breed familiarity with thoughts of crime.

Society has relaxed too much. The death penalty is a necessity and must not be abolished, else all discipline of society will be relinquished. Though society "revolts at the old religious dogma of the retribution of hell, the church still retains it as essential in its terrible dissuading appeal to the imagination of men" (*New York Sun*). Let us, therefore, in our penology, adhere to what the test of time has proven to be an efficient check if only it be carried out as has been done in Germany and Great Britain.

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## BIBLIOGRAPHY.

**MacDonald, C. F.**

Report on the execution by electricity of William Kemmler, alias John Hart, Albany, N. Y., 1890.

**MacDonald, C. F.**

The infliction of the death penalty by means of electricity, being a report of seven cases. Albany, N. Y., 1893.

**Spitzka, E. C.**

Vorläufige Mittheilung betreffs des Leichenbefundes bei dem ersten durch Elektricität Hingerichteten. *Medicinische Monatschrift* (New York), August, 1890.

**Fish, P. A.**

The action of strong currents of electricity upon nerve cells. *Proc. American Microscopical Soc.,* XVII., 1895.

**Bell, Clark.**

Electricity and the death penalty. *Alienist and Neurologist.*

**Holmes, E. W.**

Anatomy of Hanging. *Pennsylvania Med. Jour.,* July, 1901.

**Gerry, Southwick and Hale.**

Report of the Commission to Investigate and Report the Most Humane and Practical Method of Carrying into Effect the Sentence of Death in Capital Cases. Albany, N. Y., January 17, 1888.

**Spitzka, E. A.**

Report of the Postmortem Examination of Leon Czolgosz. *American Journal of Insanity,* 1902.

**Spitzka, E. A.**

Execution and Postmortem Examination of the three Van Wormer Brothers. *N. Y. Daily Medical Journal,* February 1, 1904.

**Spitzka, E. A.**

Notes on autopsy of Toni Turkofski, electrocuted murderer. *Medical Critic,* August, 1903.

**Jellinek, S.**

Elektropathologie. Stuttgart (F. Enke), 1903.

# PRELIMINARY NOTE ON THE BRAINS OF NATIVES OF THE ANDAMAN AND NICOBAR ISLANDS.

By EDW. ANTHONY SPITZKA, M.D.

(*Read April 23, 1908.*)

Physical anthropology, or comparative human morphology, has been largely based upon cranial configuration. Since the days of Camper and Blumenbach, the classification of the human races is based on more conprehensive morphologic foundations, for with cranial morphology as the first criterion, there have been added criteria derived from the entire skeleton, the soft tissues and the brain. The last-mentioned organ has been the least studied because it is usually most difficult to obtain, preserve and study. Nevertheless, interest in this subject is manifestly increasing among anatomists and anthropologists, for they appreciate the fact that there is a pressing need for fruitful research in anthropologic encephalometry among the exotic races, so rapidly becoming impure or even extinct. Many American Indian tribes have disappeared; the volcanic outbreak in Martinique has wiped out nearly all Caribs. The Australian natives driven to the desiccated wastes of the interior, many African tribes succumbing in the arid deserts, the Eskimos decimated by epidemics of small-pox, measles and pneumonia—all these and many others are dying out and warn us to make haste in recording observations upon them while they still exist.

It has been my good fortune to pursue comparative studies in cerebral morphology based upon the brains of the white race, of Eskimos, Japanese, Chinese, Negroes and Papuans. I am now able to add the brain of a native of the Andaman Islands and one of a native of the Nicobar Islands. For this exceptional privilege I am indebted to the efforts of Dr. W. W. Keen, whose correspondence with Lord Curzon, then Viceroy of India, opened the way to communication with Mr. H. H. Risley, Director of Ethnography for India; Mr. W. R. H. Merk, Superintendent of Port Blair, and Major

A. R. S. Anderson (M. B. Cantab.) I.M.S., senior medical officer at Port Blair, Andamans. To all these I desire to acknowledge herewith my thanks.

The Andaman Archipelago is a group of densely wooded islands about 1,760 square miles in area, situated in the Bay of Bengal about 180 miles southwest of Cape Negrais, Burma, and about 60 miles distant from the more southerly Nicobar Islands. The inhabitants have been considered a most primitive and savage race. Accounts of their cannibalism are found in the ancient Chinese writings and the Andamanese are probably referred to by Ptolemy as the "anthropophagi." Port Blair is a convict settlement and the convicts are deterred from making efforts to escape by their fear of the natives. From the observations of E. H. Man, who, more than any other, has made the race a study, it appears that the Andamanese are Negritos and not Papuans. They are well made and well proportioned. Their skulls are brachycephalic. Their lips are not thick, their profiles are good and they have no peculiar odor like that which is found in the African race. Their extremities are small, but the heel projects slightly to the rear. The average height of the men is 149 cm., of the women 140 cm. The average weight of the men is 98 and 93 pounds respectively. The color of the Andamanese is generally dark bronze or copper color; often the color of soot and even quite black. The hair is woolly, but its cross-section is not always elliptical. In a letter to the Smithsonian Institution, Dr. Abbott says of them: "They are a happy, merry, little people, infantile both in looks and behavior. Unfortunately they are dying out. Contact with civilization is making the women barren and there are comparatively few children."

Mr. Man thinks that it has been pretty well demonstrated that these Negritos in the Andaman Archipelago, so unlike any of their immediate neighbors, are aborigines and have inhabited the group from prehistoric times. The population in 1901, Dr. Anderson writes me, was 2,200, including women and children.

The Andamanese wear no clothing; its place is taken in a measure by necklaces, circlets for the head, garters, bracelets and belts. They live in thatched huts and sleep on mats. Stones are used as anvil and hammer, clam shells as knives. They fashion old barrel hoops from wrecked ships into jagged knives. The only thing resembling a musical instrument is a wooden shield-like drum upon which the performer keeps time by striking it with his foot. They make some pottery; the base of the pot is in the form of a cup. To this roll after roll is added and the sides built up, the inner and outer surfaces are smoothed off with an arca shell and ornamented with wavy, checkered or striped designs by means of a pointed stick and baked by placing pieces of burning wood both inside and around the vessel. They make cane baskets, wooden trays and buckets. String is made from vegetable fiber (orchid and Anadendron) and used in making harpoon lines, turtle nets, fishing nets, bowstrings coated with wax, lashings, reticules and necklaces. Bows and arrows, harpoons and fish spears are used in hunting. They build outrigger canoes and simple dugouts which are propelled by paddles, or, in shallow water, by poles or the shaft of a turtle harpoon.

Morphologically, the Andamanese form a definite group. The following criteria are given by Duckworth:[1]

| | |
|---|---|
| Cranial index | 82.1 |
| Alveolar index | 102.0 |
| Nasal index | 50.9 |
| Height index | 77.9 |
| Cranial capacity | 1,266 c.c. |

The skull is small and round, with prominent jaws. It is cryptozygous, muscular ridges are not very prominent, the mastoid processes are small, and the external auditory meatus is shallow. Brow-ridges are not developed, and sexual differences are often obscure in these skulls. The face is prognathous, the prognathism affecting chiefly the alveolar maxillary margin and being therefore subnasal. The chief distinction is the association of a highly brachycephalic skull of small capacity with dwarf stature and prognathism. The lumbo-vertebral index denotes simian affinities. The sacral curve is very slight, indicating a low position among hominidæ. The scapula is the most pithecoid amongst hominidæ with the possible exception of the Bambuté dwarfs of Africa. The proportions of the limb-bones are simian as regards the radio-humeral and the tibio-femoral, but not as regards the intermembral of humero-femoral indices.

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[1] Duckworth: "Morphology and Anthropology," Cambridge Biological Series, 1904.

## The Brain.

[Preliminary Report.]

The brain is that of an Andamanese named Juran of the tribe called Aka-yere or Aka-Jaro-da. Juran was a male, aged about 45 years, who died at Port Blair of pulmonary tuberculosis on June 30, 1905. The brain was removed by Dr. Anderson about one hour after death and immersed in a mixture of formalin and water. Its weight while fresh was not noted before being sealed and transported. When received about eight months later it weighed 1,193 grams, as follows:

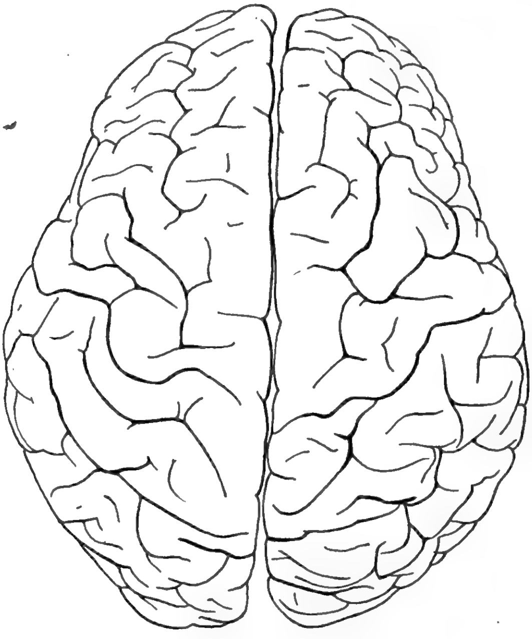

Fig. 1. Brain of Andamanese (dorsal view).

| | Grams. |
|---|---|
| Left hemicerebrum | 532 |
| Right hemicerebrum | 525 |
| Cerebellum, pons and oblongata | 136 |
| Total | 1,193 |

The specimen continued to lose weight slightly and in April, 1908, after removal of the cerebral pia-arachnoid, weighed as follows:

| | Grams. |
|---|---|
| Left hemicerebrum | 493 |
| Right hemicerebrum | 490 |
| Cerebellum, pons and oblongata | 130 |
| Total | 1,113 |

Various calculations indicate that the fresh weight of this brain was probably between 1,200 and 1,250 grams.

The brain is broad and short.[2] The frontal lobes are less massive than in whites. The fissuration is well marked but not very complex. The precallosal length is less than in whites. The callosum is of good size, comparing well with those of whites. The calcarine fissure is interrupted on the left side. The fissural peculiarities must be considered more fully in the final publication, and, if possible, should be based upon comparison with more specimens from natives of this race. The following dimensions may be recorded here:

| | Centesimals. |
|---|---|
| Brain-length, left half | 16.1 |
| Brain-length, right half | 15.8 |
| Brain-width | 13.9 |
| Cerebral index | 86.9 |
| Horizontal circumference | 47.0 |
| Width, left hemicerebrum | 6.9 |
| Width, right hemicerebrum | 7.0 |
| Left occipito-temporal length | 12.6 |
| Right occipito-temporal length | 12.4 |
| Length of callosum | 7.3 |
| Percentage of callosal length | 45.3% |
| Left centro-temporal height | 10.6 |
| Right centro-temporal height | 10.6 |
| Left centro-olfactory height | 8.7 |
| Right centro-olfactory height | 8.7 |

Arc Measures.

| | | |
|---|---|---|
| Left | Frontal | 14.5 |
| | Parietal | 5.0 |
| | Occipital | 5.5 |
| Right | Frontal | 14.5 |
| | Parietal | 4.5 |
| | Occipital | 6.0 |

Cerebral Indices.

| | | |
|---|---|---|
| Left | Frontal | 58.0 |
| | Parietal | 20.0 |
| | Occipital | 22.0 |
| Right | Frontal | 58.0 |
| | Parietal | 18.0 |
| | Occipital | 24.0 |

---

[2] It was somewhat flattened upon its dorsum during transportation.

HORIZONTAL DISTANCES (IN CENTESIMALS).
FROM FRONTAL POINT TO:

| | | | |
|---|---|---|---|
| Left Lateral Aspect | 1. | Tip of temporal lobe | 23.0 |
| | 2. | Sylvian-presylvian junction | 31.0 |
| | 3. | Ventral end of central fissure | 44.1 |
| | 4. | Sylvian-episylvian junction | 62.1 |
| Left Mesal Aspect | 6. | Frontal edge of callosum | 22.3 |
| | 7. | Porta (Foramen of Monro) | 42.2 |
| | 8. | Dorsal end of central fissure | 64.6 |
| | 9. | Dorsal intersection of paracentral fissure | 71.4 |
| | 10. | Caudal edge of callosum | 67.9 |
| | 11. | Occipito-calcarine junction | 78.2 |
| | 12. | Dorsal intersection of occipital fissure | 88.2 |
| Right Lateral Aspect | 1. | Tip of temporal lobe | 21.8 |
| | 2. | Sylvian-presylvian junction | 31.4 |
| | 3. | Ventral end of central fissure | 46.8 |
| | 4. | Sylvian-episylvian junction | 63.4 |
| Right Mesal Aspect | 6. | Frontal edge of callosum | 20.5 |
| | 7. | Porta (Foramen and Monro) | 41.6 |
| | 8. | Dorsal end of central fissure | 70.5 |
| | 9. | Dorsal intersection of paracentral fissure | 77.0 |
| | 10. | Caudal edge of callosum | 67.3 |
| | 11. | Occipito-calcarine junction | 76.2 |
| | 12. | Dorsal intersection of occipital fissure | 91.6 |

Cross-section area of callosum = 5.85 sq. ctm.

## NICOBARESE BRAIN.

With regard to the ethnic position of the Nicobarese there exists considerable doubt. They are very different from the Andamanese. Their color is a light brown, the hair is straight and black, and apparently they are of ancient Mongolian origin with probably no admixture of Papuan or Negrito elements. Their stature is medium (158–163 cm.), not small as are the Andamanese.

The brain is that of an individual from Kar Nicobar, a male, aged 25, who died of hypertrophic cirrhosis of the liver and fatty degeneration of the heart in the hospital at Port Blair. The brain weighed 49 ounces avoirdupois or 1,389 grams. The body-weight was 136.5 pounds, while the stature was 170 cm.

Major Anderson injected about 10 c.c. of 5 per cent. formaldehyde into the ventricles through the tuber and immersed the brain in the same mixture. The specimen reached me in March, 1906, a little over three months after its removal from the head.

Its present weight, divested of the cerebral pia-arachnoid, is 1,257 grams. The brain is somewhat flattened and elongated. The fissural pattern is fairly good but not as complex as in the average

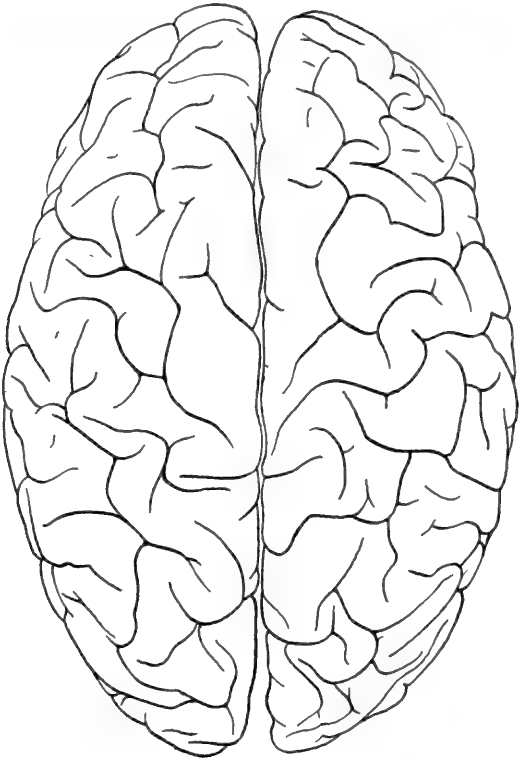

FIG. 2. Brain of Nicobarese (dorsal view).

white brain. The calcarine fissure is interrupted on both sides, the interruption being somewhat concealed on the left side. The callosum is small, a fraction over 5 sq. cm. The indusium, however, is quite massive, and further study of rhinencephalic parts may prove interesting. The insula is slightly visible on both sides.

The measurements of this specimen are as follows:

| | CENTESIMALS. |
|---|---|
| Brain-length, left | 19.1 |
| Brain-length, right | 18.5 |
| Brain-width | 13.3 |
| Cerebral index | 70.0 |
| Horizontal circumference | 52.0 |
| Width, left hemicerebrum | 6.9 |
| Width, right hemicerebrum | 6.4 |
| Left occipito-temporal lobe | 14.3 |
| Right occipito-temporal lobe | 14.2 |
| Length of callosum | 8.5 |

| | |
|---|---|
| Percentage of callosal length | 44.7% |
| Left centro-temporal height | 9.2 |
| Right centro-temporal height | 8.7 |
| Left centro-olfactory height | 8.2 |
| Right centro-olfactory height | 8.0 |

### Arc Measures.

| | | |
|---|---|---|
| Left | Frontal | 16.0 |
| | Parietal | 4.5 |
| | Occipital | 5.5 |
| Right | Frontal | 16.5 |
| | Parietal | 5.0 |
| | Occipital | 5.0 |

### Cerebral Indices.

| | | |
|---|---|---|
| Left | Frontal | 61.5 |
| | Parietal | 17.3 |
| | Occipital | 21.2 |
| Right | Frontal | 62.3 |
| | Parietal | 18.8 |
| | Occipital | 18.8 |

### Horizontal Distances (in Centesimals).

### From Frontal Point to:

| | | |
|---|---|---|
| Left Lateral Aspect | 1. Tip of temporal lobe | 25.1 |
| | 2. Sylvian-presylvian junction | 30.3 |
| | 3. Ventral end of central fissure | 41.8 |
| | 4. Sylvian-episylvian junction | ? |
| Left Mesal Aspect | 6. Frontal edge of callosum | 20.0 |
| | 7. Porta (Foramen of Monro) | 38.2 |
| | 8. Dorsal end of central fissure | — |
| | 9. Dorsal intersection of paracentral fissure | 65.4 |
| | 10. Caudal edge of callosum | 64.4 |
| | 11. Occipito-calcarine junction | 81.1 |
| | 12. Dorsal intersection of occipital fissure | 83.2 |
| Right Lateral Aspect | 1. Tip of temporal lobe | 24.6 |
| | 2. Sylvian-presylvian junction | 28.2 |
| | 3. Ventral end of central fissure | 41.3 |
| | 4. Sylvian episylvian junction | 55.0 |
| Right Mesal Aspect | 6. Frontal edge of callosum | 18.3 |
| | 7. Porta (Foramen of Monro) | 37.7 |
| | 8. Dorsal end of central fissure | 61.2 |
| | 9. Dorsal intersection of paracentral fissure | 63.8 |
| | 10. Caudal edge of callosum | 63.8 |
| | 11. Occipito-calcarine junction | 75.4 |
| | 12. Dorsal intersection of occipital fissure | 87.4 |

Cross-section area of callosum = 5.02 sq. ctm.

Jefferson Medical College,
Philadelphia.

# DETERMINATION OF DOMINANCE IN MENDELIAN INHERITANCE.

By CHARLES B. DAVENPORT, Ph.D.

(*Read April 25, 1908.*)

The longer one investigates the phenomena of heredity the more one is impressed with the grandeur of the discovery made over forty years ago by Gregor Mendel. His method is not less important than its results. Following him, in studying heredity one considers a single character at a time. One notes the result in the offspring when this character assumes contrasted forms in the two parents or when one parent has the character and the other lacks it. Under these circumstances one frequently, nay, usually, finds that the condition in one parent dominates over that in the other parent, so that the offspring are all alike, and like one parent, in respect to that character. The opposite, or recessive, quality is not lost, however. It persists in the germ plasm and one half of the germ cells of the individuals belonging to the first generation of hybrids contain the dominant and one half the recessive quality.

Dominance, it will be observed, it a matter of the soma. The hybrid fertilized egg contains both contrasting qualities and so, probably, do all of the cells of the body. But only one of the qualities ordinarily makes its appearance. It has been suggested that a struggle occurs between the contrasted qualities and the stronger—called the *dominant*—wins. The question is what determines this assumed greater strength of the dominant quality? What determines dominance?

Various replies have been given to this question. It has been suggested that the dominant quality is the *older* and although this is sometimes true it so often fails to be so that age cannot be regarded as the primary cause of dominance. Frizzling and silkiness of fowl's feathers are each novelties but one dominates over the ordinary flat feather and the other is dominated by it. Much evidence of this sort could be adduced proving the insufficiency of the theory of the recessive nature of novelties. A different theory has been suggested by deVries, namely, when an individual having the characteristic patent is crossed with one in which it is latent the patent characteristic is dominant, the latent recessive. A similar expression has been proposed by Hurst who concludes that the presence of a quality usually dominates over its absence. This expression of the facts is, in the main, true but it is too narrow, inasmuch as it assures that the mendelian result occurs only when a character is crossed with its absence; but this I shall show directly is by no means true.

Two years ago I suggested that a *progressive* variation, one which means a further stage in ontogeny, will dominate over a condition due to an abbreviation of the ontogenetic process—or a condition less highly developed than the first. Recent studies have thrown additional light on this matter and I wish to treat it now generally. First let me present some illustrations. Many poultry have feathers on the feet; these constitute the so-called *boot.* If a "booted" bird be mated with a non-booted all offspring are booted—booting is dominant over its absence. Booting occurs, however, in an infinity of grades. For convenience I recognize ten, usually determined by inspection. If a bird with a boot of grade 8 or 9 be crossed with a bird with boot of grade 2 or 3, both being pure dominants, then the stronger condition is dominant in the offspring, so that their average grade is about 8.

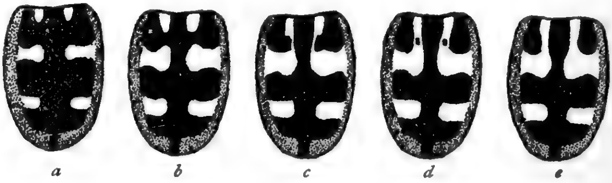

FIG. 1.

A second illustration may be drawn from certain studies made on the asparagus beetle by Dr. F. E. Lutz, of the Carnegie Institution of Washington. In the embryonic condition the outer wing covers of this beetle are nearly pigmentless or yellow. Before emerging from the pupal condition black pigment is laid down. The pigmented area is variable in amount. The more extensively pigmented condition is dominant over the less extensively pigmented (*a* over *c, d* or *e*—see Fig. 1). In this case, also, it is clear that the facts are better expressed by the statement that the more developed condition dominates over the less developed.

Still another case is that of human eye color. The pigmentation of the iris is variable in amount. The blue iris is without pigment. A small amount of black pigment (with or without yellow) produces the grays; still more pigment yields browns and blacks. Now it appears that the offspring of parents one of whom has gray eyes and the other blue eyes will have gray eyes or blue eyes, but not brown eyes; and gray will show itself dominant over blue. Similarly brown iris color is dominant over gray; the more advanced condition of pigmentation over the less advanced. We have not here to do with a qualitative difference of the presence of a character opposed to its absence, but of a qualitative difference only.

The heredity of human hair color follows a similar law. In one series red pigment is absent in the hair and such colors as flaxen or tow, light brown, brown, dark brown and black may be distinguished. The records collected by Mrs. Davenport and myself show that two flaxen-haired parents have flaxen-haired children and probably only such. Two parents with light brown hair have chil- apparently only such. Two parents with light brown hair have children of two parents each with dark brown or black hair produce children with all of the varieties of hair color. This result means that any lighter color is recessive to any darker color.

The facts recited above and many others thus support the view that, where various stages, *a, b, c,* in the progressive development of a quality are found in individuals of the same race or species, the more progressive condition will often behave as a dominant toward the less progressive condition. The extreme case is, of course, that in which the organ or quality is absent in one parent and present in the other; but this seems to be only a special case of a more general law.

As to the universality of this law it is still early to speak with confidence. We know too little of the developmental factors of an organ to decide, in many cases, whether a difference is due to a progressive or a retrogressive change. For instance, the long angora coat of rabbits is recessive to short coat; and this has been cited as a clear case of recessiveness of the advanced condition. But it seems doubtful if such is the case. For the angora coat retains an embryonic quality (viz., of continued growth) which is present in the infancy of the short-haired rabbit and is then inhibited. The inhibiting factor is present in short-haired rabbits and absent in angora rabbits and the presence of the inhibiting factor dominates over its absence. At one time I thought that the dominant white plumage of some poultry was a case of dominance of absence of color. But it now appears that we have among poultry recessive whites which are true albinos, and the *dominant* whites which must be regarded as "grays," in which pigmentation is obscured by an additional factor like that which turns black hair gray. This graying factor is dominant over its absence.

It is possible that the future may show that, in accordance with the ideas of deVries, an advanced grade of a character may be regarded as a sum of minute equivalent elementary units; by the dropping out of these units one at a time a character passes through a series of degradational stages. Then a light brown hair may have one unit of melanic pigment, brown hair two units, dark brown three units, and black hair four units. If this should prove to be true then the four unit condition would dominate over the three unit condition, or the fourth unit would dominate over its absence. But such evidence as I have at present does not favor this view. I am inclined rather to the hypothesis that when the germinal determiner of greater intensity meets that of less intensity it dominates over the latter. This hypothesis receives support from another set of facts which go to prove that the idea of varying intensity of a determiner is a true one. This set of facts is derived from the combs of poultry. In one race of poultry—Polish fowl—the comb consists of a pair of horns or broad flaps which lie far back near the base of the beak; and there is no median comb. In the Minorca and most other fowl there is a single median comb. Now when these two races are crossed we find that the median comb dominates over the absence of median comb; sometimes *completely,* running in the hybrid from the base of the beak to in front of the nostrils; sometimes *incompletely,* occupying only the anterior half or fourth of the beak. It seems to me clear that in the varying proportions of this median comb in the hybrids we have at once evidence for, and a measure of, varying intensity of dominance. Now it may reasonably be asked whether, when the long-combed and short-combed hybrids are mated together, the long comb dominates over the short. The answer is complicated by the fact that the Polish "horns" reappear in this second generation; but, leaving this aside, we find that there is a greater preponderance of *long* median combs than simple mendelian expectation calls for and this indicates that the longer median comb tends, but not always perfectly, to dominate the shorter median comb; or, in other words, the more intense determiner dominates the less intense.

To sum up, I think it is clear that dominance in heredity appears when a stronger determiner meets a weaker determiner in the germ. The extreme case is that in which the strong determiner meets a determiner so weak as to be practically absent as when a red flower is crossed with a white. In such cases we have the clearest examples of mendelian inheritance. But there is an entire gamut of cases where the opposed determiners are of varying relative potency. The phenomenon of determinance is seen in these cases also; but the mendelian law in them is sometimes obscured and sometimes merely not applicable.

Cold Spring Harbor, Long Island, N. Y., April, 1908.

# THE SANTA CRUZ TYPOTHERIA.

(Figures 1–10.)

By WILLIAM J. SINCLAIR.

(*Read April 24, 1908.*)

The Typotheria are a group of semi-ungulate mammals of strictly South American origin appearing first in the Notostylops beds of Patagonia.[1] During the Santa Cruz epoch four genera are represented but what is lacking in generic and specific diversity is more than compensated for by an abundance of individuals. The total number of common species apparently does not exceed eight, but this has been increased to no less than fifty-one by failing to estimate at their true value characters due to age and others which seem to be of the nature of individual variations in size, the result no doubt of the extremely fragmentary character of the material hitherto available. Even with the large suites of specimens in the collections

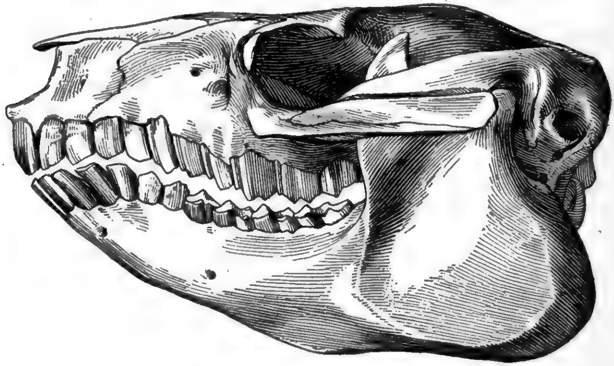

FIG. 1. Skull of *Protypotherium australe* Ameghino, side view, three fourths the natural size. (No. 9565 American Museum of Natural History collection.)

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[1] *Isotypotherium, Epitypotherium.*

at Princeton University and the American Museum of Natural History it has been found impossible to separate in a satisfactory manner the species of the genus *Protypotherium*. An almost exact intergradation in size without appreciable difference in structure is observable between the largest species *Protypotherium australe* (Fig. 1) and the smallest *P. attenuatum*. As none of the collections have been made with strict regard to stratigraphic sequence, we are not in a position to say whether these differences represent individual variations or true mutations. The former alternative has been adopted in monographing the group (see the forthcoming Volume VI., Part I. of the "Reports of the Princeton University Expeditions to Patagonia").

## Classification of the Santa Cruz Typotheria.

The Typotheria are grouped by Scott[2] as a suborder of the Toxodontia and may be defined as follows:

Plantigrade or digitigrade mammals with pentadactyl[3] or tetradactyl feet, strongly interlocking carpus with os centrale and serial or slightly interlocking tarsus with hemispherical astragalar head. Dentition usually complete but tending toward reduction of the lateral incisors, canine and anterior premolars in specialized forms. Median incisors more or less enlarged and functional as cropping teeth. Molars hypsodont, lophoselenodont in crown pattern, curving inward above and outward below. A clavicle is present in some forms. Femur with third trochanter. Fibula articulating with calcaneum.

Two well-marked families are recognizable among the Santa Cruz representatives of the suborder for which the names Interatheridæ and Hegetotheridæ have priority. Each contains a large and a small genus of which, in either case, the former is the less specialized. The following key to the families and genera may facilitate the determination of new material:

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[2] Scott, W. B., "The Miocene Ungulata of Patagonia," *Rept. British Asso. Adv. Sci.*, 1904, pp. 589–590.

[3] Ameghino figures a pentadactyl manus in *Pachyrukhos typicus*, "Contrib. al conocimiento de los mamíferos fósiles de la República Argentina," *Actas de la Academia Nacional de Ciencias en Córdoba*, T. V., Pl. 13, fig. 14, 1889, and in *Typotherium*, *ibid.*, Pl. 18, fig. 5.

## Order *TOXODONTIA* Owen.

## Suborder TYPOTHERIA Zittel.

A. Family Interatheridæ. Median incisors rooted; third and fourth premolars not completely molariform, squamoso-mastoid region dilated and cancellous; malar long and narrow, inclosed between temporal process of maxillary and squamosal; maxillary orbital; carotid canal and foramen lacerum posterius fused; tibia and fibula unfused distally; pes paraxonic, digits II. and V. equally reduced and small, digits III. and IV. large and of equal length; astragalar trochlea bilaterally symmetrical; no naviculo-calcaneal facet; calcaneum with large fibular facet.

1. *Protypotherium.* Dental formula $\frac{3}{3}, \frac{1}{1}, \frac{4}{4}, \frac{3}{3}$ in close series. Lateral incisors unreduced; canine incisiform; upper molars with deep internal inflection and slight antero-external ridges; $M_3$ externally bilobate; temporal bar of maxillary with slight descending process; humerus with internal epicondylar foramen; terminal phalanges laterally compressed hoofs with slight clefts in manus.
2. *Interatherium.* Dental formula $\frac{3}{3}, \frac{1}{1}, \frac{4}{4}, \frac{3}{3}$, with diastemata between the lateral incisor, canine and first premolar, varying with the species. $I^3$ reduced, often wanting; upper molars with deep internal inflection and prominent antero-external ridges; $M_3$ externally trilobate; temporal bar of maxillary with strong descending process; humerus without internal epicondylar foramen; terminal phalanges laterally compressed hoofs with or without clefts.

B. Family Hegetotheridæ. Median incisors rootless; third and fourth premolars molariform; mastoid dilated inclosing a large hollow cavity; malar large excluding maxillary from orbit; carotid canal and foramen lacerum posterius widely separated; tibia and fibula firmly fused both proximally and distally; pes approaching mesaxonic with digit III. the longest, digit V. greatly reduced and digits II. and IV. shorter than III. but robust; astragalar trochlea bilaterally asymmetrical; navicular and calcaneum in articulation; small fibulo-calcaneal facet.

1. *Hegetotherium. Dental formula* $\frac{3}{3}, \frac{1}{1}, \frac{4}{4}, \frac{3}{3}$. Second and third upper and third lower incisor vestigial; canine vestigial; upper molars internally convex, without inflection except in $M^3$; ectoloph smooth; terminal phalanges greatly flattened transversely with prominent clefts.
2. *Pachyrukhos.* Dental formula $\frac{1}{2}, \frac{0}{0}, \frac{3}{3}, \frac{3}{3}$. All the upper molars internally convex; ectoloph smooth; terminal phalanges hoof-like without clefts in Santa Cruz species.

The Santa Cruz typotheres are animals of somewhat rodent-like appearance, varying in size from a cotton-tail rabbit to a cavy. A review of the more important skeletal characters of the group may be of value, even though it involve some repetition.

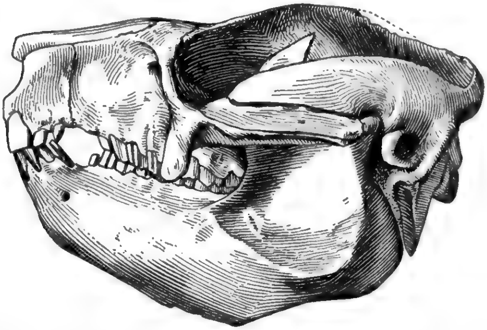

FIG. 2. Skull of *Interatherium robustum* Ameghino, side view, three fourths the natural size. (No. 9263 American Museum of Natural History collection.)

1. *The Skull.*—The facial portion of the skull is slender and more or less excavated longitudinally while the brain case is broad and well expanded. The orbits are central, circular in outline, quite prominent in *Hegetotherium, Pachyrukhos* and *Interatherium* and unenclosed posteriorly. The jugal arches are robust in all except *Pachyrukhos* and moderately expanded. The premaxillæ are short and heavy with scarcely any ascending process; the nasals are broad posteriorly, tapering forward to blunt points; the interorbital tract plane and the sagittal and lambdoidal crests low. The most promi-

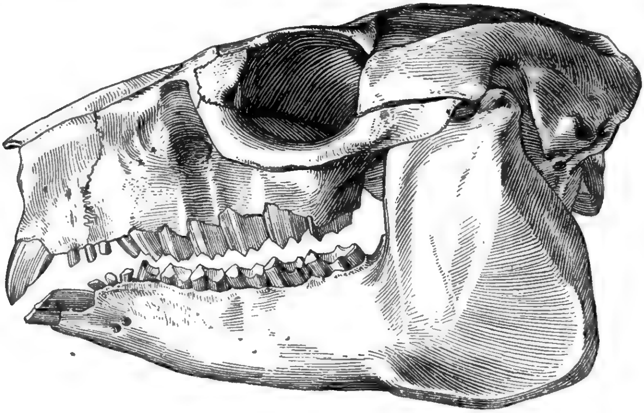

FIG. 3. Skull of *Hegetotherium mirabile* Ameghino, side view, three fourths the natural size. (No. 15542 Princeton University collection.)

nent feature of the back of the skull is the greatly distended mastoid tract which may either be filled with cancellæ or lodge a large cavity. In either case there is direct communication with the tympanic bulla and the dilation appears to have functioned as a secondary resonator, perhaps associated with nocturnal habits. The palate is concave throughout, terminating posteriorly in a pair of stout processes. The mandible is heavy and deep, without trace of suture in the firmly fused symphysis.

2. *Dentition.*—Beginning with the normal incisor formula in *Protypotherium* (Fig. 1) the Santa Cruz typotheres show a well-marked tendency toward an increase in size of the median incisors at the expense of the lateral incisors, canine and anterior premolar until the extreme stage of reduction in *Pachyrukhos* (Fig. 4) is attained. The teeth undergoing elimination are reduced to simple cylinders. It is not to be understood that *Protypotherium, Interatherium, Hegetotherium* and *Pachyrukhos* constitute a phyletic series because they represent successive stages in the process of dental reduction associated with the hypertrophy of the median incisors. As already indicated in the key to the genera, two divergent lines are represented and not a single progressive series. A rather curious feature of the lower incisors in *Protypotherium* is the presence in the first and second of a deep median cleft producing a fork-like structure recalling a somewhat similar division of the lower incisor crowns in the Hyracoidea. In all the Santa Cruz typotheres the enamel layer on the enlarged incisors tends to be confined to the anterior surface of the crown. The molars in all the genera are constructed on much the same plan but only in *Protypotherium* are absolutely unworn teeth known, consisting essentially of a broadly concave ectoloph (*e*, Fig. 8, *A*) and a pair of crescents with the convexity directed inward (*ac, pc,* Fig. 8, *A*), of which the anterior horns are fused with the ectoloph inclosing a reentrant. A crista-like ridge from the ectoloph (*c,* Fig. 8, *A*) is separated from the anterior crescent by a deep notch. A slight ridge (*pp,* Fig. 8, *A*) blocks the shallow valley inclosed by the posterior crescent. As the tooth wears the antero-external angle of the crown elongates and is channeled by a shallow groove producing the ridges noted in the key to the genera.

In the lower molars the convexity of the crescents is reversed so that the reentrant fold is external (Figs. 1, 3, 9, *A*). A prominent lobe spanning the arc of the posterior crescent (*pp*, Fig. 9, *A*) is not peculiar to the teeth of the Typotheria alone, but is present also in *Nesodon* (Fig. 9, *B*), *Astrapotherium, Theosodon* and other extinct ungulates from South America. In the last lower molar the development of the third lobe present in *Interatherium* is accomplished by the deepening of the shallow groove indicated in *Protypotherium* at the point marked *pc* in Fig. 9, *A*.

As mentioned in the generic key the premolars are sometimes molariform and sometimes not, differing from the molars in the latter case in having the anterior crescentic lobe smaller than the posterior.

Roots are developed only in the deciduous molars but as these have been observed only in *Protypotherium* and *Interatherium* it is not altogether certain whether this character is of family or subordinal value. So far as can be ascertained the crown pattern seems to have been the same in the deciduous and permanent series, the milk teeth resembling their successors. The order of replacement seems to have been the normal one.

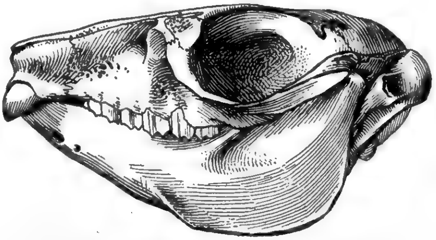

FIG. 4. Skull of *Pachyrukhos moyani* Ameghino, side view, three fourths the natural size. (Reconstructed from several specimens.)

A thin layer of cement is usually observable on the molars and premolars of all the genera.

3. *Axial Skeleton.*—The dorso-lumbar vertebral formula in *Interatherium* is twenty-two, of which fifteen are dorsals. It was probably the same in *Protypotherium* but in *Pachyrukhos* eight lumbars are present. Five vertebræ are coössified, in the sacral complex of which three are true sacrals in contact with the ilium and

two belong to the caudal series. The length of the tail seems to have varied. In *Protypotherium* and *Interatherium* it is both long and heavy while in *Pachyrukhos* there is reason to believe that it was quite short.

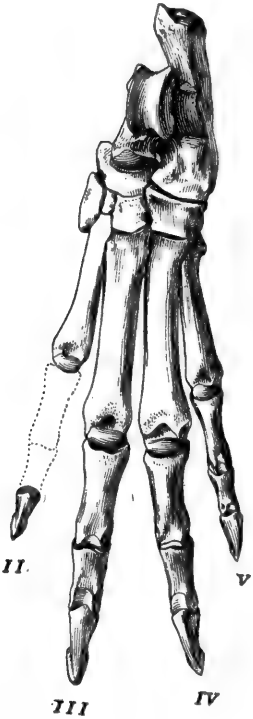

Fig. 5. Left hind foot of *Protypotherium australe* Ameghino, three fourths the natural size. (No. 9149 American Museum of Natural History collection.)

4. *Foot Structure.*—Almost nothing has hitherto been known of the structure of the feet in the Santa Cruz typotheres, but definite information is now available for all the genera except *Hegetotherium,* in which the manus is still unknown, but from the close structural resemblance of *Hegetotherium* and *Pachryukhos* it is probable that it was not unlike that of the latter, which in turn does not differ materially from the manus of *Interatherium* and *Protypotherium* (Fig. 6, *A*). In the Santa Cruz forms both manus and pes are tetradactyl without the slightest trace of an opposable thumb or great toe.[4] The carpus is strongly interlocking and shows no trace of the centrale. Two types of hind foot are developed (Figs. 5 and 7, *A*) simulating the paraxonic and mesaxonic symmetry of the feet of the Artiodactyla and Perissodactyla. These are probably to be correlated in the Typotheria with cursorial and saltatorial modes of progression. *Pachyrukhos* was certainly a jumping animal as shown by the greater length and strength of the hind limbs and inner digits of the pes. In fact, the structure of both the fore and hind limbs in this animal

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[4] A pentadactyl manus with separate centrale in the carpus and opposable thumb and a pentadactyl pes with large opposable hallux figured by Ameghino, *Revista Argentina de Hist. Nat.*, I., pp. 393, 394, figs. 95, 96 and referred to *Interatherium* (*Icochilus*) *robustum* do not pertain to this genus. The same figures with the erroneous determination appear also in Zittel's "Handbuch der Palaeontologie," IV., p. 493, fig. 407.

closely resembles that of the rabbit. From the numerous structural similarities between *Pachyrukhos* and *Hegetherium* it may be inferred that the latter was also saltatorial. Its broad, shallow astragalar trochlea is in contrast with the narrow, more deeply incised trochlea of the cursorial *Protypotherium* and *Interatherium*. Both of these genera have the fore and hind limbs of approximately equal length. The terminal phalanges in the Santa Cruz typotheres are hoof-like and in *Hegetotherium* have prominent median clefts.

## Relationships of the Santa Cruz Typotheria.

1. *With the Toxodonta.*—In the evolution of the teeth and feet, the Santa Cruz Typotheria are less advanced than their contemporaries, the Nesodons. The feet of *Nesodon* (Figs. 6, *B*, 7, *B*) are tridactyle with the axis passing through the third digit. The manus has originally been tetradactyl like that of *Protypotherium* (Fig. 6, *A*) but has lost almost all trace of the fifth digit, a mere vestige, not shown in the figure, remaining. The other bones of the wrist and foot have not suffered any displacement as a result of this loss but interlock in the same way as in *Protypotherium*. The hind foot

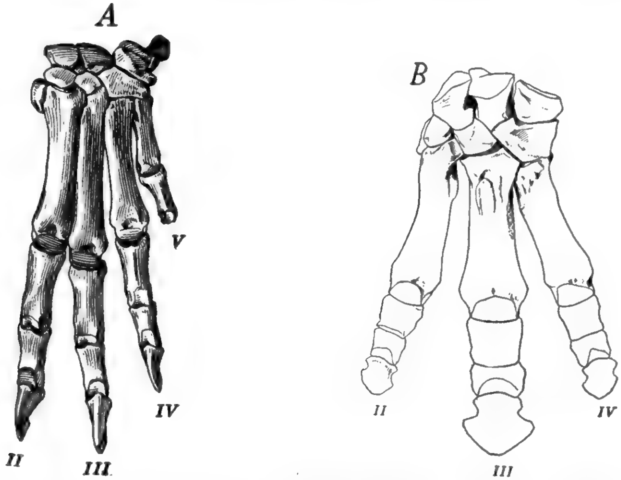

Fig. 6. *A*. Left fore foot of *Protypotherium australe* Ameghino, three fourths the natural size. (No. 9149 American Museum of Natural History collection.) *B*. Left fore foot of *Nesodon imbricatus* Owen, about one fifth the natural size. (No. 15460 Princeton University collection.)

of *Nesodon* (Fig. 7, *B*) is the realization of a structure already foreshadowed in the pes of *Hegetotherium* (Fig. 7, *A*). The fifth digit, which is greatly reduced in *Hegetotherium*, has here disappeared and the ento- and meso-cuneiforms have united to a single bone. The shortening of the neck of the astragalus and the increase in size of the fibular facet on the calcaneum are, perhaps, adaptations to the support of weight. Although the molars of *Nesodon* appear exceedingly complex, owing to the development of secondary enamel folds, the primary elements can be homologised with those displayed in the simpler crown pattern of *Protypotherium*, as indicated by the similar lettering in Figs. 8 and 9. This comparison can not yet be

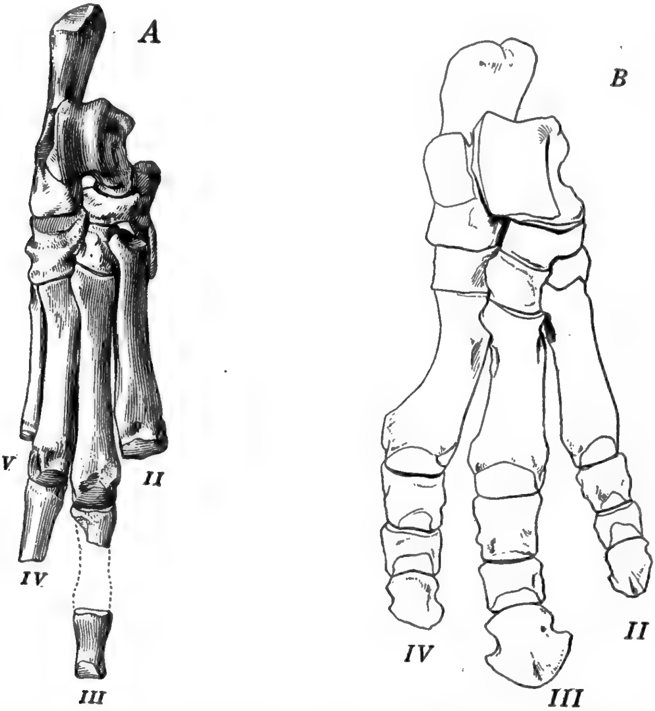

FIG. 7. *A. Hegetotherium mirabile* Ameghino, right hind foot, three fourths the natural size. (No. 15542 Princeton University collection.) *B. Nesodon imbricatus* Owen, right hind foot, about one third the natural size. (No. 15460 Princeton University collection.)

extended to the other Santa Cruz genera, *Hegetotherium, Pachyrukhos* and *Interatherium,* as unworn molars of these are not available. *Nesodon* differs from the Typotheria in the enlargement and caniniform character of the second incisor above and the third below, while in the Typotheria the median incisor in both jaws is the only one tending toward great increase in size. In none of the Santa Cruz Typotheria is there a trace of the double deciduous dentition characteristic of *Nesodon.*

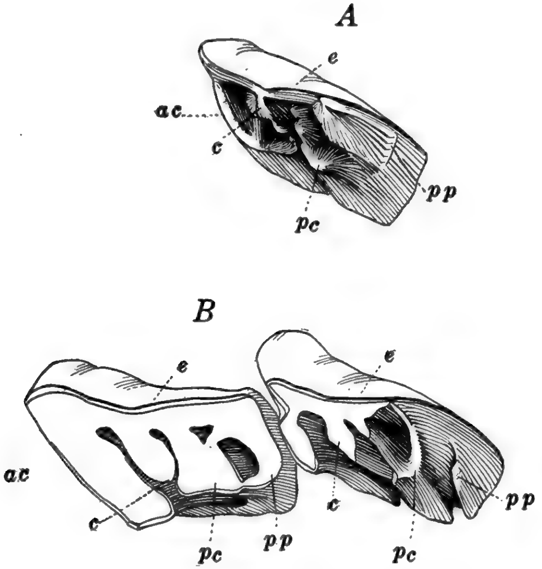

Fig. 8. *A.* Unworn third upper molar of a young *Protypotherium,* four and one half times the natural size. (No. 9482 American Museum of Natural History collection.) *B. Nesodon imbricatus* Owen, second and third upper molars slightly worn, three fourths the natural size. (No. 15135 Princeton University collection.) *ac,* antero-internal crescent; *pc,* postero-internal crescent; *e,* ectoloph; *c,* crista; *pp,* posterior pillar.

From these resemblances in dentition and foot structure it seems permissible to infer that the Toxodonta and Typotheria had a common origin, but the facts at present available do not justify us in saying more.

2. *With Typotherium.*—Difficult as it is to ascertain the relationship existing between the Santa Cruz Typotheria and the Nesodons,

it is even more so to determine their degree of kinship with *Typotherium.* From their small size it seems quite probable that none of the Santa Cruz Typotheria are in the direct line of descent culminating in this genus. This is confirmed by the degree of specialization in dentition and foot structure which *Typotherium* displays. The teeth of the latter show a greater complexity of folding than is attained by any of the Santa Cruz typotheres, while the feet are less specialized with a pollex in the manus which has been lost in *Protypotherium,* the most generalized of the Santa Cruz typotheres (Fig. 6, *A*), and with digit V. of the pes less reduced than in the most specialized of the latter (*Pachyrukhos*). A pollex has been figured by Ameghino[5] in the manus of *Pachyrukhos typicus,* but none has been found in any Santa Cruz specimen. The manus in *Hegetotherium* is unknown, so the above statement regarding the

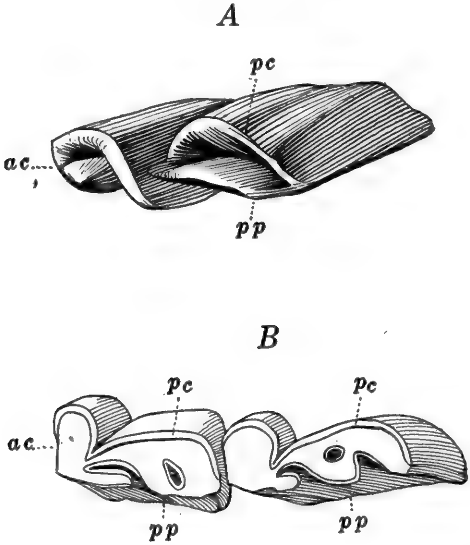

FIG. 9. *A.* Unworn third lower molar of a young *Protypotherium,* four and one half times the natural size. (No. 9482 American Museum of Natural History collection.) *B. Nesodon imbricatus* Owen, two lower molars, three fourths the natural size. (No. 15135 Princeton University collection.) *ac,* anterior crescent; *pc,* posterior crescent; *pp,* posterior pillar.

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[5] Ameghino, Florentino, "Contrib. al conoc., etc.," Pl. 13, fig. 14.

degree of specialization in foot structure displayed by *Typotherium* may require some modification in the light of fuller knowledge.

3. *With the Rodents.*—In many features of skull and skeleton the Typotheria resemble the rodents. This is most apparent in *Pachyrukhos,* which seems to have been a saltatorial animal, but in none of the Typotheria are the following characters peculiar to rodents developed:

*A.* Persistently growing, chisel-shaped incisors (I. 2/2 of the permanent series, Weber).[6] I. 1/1 of the permanent series is enlarged in some of the Typotheria and may grow persistently but is modified for cropping and not for gnawing.

*B.* More or less antero-posterior elongation of the mandibular condyle and corresponding modification of the glenoid fossa to permit backward and forward movement of the lower jaw. In the Typotheria the condyle is approximately circular in outline with the glenoid surface flattened and the movement of the mandible is from side to side.

*C.* Frequent outward curvature of the crowns of the upper molars and inward curvature of those of the inferior series in hypsodont forms. The reverse is true in the Typotheria.

*D.* Contact of ascending process of premaxillary with frontal. This process is short and robust in the Typotheria and is widely separated from the frontal by the maxillary.

*E.* Elongation of the mandibular angle. The angle is evenly convex in the Typotheria.

*F.* The astragalus in rodents is characterized by a broad, short, rather shallow trochlea with the crests sharp and equally developed, distinct neck and flattened head, convex distally; trochlea symmetrical to the vertical plane; fibular and internal malleolar facets vertical; body limited posteriorly; no astragalar foramen. In the Santa Cruz Typotheria the body is deeper than in rodents, the crests may or may not be equally developed and the head is globular without antero-posterior flattening. The symmetry of the trochlea with respect to the vertical plane varies in the different families. In the other characters they resemble rodents.

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[6] "Die Säugetiere," p. 480, 1904.

*G.* The presence of a free centrale in the carpus in all rodents except the Hystricidæ and *Caelogenys* and the general fusion of the scaphoid and lunar in all except the Bathyergidæ, Ctenodoctilidæ and Lagomorpha.[7] The centrale is wanting in the carpus of the Typotheria and the lunar is always free.

*H.* The presence of a tibial sesamoid in all the simplicidentate rodents. This is not found in the tarsus of the Typotheria.

The Typotheria resemble rodents in the elongation of the anterior portion of the skull with the reduction of the incisor-canine-premolar series (*cf.* Figs. 3 and 4), in the enlargement and often permanent growth of the median incisors (not homologous with the enlarged incisors in rodents, see under *A,* above), in the development of a mastoid dilation which may be filled with cancellæ (Interatheridæ) as in many rodents and connected with the auditory bulla, in the shape of the proximal articular surfaces between the radius and ulna, in the broad anteriorly directed transverse processes of the lumbar vertebræ and in several other characters of minor importance.

In view of the striking differences in structure indicated in the preceding paragraphs, it seems probable that these resemblances are to be explained as instances of convergence.

4. *With the Hyracoidea.*—A more or less intimate relationship between the Typotheria and Hyracoidea is commonly assumed but with the complete material now available it is difficult to see on what grounds this hypothesis can be maintained. The hyracoid carpus is arranged on the linear plan with separate centrale while in the tarsus the astralagus is unlike that of any other mammal in possessing a large step-like articulation for the internal tibial malleolus (Fig. 10).

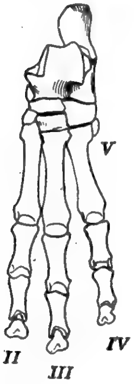

Fig. 10. Left hind foot of *Procavia* (*Dendrohyrax*) *arborea,* ¾ natural size. (No. 365 Princeton University osteological collection.)

In striking contrast with hyrax, the carpus in the Typotheria is strongly interlocking without centrale, and the internal tibial malleolus is applied to the lateral surface of the astragalus without trace

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[7] Weber, *loc. cit.,* p. 476.

of the supporting shelf (Figs. 5 and 7, *A*). The flat astragalar head in the Hyracoidea and the articulation of the fibula with the astragalus instead of with the calcaneum are additional points of difference, all of which are more than sufficient to offset similarities in skull structure which are confined to a few points, such as the cancellous dilation of the mastoid, the shape of the posterior border of the palate, and the increase in depth posteriorly of the mandible. In the Hyracoidea the molar takes part in forming the outer portion of the glenoid cavity, the parietal enters into the postorbital process and the base of the coronoid just back of the last lower molar is perforated by a large foramen, a superior branch of the alveolar canal. None of these characters are exhibited by the Typotheria. In the hyracoid dentition, the first upper incisor is a persistently growing downwardly curved tusk of triangular cross-section. In some of the Typotheria this tooth may grow persistently but it is always antero-posteriorly compressed, transversely expanded and modified for cropping, never appearing as a tusk. The molars of the Hyracoidea are lophoselenodont and either brachyodont or short hypsodont while in the Typotheria they are extremely hypsodont, developing roots only in the deciduous series. The crown pattern of the hyracoidean molar bears more resemblance to that of some of the early horses and rhinoceroses than to the molar pattern in the least specialized of the typotheres (Figs. 8 and 9).

The so-called hyracoids from the Fayum Province of Egypt (*Saghatherium, Megalohyrax*) are as yet known only from fragments of the skull and dentition but, so far as the available material permits comparison, resemble the modern Hyracoidea and not the Typotheria which would probably not be the case if the two orders were related as it would naturally be expected that a closer similarity should exist between the Eocene and Miocene representatives of an order than between the latter and the recent forms. All the Egyptian hyracoids have the base of the coronoid perforated by a branch of the dental canal as in the recent forms[8] and unlike the Typotheria.

[8] Communicated by Mr. Walter Granger, of the American Museum of Natural History.

Various pre-Santa Cruz genera (*Archæohyrax, Argyrohyrax*) have been referred to the Hyracoidea. Their foot structure is still unknown but the skull and dentition, to judge from the photographs, figures and descriptions examined by the writer, are not hyracoidean in character. Too little is known of these forms to warrant a discussion of their relationship with the Santa Cruz Typotheria, but there can be little doubt that they should be referred to the same suborder.

PRINCETON UNIVERSITY, April, 1908.

# NOTES ON SOME CHILEAN COPPER MINERALS.

### By HARRY F. KELLER.

(*Read April 24, 1908.*)

Some time ago my brother, Mr. Hermann A. Keller, presented me with a fine suite of mineral specimens collected by him on a professional trip to Chilean mining localities. The minerals, which include native sulphur and copper, various oxides, chlorides, sulphates, borates and silicates, were for the most part readily identified by their characteristic appearance or by simple tests, but some of them aroused my curiosity, partly because of their rare occurrence, and partly on account of their beauty or exceptional purity. I was thus led to make a number of qualitative and quantitative analyses, the results of which appear to me sufficiently interesting to be placed on record. In the present paper I shall confine myself to the description of some minerals containing copper as either a principal or a minor constituent.

## Cupreous Manganese.

It is well known that in many varieties of psilomelane or wad the manganous oxide is partially replaced by oxide of copper, and that special names have been given to some of those varieties in which the proportion of the latter oxide is considerable. Among them is the peloconite from Remolinos, Chile, which was first described by Richter,[1] and chemically characterized by Kersten.[2] Its quantitative composition, however, does not appear to have been fully determined. The material supplied by my brother included several very fine specimens of a cupreous manganese from Huiquintipa, Province of Tarapacá, and these are unquestionably identical with Richter's peloconite. With the one exception of the specific gravity, the physical and chemical characters of the new material are precisely

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[1] *Poggendorffs Annalen,* 21, 590.

[2] *Schweigger's Journal,* 66, 7.

similar to those of the Remolinos occurrence. The mineral is massive and amorphous, has a conchoidal fracture, a bluish-black color and a liver-brown streak. Its hardness is between 3 and 4, and the specific gravity 3.683 (instead of 2.5–2.6). When broken into small pieces and carefully picked with the aid of a lens, the material appeared quite homogeneous except for a few particles of quartz and some green or bluish specks of a copper compound on the outside and along the crevices. A qualitative analysis showed that it contains the oxides of manganese, copper and iron, together with water and varying amounts of admixed silica. To ascertain whether the mineral has a definite chemical composition analyses were made of carefully selected samples from different specimens. It was found that the silica, which separates on dissolving the substance in hydrochloric acid, is not uniformly distributed through the mass. Its percentage varied from 12 per cent. to 32 per cent., and its microscopic examination showed that it consists entirely of quartz. There could be no doubt, then, that it is simply an admixture, and that in calculating the composition, the silica (of which only a trace dissolves with the mineral) should first be deducted from the amount of the substance taken. The results of the analyses were as follows:

| | I. | II. | III. | IV. |
|---|---|---|---|---|
| Oxygen | 14.37 % | 14.18 % | 13.89 % | not det. |
| Manganous oxide | 69.61 | 68.95 | 69.44 | 70.61 % |
| Cupric oxide | 5.86 | 6.05 | 5.69 | 6.48 |
| Cobalt oxide | .48 | .56 | not det. | not det. |
| Barium oxide | .36 | .47 | not det. | not det. |
| Ferric oxide | 2.05 | 1.94 | 1.89 | 4.22 |
| Alumina | 1.92 | 1.91 | 2.10 | |
| Water | 5.14 | 5.29 | | |
| | 99.79 % | 99.35 % | | |

It is seen from these figures that the proportions of the several constituents of the mineral are fairly constant. The composition is that of psilomelane, in which part of the manganese is replaced by copper. It is difficult to account for the very constant proportions of oxide of iron and alumina.

Regarding the determinations of water and of available oxygen, I may mention that the former was made by heating the substance in a current of dry air and collecting the moisture in calcium chloride, while the latter was estimated iodometrically in I. and II., and indirectly in III., by heating a weighed portion, first in air and then in hydrogen, and allowing for the water and the reduction of the oxides of copper and iron. As a matter of course this method is less reliable, but the result nevertheless agrees quite well with the iodometric determinations.

## CHALCANTHITE AND A DOUBLE SULPHATE OF COPPER AND MAGNESIUM.

Among the specimens that claimed my special attention there was one[3] consisting of irregular and rounded masses, and which was labeled "sulphate of copper and aluminium." While the shape of the little lumps was about the same, three distinct kinds of material could readily be picked from the specimen, even without the help of a magnifying glass.

One of these substances had a deep blue color and was recognized without difficulty as chalcanthite. The blue masses were evidently crystals which were strongly corroded and slightly effloresced on the surface. A quantitative analysis confirmed the composition $CuSO_4 + 5H_2O$, with very small amounts of iron and magnesium sulphates, and a slight admixture of silicious matter. It gave:

| | Found. Per Cent. | Calculated. Per Cent. |
|---|---|---|
| Sulphur trioxide | 32.21 | 32.1 |
| Cupric oxide | 31.52 | 31.8 |
| Ferrous oxide | .30 | |
| Magnesium oxide | .35 | |
| Water | 35.79 | 36.1 |
| | 100.19 | 100.0 |

More interesting were the bluish-white masses which formed the larger portion of the specimen. They were earthy and friable, but presented shapes and surfaces exactly similar to those of the chalcanthite, suggesting a pseudomorph after the latter. In composition, however, the material was found to differ from chalcanthite in

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[3] From Copaquire, Province of Tarapacá.

that it contained a large proportion of magnesium sulphate. Analyses of two different samples yielded:

| | Found. | | Calculated for (Cu, Mg)$SO_4+5H_2O$: |
|---|---|---|---|
| | I. | II. | |
| Sulphur trioxide | 35.74% | 35.67% | 35.84% |
| Cupric oxide | 12.41 | 12.46 | 11.89 |
| Magnesium oxide | 11.42 | 11.36 | 11.95 |
| Ferrous oxide | .97 | 1.05 | |
| Manganous oxide | .23 | .41 | |
| Nickel oxide | trace | .06 | |
| Water | 38.45 | 38.31 | 40.32 |
| | 99.22% | 99.32% | 100.00% |

The conclusions to be drawn from these results are, first, that the mineral is an isomorphous mixture of the sulphates of copper and magnesium; secondly, that this double salt contains five molecules of water of crystallization; and thirdly, that for each molecule of copper sulphate there are present (very nearly) two molecules of magnesium sulphate. The shortage in the water content is doubtless owing to efflorescence, and there should be credited to the magnesia content an amount equivalent to the percentages of the oxides of iron and manganese.

Under the name of cupromagnesite a double sulphate of copper and magnesium has been described by Scacchi. It occurs in the form of green crusts on lava from the Vesuvius, and is believed to be isomorphous with melanterite, containing, like the latter, seven molecules of water of crystallization. I have seen no reference to a mineral of the same composition as that above described.

Associated with the chalcanthite and the double sulphate of copper and magnesium were other little masses, dirty-white in color and more or less stained with ferric oxide. They were very hard and consisted almost entirely of silica, containing only trifling amounts of oxide of iron and magnesia. It is puzzling to explain why these masses should simulate the form of the accompanying soluble sulphates.

## BROCHANTITE(?) CONTAINING ARSENIC ACID.

Very small quantities only were available of an emerald green mineral which was observed partly in fine acicular crystals disseminated through a silicious rock, and partly as an incrustation upon quartz. On account of its physical characters, as well as the strong reaction its solution gave with barium chloride, I was first inclined to regard it as a typical brochantite. This impression was confirmed by rough estimations of the copper and sulphur trioxide, but as these tests had been made on impure material, I decided to attempt the analysis of a carefully prepared sample. To obtain about .5 grm. of the substance, I found it necessary to sacrifice the best specimens in my possession, and my patience was put to a severe test in picking the minute crystals under the lens. They were sorted over and over until the microscope showed only a few remaining specks of quartz adhering to the larger crystals of the copper mineral.

The quartzy material from which this sample had been picked still contained considerable quantities of the copper mineral, and it occurred to me that it might serve for a qualitative, and, perhaps, a preliminary quantitative analysis. Accordingly the material was extracted with hydrochloric acid, and the resulting green solution divided into equal parts. When the copper had been precipitated with hydrogen sulphide, it was noticed that yellow flakes began to form, and after the liquid saturated with the gas had been allowed to stand in a warm place over night, a considerable amount of the yellow precipitate had settled on the black copper sulphide. There could be no doubt, then, that arsenic was present in the form of arsenic acid. The sulphides were separated and worked up in the usual manner, and the filtrate was searched for other metallic ions. It yielded only traces of iron oxide and alumina. The other half of the original solution was used for the determination of the sulphur trioxide and the arsenic acid. The results of the determinations, calculated for the entire amount of copper mineral dissolved, gave:

| | |
|---|---|
| Copper | .5068 grms. |
| Sulphur trioxide | .0783 grms. |
| Arsenic anhydride | .1309 grms. |

The question now arose as to whether the very large proportion of arsenic acid found really constituted an integral part of the supposed brochantite, or whether it did not belong to another mineral contained in the rock. The test previously made seemed to preclude such an arsenic content of the mineral under examination.

In view of the very limited amount of material available for analysis, it seemed best to dispense with the water determination and confine the characterization of the mineral to ascertaining the specific gravity and an estimation of the base and the acids. The following results were obtained:

| | I. Per Cent. | II. Per Cent. |
|---|---|---|
| Specific gravity | 3.160 | |
| Sulphur trioxide | 16.32 | 16.63 |
| Arsenic anhydride | 2.31 | 2.40 |
| Copper oxide | 68.90 | 68.68 |
| Silica | 1.63 | 1.18 |

If we deduct the quartz from the substance taken for analysis, the percentages of sulphur trioxide and oxide of copper will be found to approach very nearly to those in brochantite which contains:

| | Per Cent. |
|---|---|
| Sulphur trioxide | 17.7 |
| Cupric oxide | 70.3 |
| Water | 12.0 |

and it is difficult to explain the rôle of the arsenic acid which is equivalent to about 4.4 per cent. of sulphur trioxide. To establish a definite formula for the compound it would be necessary to ascertain by further analyses whether or not the proportion of arsenic anhydride is constant, and to complete the analysis by an exact determination of the water. The specimens in my possession, unfortunately, are not sufficient for this purpose.

The specimens were collected at Copaquire, Province of Tarapacá.

## ATACAMITE.

In conclusion I desire to call attention to some magnificent specimens of atacamite from Paposo in the Province of Antofagasta. They do not show the usual slender prisms, but consist of aggregates of fairly large crystals, closely resembling the octahedron of the isometric system modified by the cube and the rhombic dodecahedron. On closer examination, however, it would seem that they are really combinations such as have been observed on the atacamite

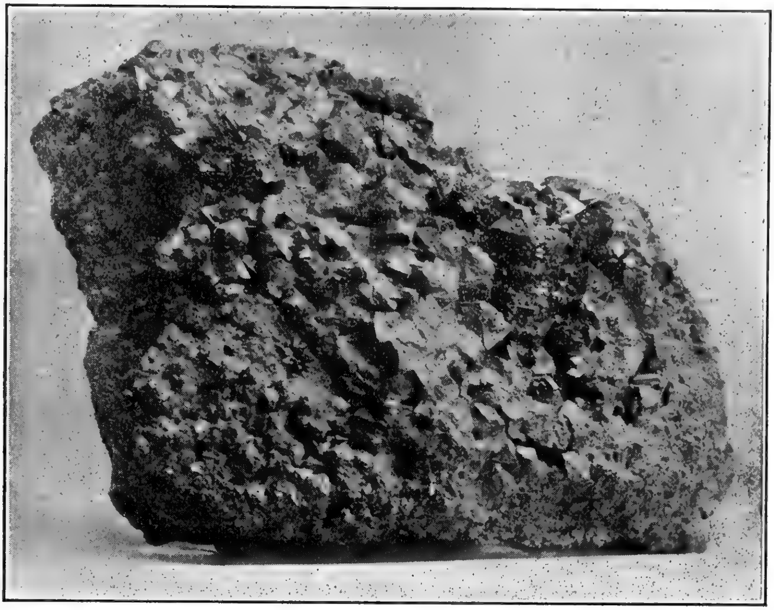

FIG. 1. Atacamite from Paposo, Chile.

from certain localities in South Australia.[4] As was to be expected, the analysis showed the specimens to be an atacamite of unusual purity and of normal composition. It yielded:

Sp. gr. .................................. 3.738

| | Found. Per Cent. | Calculated for $CuCl_2.3Cu(OH)_2$. Per Cent. |
|---|---|---|
| Chlorine | 16.51 | 16.6 |
| Copper | 14.79 | 14.9 |
| Cupric oxide | 55.28 | 55.8 |
| Water | 12.42 | 12.7 |
| Insol. | .79 | |
| | 99.79 | 100.0 |

CENTRAL HIGH SCHOOL, PHILADELPHIA.

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[4] I hope to verify this by actual measurement.

# PROGRESS OF THE DEMARCATION OF THE ALASKA BOUNDARY.

By O. H. TITTMANN,

U. S. Commissioner.

(*Read April 24, 1908.*)

The boundary between the British and Russian possessions in North America was defined by the Treaty of St. Petersburg of 1825. When the United States purchased the Russian possessions, or Alaska, in 1867, it was believed that the territorial jurisdiction of the United States and Great Britain could not become a matter of controversy. This view is evidenced by the remark made by Charles Sumner in his speech advocating the purchase of Alaska. "I am glad," said he, "to begin with what is clear and beyond question. I refer to the boundaries fixed by the treaty."

The total length of the boundary referred to by Mr. Sumner is twelve hundred miles. It divides itself naturally into two sections of about six hundred miles each. One is the section bounded by the 141st meridian, and the other the irregular boundary delimiting the narrow coast strip of southeastern Alaska. No dispute has ever arisen as to that part of the boundary defined as being the 141st meridian of longitude west of Greenwich. As is well known, however, a contention arose as to that part of the boundary which delimits the stretch of coast extending from the neighborhood of Mt. St. Elias southeasterly to and through the Portland Canal. A modus vivendi in 1878, affecting the Stikine River, and another in 1899, relating to the country at the head of Lynn Canal, made temporary provision for customs and police purposes. The dispute relating to that part of the boundary was happily settled by the Tribunal of London which was constituted under a convention signed at Washington January 24, 1903.

Hon. John W. Foster, the agent of the United States in this important case, remarks in his report to Secretary Hay:

> "It is a noteworthy fact that this important adjudication was brought to a close within less than eight months from the time when the treaty creating the tribunal went into effect. Such a prompt result is almost without parallel in the intercourse of nations."

Equally prompt was the action of the governments in appointing commissioners in accordance with a requirement of the convention constituting the Tribunal. Within a few months, that is, in the spring of 1904, the commissioners, Mr. W. F. King, on behalf of the British Government, and your speaker, representing the United States, began the delimitation of that part of the boundary which had been in dispute. The commissioners were guided in their plans by maps, accompanying the decision, on which the Tribunal had marked certain mountain peaks as being the mountains contemplated by the Treaty of 1825.

It is the business of the commissioners to identify the peaks, to establish their geographical position, to mark by visible monuments, wherever possible, the turning points in the line and such other points as may be necessary, and to describe and define the line between the points selected by the Tribunal. There was a stretch of about one hundred and twenty miles where the topographic information was insufficient, and there the commissioners were directed to make additional surveys and to select mountain peaks within certain prescribed limits to define the boundary. The commissioners decided to mark at once certain river crossings and the mountain passes and to connect all the boundary peaks by a continuous triangulation based on the trigonometric datum adopted by the Coast and Geodetic Survey for southeastern Alaska.

The boundary line, starting from the neighborhood of Mt. St. Elias, crosses that summit and other high peaks of the St. Elias Alps and the Fairweather Range. In general, it lies amid perpetual snow and ice except when it drops abruptly into the river valleys only to rise again into regions of perpetual snow. Finally, it reaches the head of Portland Canal and becomes a water boundary.

In the four years since work was begun on this portion of the boundary the commissioners have fixed trigonometrically all the peaks except two near Mt. St. Elias and those in the region between the Whiting River and Devil's Thumb, and some of the peaks south of the Unuk River. The passes, valleys and river crossings have been monumented with the exception of the crossing of the Alsek in the north and the valleys of the affluents of the Iskut and the crossing of the Le Duc and Chicamin rivers in the south. The turning points of the water boundary in Portland Canal also remain to be fixed by reference to points on shore.

## THE 141ST MERIDIAN.

According to the Treaty of 1825 the 141st meridian west of Greenwich forms the eastern boundary of Alaska from the Arctic Ocean to near Mt. St. Elias. It was not until 1889—twenty-two years after the acquisition of Alaska—that any steps were taken by our government towards establishing the location of the 141st meridian on the ground. In that year the Coast and Geodetic Survey despatched one party to the Yukon and another to the Porcupine River to determine the boundary crossing of those rivers. The Canadian government had previously sent an engineer to the Yukon who made an astronomical determination of the boundary in the autumn and winter of 1887. The country at that time was very inaccessible and the surveyors were compelled to determine the longitude by moon culminations and occultations, and the American parties spent a whole winter in observing them. But the operations of the three parties were not carried on under an international agreement and the results therefore were not reciprocally binding on the governments concerned.

The discovery of gold and the general development of the country, however, caused the construction of a Canadian telegraph line overland to Dawson and beyond, and later the United States government laid a cable from Seattle to Sitka and thence to Valdez on Prince William Sound, whence an overland line was built by the United States War Department as far as Fort Egbert on the Yukon near the boundary. Egbert and Dawson were also connected by telegraph. This important auxiliary to longitude determination made it possible for the two governments to determine the position of the 141st meridian with all the necessary accuracy as soon as an agreement was reached and embodied in the treaty signed at Washington in August, 1906. This treaty provided for the survey and demarcation of the line and before the end of that summer the telegraphic determination of the Yukon River crossing of the 141st meridian had been completed. The telegraphic determination made by the Americans rests on the known longitude of Seattle. Signals were exchanged between Sitka and Seattle, Seattle and Valdez, Valdez and Fort Egbert, Fort Egbert and the boundary. That made by the Canadians rests on the longitude of Vancouver between which place and the boundary time signals were exchanged. As the difference between Seattle and Vancouver was also determined by the commissioners, the circuit was closed and a very satisfactory agreement was obtained.

It is worthy of remark in passing that the tracing of a meridian or parallel on the ground involves considerations which do not become apparent by an inspection of an artificial globe on which these lines are traced as smooth and regular curves. A parallel of latitude must be determined by astronomical observations, but in general the circumference of a small circle of the earth parallel to the equator will not lie in the same astronomical latitude, owing to the so-called deflection of the vertical. A series of points determined astronomically as being in the same latitude or, as in the case of a meridian, in the same longitude, will therefore in general produce on the surface of the earth a zig-zag line when they have been joined together.

In order to avoid all questions that might arise from local deflections of the zenith, it was provided by the Treaty of 1906 that the commissioners should determine by the telegraphic method a convenient point on the 141st meridian and then trace a north and south line passing through the point thus ascertained. This provision fixed the telegraph crossing of the boundary as the initial point for the longitude determination. The commissioners desired to make the determination as nearly on the 141st meridian as possible, in order to avoid a deflection error which might have been involved if the longitude had been obtained by linear measurement from a longitude observed at some distance from the boundary. The transit pier erected for the purpose of exchanging time signals was found to be in longitude 141° 00′ 00″.4, a very close hit. It is interesting to note also that the final longitude differed only 9″.43 of an arc, or 410 feet, from that derived by moon culminations about twenty years before.

The work of tracing the boundary southward from the Yukon was begun in the spring of 1907 and was carried southward a distance of about one hundred and twenty miles. Aluminum-bronze monuments were erected on the north and south banks of the river, a trigonometric and topographic survey was made extending two miles on each side of the boundary for a distance of about forty-five miles, and a broad vista was cut through the woods for the same distance. The work planned for the coming season will carry the tracing of the line as far as the great mountains south of the White River, and the topographic survey and the monumenting will be pushed until the severity of the weather compels the surveyors to abandon the work and turn their faces homeward.

# THE MOST PRIMITIVE LIVING REPRESENTATIVE OF THE ANCESTORS OF THE PLANT KINGDOM.

By GEORGE T. MOORE, Ph.D.

(*Read April 25, 1908.*)

There is but little doubt among botanists that the land flora as it now exists has originated from aquatic ancestors. Both from the morphologic and palæontologic standpoints the evidence corroborates this view. Indeed, the dependence of land plants upon an adequate water supply, together with the fact that in such groups as the Mosses and Ferns, fertilization itself can only be accomplished in the presence of water supplied from some external source, gave rise to the conclusion that the origin of the vegetable kingdom was from primitive plants living in the water, long before there was the more conclusive evidence now existing.

It would be interesting to inquire into the life histories of certain transitional groups with a view to tracing this migration from water to land. For modern morphological and physiological investigations has enabled us to do this with a considerable degree of certainty. Not only would we be able to show that the establishment of the higher representatives of our land flora had been brought about by certain methods of specialization in lower aquatic or semi-aquatic forms, but it would be possible to indicate to a certain extent at least how this process had been carried on. However such an inquiry would lead us entirely too far afield at this time and it will be necessary to grant without further discussion that the facts are sufficient to sustain the aquatic origin of the higher plants.

Naturally, in seeking for the primitive ancestors of the vegetable kingdom, attention is at once directed to the algæ, the group of plants which to a very considerable extent is more dependant upon the presence of external water for the carrying on of its vital processes than any other. Furthermore, in the present state of our knowledge, such an investigation would not be devoted to the more highly differentiated brown or red algæ, but rather to the green algæ, in which group there exists the closest resemblances to the structure of the lower land plants. The problem thus becomes one of discovering as nearly as may be possible the most primitive member of the green algæ. And by "*primitive*," of course, is not necessarily meant the simplest form, but that plant which seems to be nearest to the starting point of the phylogenetic tree and from which certain definite lines of ascent can be traced.

In considering the origin of the green algæ, numerous theories have been held and it would be impossible to give even a mere outline of the various improbable suggestions which have been advanced regarding the evolution of this group. During the past ten years, however, a great deal of light has been thrown upon the phylogenetic relationship of the algæ. Not only has the increase in our knowledge of the life histories of the algæ been considerable, but the discovery of many new genera and species has made clear the affinities of various families as never before. Of the 275 good genera now recognized among the green algæ, one fourth have been discovered and described since the appearance of Engler and Prantl's "Pflanzenfamilien"—the last complete work on the subject and still the recognized authority. The addition of so many new and in many cases important links to the chain of development of these plants, has reduced the former chaotic condition to something like order and it is no longer quite such a matter of speculation regarding the origin of the main group of the green algæ.

Ten years ago Chodat derived the green algæ from the simplest, unicellular, non-motile forms then known, namely, the Palmellaceæ. Within this family he included four genera whose simple life history showed three principal stages. From these so-called "conditions," as Chodat pointed out, developed the three important and ruling tendencies which have dominated the lower green algæ.

These are: (1) The *zoöspore condition,* or the unicellular motile stage, with the other two conditions transient or subordinate. (2) The *sporangium condition,* that is, the unicellular *non*-motile stage, with the other two conditions accidental or transient. (3) The *tetraspora condition,* where the non-motile cells are connected at right angles by the increasing consistency of the walls, giving rise to the formation of a tissue or filament. The other two conditions are reduced or transient.

Having established these three principal "conditions," Chodat proceeded to establish the phylogeny of the green algæ along these lines and succeeded in clearing up considerable obscurity which had previously existed. However, the starting point selected by Chodat has been open to some criticism and it remained for Blackman to suggest the most satisfactory explanation of the origin of this group. He, while following in a general way the theory of Chodat, took the position that the three "tendencies" had their origin *not* in the non-moile *Palmella* form, but in the motile *Chlamydomonas* type.

I have had the genus *Chlamydomonas* under investigation for several years, observing its various species for the most part in pure cultures grown upon both solid and liquid media. The vegetative cells of *Chlamydomonas* are variable in both size and shape; in general, however, they are from 20–35 $\mu$ in length and 10–20 $\mu$ in breadth, being elliptic or pyriform in outline. One end of the cell is usually produced into a colorless beak, from which two cilia always protrude. The chloroplast is quite variable in form and with one exception is provided with a single pyrenoid. Non-sexual reproduction is by means of zoöspores, which are formed by the division of the contents of the mother cell, after it has come to rest. Sexual reproduction is usually by the conjugation of naked motile gametes of similar size and in no way distinguishable from each other. It is interesting to note, however, that in addition to this method there may also be the conjugation of unequal motile gametes and in one species—to be referred to later—there takes place the conjugation of dissimilar gametes, one of which, the larger, comes to rest before conjugation. We thus have within the limits of this well defined and natural genus, not only the most primitive form of gamogenesis, but through anisogamous conjugation a gradual approach to true oögamy—the highest type of sexual reproduction developed among the algæ.

In abandoning the starting point of Chodat's theory of the development of the green algæ, it is not necessary to replace his idea relative to the three predominating tendencies manifest in the lower members of this group. While different names are attached to these conditions as recognized at the present time, they are essentially those pointed out by Chodat, namely:

1. A tendency towards the aggregation of motile vegetative cells, with a gradually larger and more specialized motile colony. This is the *Volvox* type and in no place in the plant kingdom do we have a more perfect series of development than from the simple *Chlamydomonas* form to the complex and highly differentiated *Volvox* type.

2. A tendency towards the formation of an aggregation of non-motile cells into a filament or tissue by the repeated vegetative division of an original mother cell. This is the *Tetraspora type.*

3. The *Endosphæra* type, where the tendency towards the formation of vegetative divisions and septate cell formation is reduced to a minimum. This is, of course, Chodat's *sporangium* tendency, although not so much importance is attached to it.

Without going into details it may be said that various species of *Chlamydomonas* (of which there are about thirty, all remarkably constant as regards their cytological characters), taken collectively, exhibit all these three tendencies and that the simpler forms of algæ which possess but a *single* tendency, seem clearly to have diverged from some one species of this genus.

The endosphærine tendency in *Chlamydomonas* has given rise to a single family, *Endosphæra.* This is naturally strictly unicellular and with no vegetative divisions; the reproduction of the species can take place only by the formation of zoöspores or gametes. A family so restricted as to its vegetative habit could hardly be expected to develop very far and it is interesting to note that practically all the genera are epiphytic upon other algæ or aquatic plants, and that this habit of life has undoubtedly given rise to a distinct group of fungi. The suggestion has been made that the peculiar Siphonales may have developed from this *Endosphæra type,* and while such a view is reasonable, it must necessarily, at the present time, be a mere matter of speculation.

But one family, the Volvocaceæ, has resulted from the development of the volvocine tendency. While the evolution of sex in this group has been carried to the highest possible degree, the restrictions of an enforced motile vegetative condition did not permit this family to give rise to anything further.

It is the tetrasporine tendency which has been the permanent one and has resulted in producing the higher green plants. This condition in *Chlamydomonas* resulted in the production of a series of plants which gradually replaced the formation of zoöspores by that of vegetative cell division. The resulting family was the Palmellaceæ, the one which formed the starting point in the development of the algæ, according to Chodat. While there seems to be but little question that the Palmellaceæ have given rise to most of the other families of the green algæ, there is every evidence that it was itself derived from *Chlamydomonas,* rather than the reverse, as contended by Chodat.

It is impossible at this time to even indicate the development of the higher algæ from the Palmellaceæ. With the exception of the Confervales, which seems to have developed independently of the typical green algæ, and the Conjugales, which apparently have arisen directly from the *Chlamydomonas* type, all the higher green algæ can be traced back through the Palmellaceæ with considerable certainty to their *Chalmydomonas* ancestor. The Conjugales have always been a stumbling block in constructing any developmental line of the algæ from primitive forms. But granting that the filamentous Conjugales, as well as the desmids, are unicellular (the reasons for which can not now be given) it is comparatively easy to find the origin of the conjugation habit so emphasized in this group, in *Chlamydomonas Braunii.* In this species the female or receptive cell comes absolutely to rest before fertilization and the smaller or male cell becomes attached to it. Then the entire contents of the male cell passes into the female cell, leaving behind the empty cell wall, just as in some of the desmids and in most of the filamentous-like Conjugales.

The more the genus is studied the more reasonable becomes the conclusion that *Chlamydomonas* has not only given rise to such an aberrent group as the Conjugales, but that it may safely be regarded as the phylogenetic starting point of the various lines of ascent in the true green algæ. At present in the higher algæ the *Chlamydomonas* stage is, of course, retained in the zoöspore and the gamete, a vegetative non-motile generation being interpolated between either a sexual or non-sexual motile stage. In the very highest type of reproduction in the green algæ the male gamete alone represents the *Chlamydomonas* stage. Indeed, we may well assume that the motile male gamete of the mosses and ferns constitutes the last remaining type of the original *Chlamydomonas* condition, which with other more positive evidence points to the origin of such land forms from a *Chlamydomonas*-like ancestor.

Although practically all the evidence for the position taken has necessarily been omitted, it is hoped that enough has been said to at least indicate the unique and important position occupied in the plant kingdom by the alga *Chlamydomonas.*

# THE COMPARATIVE LEAF STRUCTURE OF THE SAND DUNE PLANTS OF BERMUDA.

(With 3 plates.)

By JOHN W. HARSHBERGER, Ph.D.

(*Read April 24, 1908.*)

The writer has discussed the flora of Bermuda in two papers published in the *Proceedings of the Academy of Natural Sciences of Philadelphia* and entitled "The Plant Formations of the Bermuda Islands" (1905: 695–700) and "The Hour-glass Stems of the Bermuda Palmetto" (1905: 701–704). The study of the flora presented in these papers and the study of the microscopic anatomy of the leaves of the sand dune plants herewith given is the result of a visit to the islands during the month of June, 1905.

The sand beaches and sand dunes are found typically developed along the south shore of the main island and in a few isolated places on the north shore, as at Shelly Bay. The largest sand beaches and sand dunes on the south shore are found in the vicinity of Tuckertown Bay, on the narrow strip of south shore between Harrington Sound and the ocean. The sand dunes along the south shore in the parish of Paget are also characteristic. The sand dunes, however, in the neighborhood of Tuckertown Bay are remarkable in that they have encroached on the rocky shore line and have invaded the natural arch which is one of the scenic wonders of the islands. The sand has drifted beneath the arch and has advanced so that it covers part of the top of the arch itself.

The vegetation of the beaches and dunes here and in the vicinage of the Devil's Hole is characteristically Bermudian, while the sand dunes in Paget have been colonized in part by plants introduced by man into the islands, such as the oleander, *Nerium oleander,* and a tall fennel, *Fœniculum vulgare.* These beaches and dunes are formed of coral sand which represents the finely ground masses of coral and coralline (calcareous) sea-weeds which have grown on the fringing coral reefs. Bermuda, geologically speaking, is an atoll, a ring of coral reefs surrounding a central lagoon. The elevated land was formed by the raising of the weather edge of the reef above the level of the sea. The tops of the projecting corals were broken off and along with calcareous sea-weeds and mollusk shells were ground by surf action into a fine sand, which was formed into a beach. As the top of the beach dried in the sun, the sand was blown off and was deposited in the crevices of the coral breakwater, which gradually widened. Ultimately, by wind action, sand hills were formed. The limestone rock found throughout the islands was originally derived from broken-down coral and shells. These rocks vary in texture from loose sand to compact limestone. The process by which the coral sand was converted into limestone was very simple and it involved no great lapse of time. As the sand consists almost entirely of calcium carbonate, it was easily soluble in water containing carbon dioxide. The rain water took up a little of the calcium carbonate in the form of bicarbonate, and as it percolated through the sand, it lost its carbonic acid gas and evaporating left the dissolved calcium carbonate as a thin layer of cement uniting together the grains of sand. The rocks remain permeable to water and soluble, so that this process of solution and deposition goes on constantly until even a marble-like limestone may result. The usual building material consists of blocks of limestone sawed out of the hillside. When built as a wall sufficient solution takes place so that the stones become united together into an almost solid piece. The red soils of the islands represent the one per cent. residue of solid material after the rain has leached out all of the other constituents. When the solution, owing to wave action or constant rain action, is excessive, caverns with stalactites and sinks are formed. The honey-combed eolian rock of the shore line on which characteristic Bermuda plants occur owed its origin to similar water erosion. The sand dunes thus represent stages intermediate in the geologic changes which have combined to give the present form to the islands. They represent shifting masses of coral sand, forming flat surfaces in some places, in other places heaped into conical dunes or raised into long ridges. Frequently dune hollows exist as a result of wind action in scooping out the sand. These dunes form the setting upon which the typical sand strand plants are distributed.

PLANT DISTRIBUTION.—The upper beach at the foot of the dunes is characterized by the presence of *Cakile æqualis,* which shows a more decided branching habit than the closely related species on the coasts of the American continent, *Cakile maritima.* Besides this plant, the botanist sees clumps of *Tournefortia gnaphalodes, Scævola Plumieri* and *Croton maritimus.* The shrubs, however, grow most luxuriantly on the slopes and summits of the dunes. *Ipomæa pes-capræ,* as elsewhere in the tropics (Mexico, the West Indies), is a typical plant of the upper beach; in fact, the upper beach is characterized by its presence, with its long runners growing down from the slopes of the dunes out upon the flat, sandy beaches. On the dune slopes in Bermuda it is associated with *Scævola Plumieri* and the crab grass, *Stenotaphrum americanum.*

Back of the dune crests are found *Tournefortia gnaphalodes, Ipomæa pes-capræ, Scævola Plumieri, Juniperus bermudiana* (wind-swept forms), *Sisyrinchium bermudianum, Lepidium virginicum, Euphorbia buxifolia* (a prostrate plant growing in rosettes), *Canavalia obtusifolia* (a leguminous vine) and the prickly pear cactus, *Opuntia vulgaris.* On the dunes at Tuckertown, where the sand covers the entrance to the natural arch, *Scævola Plumieri* forms extensive clumps in pure association. *Solidago sempervirens,* as in the eastern United States, is also a dune plant, together with the smooth and hairy forms of *Borrichia arborescens, Dodonæa viscosa,* a small tree with its varnished leaves, is also a tenant of the dunes. The most interesting dune plant is *Conocarpus erectus,* which is a typical mangrove tree growing with its roots affected by salt water. In Bermuda, however, it occurs perhaps more frequently on the dry upper slopes of the dunes. In one place on the south shore, it covers nearly a quarter of an acre. The crab grass, *Stenotaphrum americanum* forms close mats on the lee side of the dunes.

The high dunes on the south shore of the parish of Paget have been invaded by a number of exotic plants, introduced by man into the islands, such as *Nerium oleander, Lantana camara, L. crocea,* while *Croton maritimus, Canavalia obtusifolia, Dodonæa viscosa, Borrichia arborescens* and *Passiflora suberosa* are among the most abundant native plants. *Yucca aloifolia* forms clumps on low sand dunes at Shelly Bay, on the north shore, associated with *Ipomœa pes-capræ, Tournefortia gnaphalodes* and *Opuntia* sp.

Ecologic Factors.—The ecologic factors, which have influenced the distribution of the typical sand strand plants of Bermuda, must be referred to briefly. As the plants of the Bermuda sand beaches and sand dunes in general show xerophytic adaptations, we must look upon these adaptive arrangements as a response to the environment. The following environmental factors must be considered as influential in producing the xerophytic structures which the leaves of the Bermuda beach and dune plants especially show:

1. The intense illumination from above is an important ecologic factor.

2. The reflection of light from the white coral sand and the foam-crested breakers beyond is important.

3. The action of the strong winds that blow across the islands must be considered as modifying plant structure.

4. The action of the salt spray blown inland by the wind is marked in the case of some plants.

5. The permeability of the sand to water, so that after a rain the surface layers quickly dry out, has its influence.

The most potent factor in the modification of leaf structure has been undoubtedly the bright illumination from above and below (by reflection) and the physiologically dry condition of the soil.

Structural Adaptations.—The leaf adaptations to light are found in the increased number of palisade layers, their presence on the upper and under sides of the leaves, and their arrangement, so that the central part of the leaf becomes palisade tissue throughout, a typical staurophyll. The depression of the stomata below the surface, as in *Sisyrinchium bermudianum,* the distribution of the stomata in pits, as in *Nerium oleander* and *Lantana involucrata,* the development of hairs as in *Tournefortia gnaphalodes,* the varnished leaves of *Dodonœa viscosa* and thick epidermal layers and cuticle are all arrangements to reduce transpiration. The succulency of the leaves of some of the dune plants is developed perhaps for water storage and the presence of latex should be mentioned as a means by which a dune plant is protected against the untoward influences of its environment.

Light has been most marked in influencing the development of leaf structure displayed by the typical sand dune plants of Bermuda. The stimuli of light have called forth functional responses which have produced changes in form or structure of the leaves, or in both. The chlorenchyma, composed of chloroplast-bearing cells, is converted into two kinds of tissues, palisade and spongy parenchyma, as a direct result of the unequal illumination of the leaf surfaces. Palisade tissue is formed as a response to light, or to low water content, or to both. When both leaf surfaces are equally illuminated, the leaf may be termed isophotic, when unequally illuminated diphotic. Diphotic leaves which are unequally illuminated show a division into palisade and spongy parenchyma, and such leaves are called by Clements[1] diphotophylls. Isophotic leaves, equally illuminated on both surfaces have a more or less uniform chlorenchyma. Clements divides such leaves into three types: (1) The palisade leaf, or staurophyll in which the palisade tissue extends from the lower to the upper epidermis. (2) The diplophyll, or double leaf, where the intense light does not penetrate to the middle of the leaf. In consequence, the upper and lower palisade layers are separated by a central loose parenchyma, which is for water storage. (3) The spongophyll, in which the rounded, loose parenchyma cells fill the leaf without palisade tissue. The influence of the light and other environmental conditions on leaf structure is perhaps best shown in the thin and thick leaves of *Conocarpus erectus* produced on different parts of the same tree differently related to the incident rays of light. A detailed description of these structures for each plant will be given at the end of the paper. The following is a classification of different leaf structures and the plants which illustrate such adaptive arrangements:

Thick Cuticle.—*Nerium oleander, Conocarpus erectus* (thin leaf), *Scævola Plumieri.*

Thick Epidermis.—*Canavalia obtusifolia, Dodonæa viscosa, Sisyrinchium bermudianum, Stenotaphrum americanum, Ipomæa pes-*

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[1] Clements, F. E., "Research Methods in Ecology," 138–145; "Plant Physiology and Ecology," 171–184.

*capræ, Cakile æqualis, Borrichia arborescens* (smooth leaf), *Croton maritimus.*

Two or Three Epidermal Layers.—*Euphorbia buxifolia, Nerium oleander, Conocarpus erectus* (thick leaf), *Croton maritimus, Tournefortia gnaphalodes.*

Two or More Rows of Palisade Cells.—*Passiflora suberosa, Dodonæa viscosa, Nerium oleander, Sesuvium portulacastrum, Cakile æqualis, Conocarpus erectus* (thin leaf and thick leaf), *Scævola Plumieri, Borrichia arborescens* (smooth and hairy leaves).

Stomata Depressed.—*Sisyrinchium bermudianum Heliotropium curassavicum, Sesuvium portulacastrum, Ipomæa pes-capræ, Cakile æqualis, Conocarpus erectus* (thick leaf), *Scævola Plumieri, Borrichia arborescens* (smooth leaf).

Stomata in Pits.—*Lantana involucrata, Nerium oleander.*

Succulent Leaf.—*Sesuvium portulacastrum, Cakile æqualis, Conocarpus erectus* (thick leaf), *Scævola Plumieri, Borrichia arborescens* (smooth leaf).

Hairy Leaf.—*Lantana involucrata, Nerium oleander, Borrichia arborescens* (hairy leaf), *Croton maritimus, Tournefortia gnaphalodes.*

Varnished Leaf.—*Dodonæa viscosa.*

Leaf Becoming Erect in Sun Position.—*Canavalia obtusifolia, Sisyrinchium bermudianum, Stenotaphrum americanum, Ipomæa pes-capræ.*

Overlapping Leaves.—*Euphorbia buxifolia, Sisyrinchium bermudianum, Stenotaphrum americanum.*

Latex Tissue.—*Euphorbia buxifolia.*

Gum-Resin.—*Conocarpus erectus.*

Crystals.—*Passiflora suberosa, Croton maritimus.*

Diphotophyll.—*Passiflora suberosa, Canavalia obtusifolia, Euphorbia buxifolia, Lantana involucrata, Nerium oleander* = 5.

Diplophyll.—*Dodonæa viscosa, Sesuvium portulacastrum, Ipomæa pes-capræ, Cakile æqualis, Conocarpus erectus* (thin leaf), *Scævola Plumieri,*[2] *Borrichia arborescens* (smooth and hairy leaves), *Croton maritimus, Tournefortia gnaphalodes* = 9.

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[2] *Scævola Plumieri* and *Tournefortia gnaphalodes* are given twice, because it is difficult to decide whether their leaves are diplophyll, or staurophyll.

Staurophyll.—*Heliotropium curassavicum, Conocarpus erectus* (thick leaf), *Scævola Plumieri, Tournefortia gnaphalodes*[2] = 4.

Spongophyll.—*Sisyrinchium bermudianum, Stenotaphrum americanum* = 2. With reference to the last two plants, it should be mentioned that the leaves of these plants stand erect, thus receiving the incident rays of light on the edge of the leaf, hence the absence of palisade tissue and the presence of spongophyll structure.

DETAILED STRUCTURE OF LEAVES.—The sections of the leaves which were studied were made free-hand with a razor. After staining, the sections were mounted for permanency in Canada balsam. The drawings of these sections were made by the use of the micro-projection, electric lantern, so that in every case with the exception of *Croton maritimus,* the drawings were made on the same scale. The sketches of stomata are none of them drawn to the same scale. The description of the histologic structure of the leaves of each species follows.

*Passiflora suberosa* is a small, slender species of the genus found growing over the sand surface of the dunes in the parish of Paget. Its flowers are small and the branch tendrils are characteristically developed. Histologically the leaf presents an upper epidermis of large thin-walled cells, and as the whole plant is brilliantly illuminated, it has two well-marked layers of palisade cells. The loose parenchyma is narrow and some of the cells of it are filled with conglomerate crystals. The stomata are slightly raised above the general epidermal surface, and are confined to the lower side of the leaf. A diphotophyll (Fig. 1, Plate II.).

*Canavalia obtusifolia,* a trailing leguminous plant, has paripinnate compound leaves with a long petiole and broadly elliptical leaflets with retuse apices and petiolules, a quarter of an inch long. The upper epidermis consists of slightly thickened cells. There are two rows of palisade cells, a considerable amount of loose parenchyma, while the slightly raised stomata are found on the upper and under sides. The adaptation to the environment of the sand dunes seems to be the folding together of the two sides of the leaves along the midrib, so that the edges of the leaves are presented to the incident rays of light. A diphotophyll (Fig. 2, Plate II.).

*Euphorbia buxifolia* is a prostrate, tufted plant of a rosette habit.

The taproot is large and strong and from it numerous branches, six to eight inches long, are formed. The leaves are opposite, small, ovate, with an acute apex and barely petiolate. The upper epidermis consists of two rows of cells, the palisade is a single layer and the loose parenchyma is compact. The lower epidermal cells are papillate and latex is present. The adaptation to the environment is shown in the latex, the two-layered upper epidermis and the overlapping arrangement of the leaves. A diphotophyll (Fig. 3, Plate II.).

*Dodonæa viscosa.*—This small sapindaceous tree occurs on the inner edges of the sand dunes. Its leaves are alternate, spatulate with the base narrowed to the point of attachment. The leaves are varnished. The upper epidermal cells are thick and provided with peltate hairs. The palisade cells are disposed in two layers. The loose parenchyma is open, while next to the lower epidermis there is a row of small cells which may be considered as a lower palisade layer. Hence the leaf is a potential diplophyll. The stomata of the upper side are slightly raised above the surface, while those on the under side have developed a small projecting beak (Fig. 4, Plate II.).

*Lantana involucrata* is one of the plants that enters the formation of the Bermuda scrub. It also invades the dunes. The leaves are hairy on both surfaces. A section of a leaf shows that the upper epidermis is without stomata, but is provided with straight, multicellular and capitate, unicellular hairs. The lower surface shows depressions provided with the capitate hairs, while the raised portions of the leaf surface between the depressions is covered with both straight, muticellular and capitate, unicellular hairs. The palisade is a single layer. The stomata project outward beyond the general surface of the lower epidermis, but they always occur in the depressions. The depressions provided with hairs and stomata and thick, hairy upper epidermal surface are structures which fit the plant to exist on the hot, sun-exposed sand dunes of the islands. A diphotophyll (Fig. 5, Plate II.).

*Nerium oleander.*—The leaf structure of the oleander, a native of the Mediterranean flora, is well known. The upper epidermis is in three layers with thick cuticle, the paliside tissue in two layers, while the under surface of the leaf is pitted, the pits being filled with straight hairs that form an air-still chamber into which the projecting stomata open. The lower epidermis is two- to three-layered, and the whole leaf is decidedly tough and leathery, and thus well adapted to growing on the sand dunes of Bermuda. A diphotophyll (Fig. 6, Plate II.).

*Sisyrinchium bermudianum.*—The Bermuda blue-eyed grass is provided with leaves that stand more or less upright, so that the incident rays of light strike the edges of the leaves. The epidermal cells on both the upper and lower morphologic sides of the leaf are thick-walled and the stomata present on both surfaces are depressed the entire width of the epidermal cells. There is no palisade tissue, the loose parenchyma filling the center of the leaf between epidermal surfaces. The vertical leaves are, therefore, isophotic and the leaf is known as a spongophyll. The vertical leaves, the thick epidermal cells and the depressed stomata fit the plant to its environment. A spongophyll (Fig. 7, Plate II.).

*Stenotaphrum americanum.* The Bermuda crab grass is a tough, wiry one, well fitted to survive in the driest places on sand dunes and rock faces. The leaf blades arise from sheaths that, together with other overlapping leaf sheaths, form a tuft that arises from the nodal regions of the wiry, prostrate, creeping stem. The blades are more or less erect and folded partially lengthwise, with the upper side innermost. The spike of closely set flowers is slightly bent, suggesting a crab's claw. The upper epidermis consists of large, open papillate cells. The loose parenchyma fills the leaf section and the under surface of the leaf has a thick epidermis with numerous stomata, provided with small guard cells reënforced by two secondary cells. The bundles are toward the upper side. The vertical isophotic leaf consequently becomes a spongophyll. The adaptations to the environment are upright, rolled leaves, thick lower epidermis and overlapping, tufted leaf sheaths (Fig. 8, Plate II.).

*Heliotropium curassavicum* resembles in its unilateral cymose inflorescence the common heliotrope. It is a slightly woody plant that grows about a foot or two tall, with alternate, narrow, oblanceolate leaves. The cells of both the lower and upper epidermis are thin-walled, with slightly sunken stomata on both sides. The chlorophyll bearing cells of the leaf (the chlorenchyma) are arranged so that their long axes are placed in a line with the incident rays of light that strike the upper surface from above and the lower surface by reflection from the sand below. A staurophyll (Fig. 9, Plate II.).

*Sesuvium portulacastrum.*—The leaf structure of this member of the family Aizoaceæ is that of a typical diplophyll, but with a slight indication of the staurophyll arrangement of the cells. The stomata present on both sides of the leaf are slightly sunken and the guard cells incline inward and downwards. The upper and lower palisade tissues show four to five layers of cells. The leaves are thick and succulent. A diplophyll (Fig. 10, Plate II.).

*Ipomœa pes-capræ.*—This tropical, seaside morning glory is a typical plant of the sandy beaches in Mexico, the West Indies and Bermuda. It grows down off the dune slopes onto the beach sand as a creeping plant, a distance of twenty to thirty feet (Fig. 1, Plate I.). The leaves are alternate, elliptical, retuse at the apex and frequently when the sun is hot and the reflection from the sand intense, the leaves fold together along the midrib and stand vertically so as to receive the incident rays of light on the upturned edges of the leaves. The walls of the epidermal cells on both sides of the leaf are thick. The stomata on both sides are sunken about half the thickness of the epidermal cells and the palisade tissue is prominent on both sides, constricting the loose parenchyma to a narrow layer. The leaf is, therefore, a true diplophyll (Fig. 11, Plate III.).

*Cakile æqualis.*—This cruciferous plant grows on open, sandy beaches in a more or less scattered manner. It branches in a much more open way than *C. maritima,* found in similar habitats on the sandy beaches of the eastern United States. The leaves are fleshy and the walls of the upper and lower epidermal cells are thickened. The stomata, which are partly sunken, are found on both the upper and the lower leaf surfaces. The palisade tissue on both sides is five layers of cells thick and the loose parenchyma is restricted to a narrow layer four cells thick in the central part of the leaf. This plant is fitted to its environment by the possession of succulent leaves, epidermal cells with thick walls, and many-layered palisade tissue. A diplophyll (Fig. 12, Plate III.). Contrast the leaf section of *Cakile maritima* (Fig. 12 *A,* Plate III.).

*Conocarpus erectus.*—The leaves of this small tree, which is a true mangrove plant, but which has adapted itself to growth on the sand dunes in Bermuda, are thin and thick. The thin leaves are found on the branches that are placed above the surface of the sand, or in more or less protected positions, while the thick, succulent leaves occur near the surface of the sand, or in exposed, unshaded positions. There is a considerable difference in the anatomical structure. The cuticle in the thin leaf is thickened and the stomata on both sides are hardly if any sunken below the surface. The upper leaf surface shows long palisade cells, while the palisade cells of the lower side are shorter. The loose parenchyma cells form a broad band in the center of the section. A diplophyll (Fig. 13, Plate III.). The thick, succulent leaf has three rows of epidermal cells and three rows of palisade cells, the cavities of which are filled with a gummy, resinous material (not tested) of a brown color. This gummy material is found in the lower palisade as well as in the upper palisade in both the thin and thick leaves and also in some of the loose parenchyma cells of the thick leaf. The stomata in the thick leaves, by the increase in the thickness of the cuticle, are sunken below the surface with an hour-glass atrium or passage outside of the thick-walled guard cells. The parenchyma cells of the leaf center are arranged in the direction of the palisade cells. A typical staurophyll (Fig. 13 *A*, Plate III.).

*Scævola Plumieri.*—This plant belongs to the family Goodeniaceæ and forms dense clumps on the dune slopes (Fig. 2, Plate I.). Its leaves are alternate, elliptical, short petiolate and obtuse. They are noted for their succulency. The epidermal cells on the upper surface have a thick cuticle with numerous thick walled, sunken stomata. The epidermal cells on the lower surface are of the same thickness as on the upper surface, the stomata being likewise sunken. The palisade cells on the upper and lower sides consist in each of three or four rows of cells, while the loose parenchyma is arranged parallel to the palisade tissue. Only a single row of central cells are not so disposed. The leaf shows, therefore, partly a staurophyll and partly a diplophyll arrangement of cell (Fig. 14, Plate III.).

*Borrichia arborescens.*—This species of the family Compositæ exists in two distinct forms, if they are not good species. One form has smooth, thick, succulent leaves, the other has thinner, densely tomentose leaves, the *Borrichia frutescens* of the Southern States. The succulent, smooth-leaved form has both thick upper and lower epidermal cells, with the stomata on both sides, but more plentiful on the lower side. The stomata are partly sunken. The palisade layers on both sides are wide, but are broken into more or less extended patches by round parenchyma cells, which reach to the epidermis. The loose parenchyma cells form a wide central area. A diplophyll (Fig. 15, Plate III.). What the thin leaf lacks in succulency, it gains in hairiness. Both sides are densely covered with straight unicellular hairs. The palisade layers are only two in number on both sides of the leaf, and the loose parenchyma is also much reduced in amount. The succulency of the thick leaf fits it as perfectly as the hairiness of the thin leaf to the trying seaside environment, where the plants producing them grow side by side. A diplophyll (Fig. 15 *A*, Plate III.).

*Croton maritimus.*—The leaves of this plant studied by Kearney[8] are bifacial, both surfaces densely covered with gray scale-like pubescence, owing to presence of multicellular, stalked, stellate hairs that cover them. The upper and lower epidermal cells have thick walls and the stomata are not sunken. The palisade tissue in both the upper and the lower sides are two cell layers in width with a few sclerotic idioblasts. The leaf in the plant grown in the United States, as depicted by Kearney, has only one row of palisade cells. Large conglomerate crystals of calcium oxalate are found in the cells of the loose parenchyma. Glandular capitate hairs are found on both leaf surfaces. A diplophyll (Fig. 16, Plate III.).

*Tournefortia gnaphalodes.*—The leaves and stems of this plant, as well as the calices of the flowers, are covered with a dense, closely appressed, grayish tomentum, resembling that on our common *Antennaria plantaginifolia* and edelweiss, *Leontopodium alpinum.* In section the hairs are unicellular, straight and of epidermal origin. The palisade is formed on the upper and lower leaf surfaces and is two cells thick. The loose parenchyma, occupying the center of the leaf, suggests an arrangement in direction parallel to the long axis

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[8] Kearney, Thomas H. "Plants of Ocracoke Island," Contributions from the United States National Herbarium V: 296.

of the palisade cells. Therefore it is a diplophyll (Fig. 17, Plate III.).

BIBLIOGRAPHY.—Little has been published on the structure of the dune plants of tropical America. The following papers are in part a contribution to our knowledge of the microscopic structure of the strand plants of the American tropics. A few of the sand dune plants are of cosmopolitan distribution and they are, therefore, described as to their morphology in the classic work of A. F. W. Schimper, "Die indo-malayische Strandflora," published as the third volume of "Botanische Mittheilungen aus den Tropen" in 1891. Thomas Kearney in 1900 published in the Contributions from the U. S. National Herbarium (V., No. 5) an important paper on "The Plant Covering of Ocracoke Island; A Study in the Ecology of the North Carolina Strand Vegetation." A chapter is devoted to the histological structure of the plants. The only plants which concern us are *Yucca aloifolia, Croton maritimus, Borrichia frutescens,* which are common also to the Bermuda strand. F. Boergesen and Ové Paulsen make a contribution to "La Vegetation des Antilles Danoises" in Revue Générale de Botanique (Tome XII., 1900), in which they discuss with figures the microscopic structure of a few of the typical strand plants. As throwing considerable light on the problems concerned in this paper on the Bermuda strand flora reference should be made to these works of general import to the botanical questions involved.

**Diels, L.**

Stoffwechsel und Structur der Halophyten, Jahrbücher für wissenschaftliche Botanik XXIII.: 309–322, 1898.

**Schimper, A. F. W.**

Pflanzengeographie auf physiologischer Grundlage, 1898.

**Solereder, H.**

Systematische Anatomie der Dicotyledonen, 1898–99.

**Warming, E.**

Halofyt Studier, Memoires de l' Académie Royale de Danemark, ser. 6, VIII., No. 4, 1897.

ILLUSTRATIONS.—The reproduced photographs (Figs. 1 and 2, Plate I.) represent the dune vegetation on the south shore of Bermuda. The upper illustration shows the thicket of composite vegetation on the crest of the dune and the long, trailing stems of *Ipomœa pes-carpæ* on the upper beach with a small clump of *Cakile æqualis* to the left in the foreground. The second illustration depicts a clump of *Scævola Plumieri,* with the Bermuda cedar, *Juniperus bermudiana,* and in the background the grayish-green bushes of *Tournefortia gnaphalodes.* Reference is made to the drawings of microscopic structure in the classified description of dune plants throughout the paper.

FIG. 1.

FIG. 2.

PLATE II

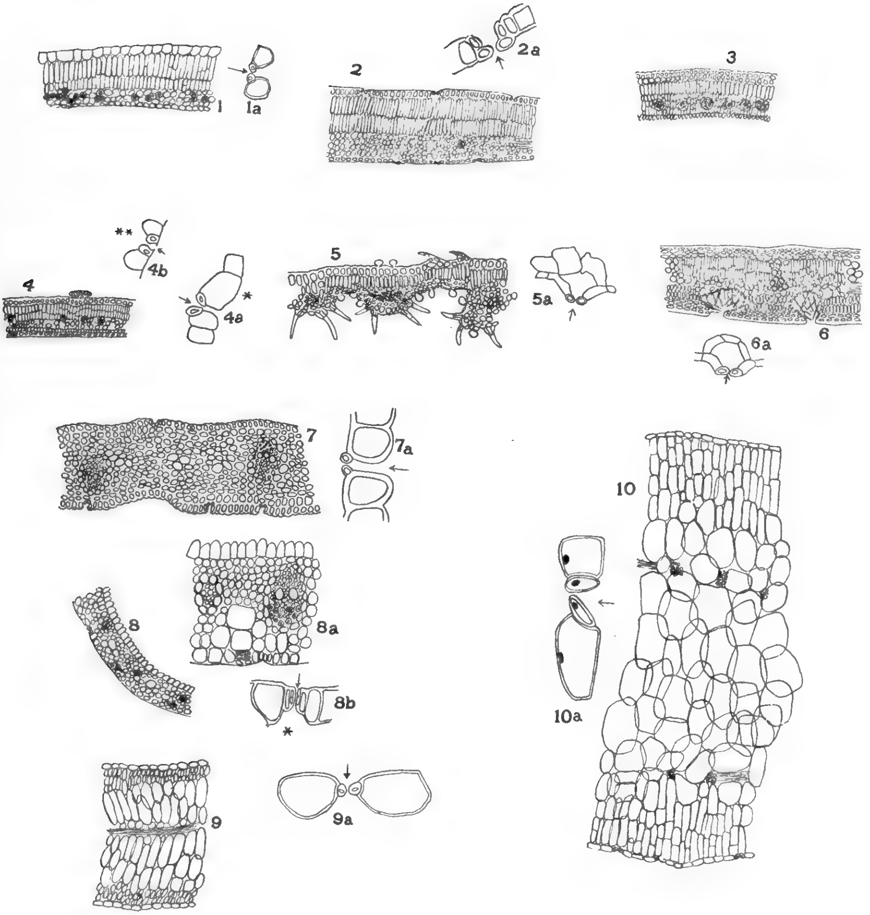
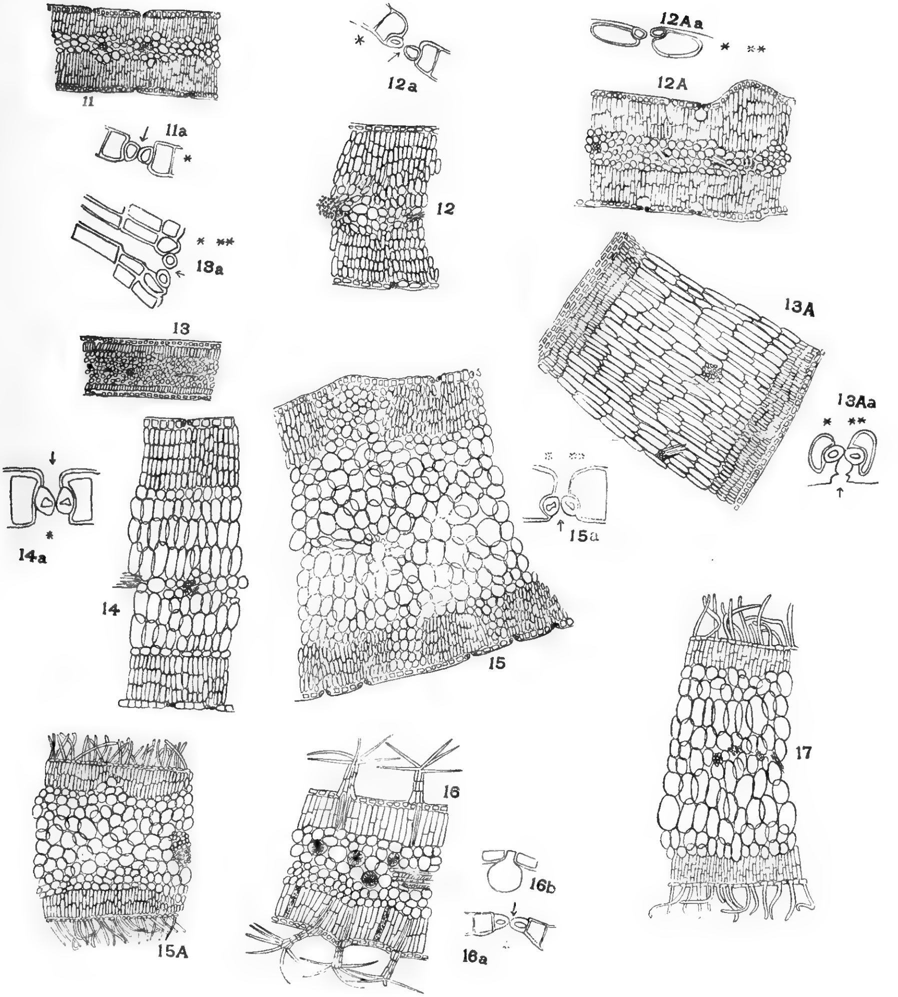


PLATE III


11
11a
12a
12
12Aa
12A
13a
13
13A
13Aa
14a
14
15
15a
15A
16
16b
16a
17

# SOLUTION OF ALGEBRAIC EQUATIONS IN INFINITE SERIES.

By PRESTON A. LAMBERT.

(*Read April 25, 1908.*)

## I. Introduction.

1. The object of this investigation is to develop a method for determining all the roots, real and imaginary, of an algebraic equation by means of infinite series.

2. Suppose the given equation to be represented by $f(y)=0$. The method consists in introducing a factor $x$ into all the terms but two of the given equation; expanding $y$, which now is an algebraic function of $x$, into a power series in $x$; placing $x$ equal to unity in this power series. The resulting value of $y$, if convergent, is a root of the given equation expressed in terms of the coefficients and exponents of the equation.

3. The method presupposes the solution of the two-term equation

$$ay^n+b=0.$$

In fact the roots of this equation when written in the form

$$y^n=-\frac{b}{a}=r(\cos\theta+i\sin\theta)$$

are found to any required degree of approximation from the formula

$$y=r^{\frac{1}{n}}\left(\cos\frac{2s\pi+\theta}{n}+i\sin\frac{2s\pi+\theta}{n}\right),$$

where

$$s=0,1,2,3,4,\cdots,n-1.$$

4. The method proceeds step by step from the two-term equation to the three-term equation, from the three-term equation to the four-term equation, and so on.

## II. The Three-term Equation.

5. In the three-term equation

$$ay^n + by^k + c = 0$$

the two terms from which the $x$ is to be omitted can be selected in three different ways. This gives rise to the three equations

$$(1) \qquad ay^n + by^kx + c = 0$$

$$(2) \qquad ay^n + by^k + cx = 0$$

$$(3) \qquad ay^nx + by^k + c = 0$$

each one of which defines $y$ as an algebraic function of $x$.

6. Values of $y$ expressed as power series in $x$ may be found from each one of these three equations by any one of the following three methods, which, however, are essentially the same.

7. *The Multinomial Theorem.*—Assume that the power series for $y$ is

$$(4) \qquad y = p_0 + p_1x + p_2x^2 + p_3x^3 + p_4x^4 + \cdots.$$

The multinomial theorem asserts that the coefficient of $x^r$ in the expansion of $y^n$ is

$$(5) \qquad \Sigma \frac{n!}{q_0!\, q_1!\, q_2! \cdots q_s!} p_0^{q_0} p_1^{q_1} p_2^{q_2} \cdots p_s^{q_s} x^{q_1+2q_1+3q_3+\cdots sq_s},$$

provided

$$(6) \qquad q_1 + 2q_2 + 3q_3 + \cdots sq_s = r$$

$$(7) \qquad q_0 + q_1 + q_2 + \cdots q_s = n.$$

The expansion of $y^k$ is obtained in like manner.

Assuming that the power series (4) represents the algebraic function defined by equation (1), the substitution of the expansions of $y^n$ and $y^k$ in equation (1) must give an identity. This identity is

$$(8) \qquad \begin{array}{r|l|l|l|l}
0 \equiv ap_0^n & +anp_0^{n-1}p_1 & x+\frac{an(n-1)}{1\cdot 2}p_0^{n-2}p_1^2 & x^2+\frac{an(n-1)(n-2)}{1\cdot 2\cdot 3}p_0^{n-3}p_1^3 & x^3+\cdots \\
+c & +bp_0^k & & & \\
 & & +anp_0^{n-1}p_2 & +an(n-1)p_0^{n-2}p_1p_2 & \\
 & & +bkp_0^{k-1}p_1 & +anp_0^{n-1}p_3 & \\
 & & & +\frac{bk(k-1)}{1\cdot 2}p_0^{k-2}p_1^2 & \\
 & & & +bkp_0^{k-1}p_2 &
\end{array}$$

In this identity the coefficient of each power of $x$ equals zero. Hence $p_0$ is the root of the two-term equation

$$ap_0{}^n + c = 0.$$

The coefficient of the first power of $x$ equated to zero determines $p_1$ uniquely in terms of $p_0$; the coefficient of $x^2$ equated to zero determines $p_2$ uniquely in terms of $p_0$ and $p_1$; in general, the coefficient of $x^s$ equated to zero determines $p_s$ uniquely in terms of $p_0, p_1, p_2, \cdots, p_{s-1}$. All the successive coefficients of the power series (4) are therefore determined uniquely in terms of $p_0$, any one of the roots of the two-term equation $ap_0{}^n + c = 0$.

The power series representing the algebraic functions defined by equations (2) and (3) are determined in precisely the same manner. Unfortunately if the coefficients of the power series are determined in this way it is difficult to recognize the law which will enable one to write the general term of the power series, which is necessary for the application of a convergency test.

When $x$ is made unity, the equations (1), (2) and (3) become the three-term equation

$$ay^n + by^k + c = 0$$

and the power series, if convergent when $x = 1$, becomes the solution of this equation.

If it is known in advance that some one of equations (1), (2), (3) furnishes a power series which is convergent when $x = 1$, the multinomial theorem determines in an elementary and direct manner the coefficients of the power series.

8. *Maclaurin's Series.*—The algebraic function $y$ defined by the equation

$$ay^n + by^k x + c = 0$$

can be expanded into a power series in $x$ by means of Maclaurin's series

$$(9) \qquad y = y_0 + \frac{dy_0}{dx_0} x + \frac{d^2 y_0}{dx_0^2} \frac{x^2}{1 \cdot 2} + \frac{d^3 y_0}{dx_0^3} \frac{x^3}{1 \cdot 2 \cdot 3} + \cdots.$$

The expansion is identical in form with the expansion obtained by means of the multinomial theorem and consequently has the same disadvantage.

9. *Lagrange's Theorem.*—The equation

$$ay^n + by^k x + c = 0$$

may be written

$$y^n = -\frac{c}{a} - x\frac{b}{a}y^k. \tag{10}$$

Placing $y^n = z$, whence $y = z^{1/n}$, this equation becomes

$$z = -\frac{c}{a} - x\frac{b}{a}z^{\frac{k}{n}}. \tag{11}$$

Lagrange's theorem asserts that if

$$z = v + x\phi(z)$$

$$\begin{aligned} f(z) = f(v) + x\phi(v)f'(v) + \frac{x^2}{1\cdot 2}\frac{d}{dv}\{\overline{\phi(v)}^2 f'(v)\} + \cdots \\ + \frac{x^n}{n!}\frac{d^{n-1}}{dv^{n-1}}\{\overline{\phi(v)}^n f'(v)\}\cdots. \end{aligned} \tag{12}$$

If now

$$f(z) = z^{\frac{1}{n}}, \quad \phi(z) = -\frac{b}{a}z^{\frac{k}{n}},$$

and after the derivatives in series (12) have been formed $v$ is replaced by $-c/a$, there results, making $x$ unity,

$$\begin{aligned} z^{\frac{1}{n}} = y = \left(-\frac{c}{a}\right)^{\frac{1}{n}} + \frac{b}{nc}\left(-\frac{c}{a}\right)^{\frac{1+k}{n}} + \frac{b^2}{2!\,n^2c^2}(1+2k-n)\left(-\frac{c}{a}\right)^{\frac{1+2k}{n}} \\ + \frac{b^3}{3!\,n^3c^3}(1+3k-n)(1+3k-2n)\left(-\frac{c}{a}\right)^{\frac{1+3k}{n}} \\ + \frac{b^4}{4!\,n^4c^4}(1+4k-n)(1+4k-2n)(1+4k-3n)\left(-\frac{c}{a}\right)^{\frac{1+4k}{n}} + \cdots. \end{aligned} \tag{13}$$

In series (13) the law of formation of the successive terms is evident and this law is readily proved by induction by using Lagrange's theorem.

Series (13) may be more concisely written by placing

$$\left(-\frac{c}{a}\right)^{\frac{1}{n}} = y_0,$$

so that $y_0$ is a root of the two-term equation

$$ay_0^n + c = 0,$$

and denoting the continued product

$$(1 + sk - n)(1 + sk - 2n)(1 + sk - 3n)\cdots[1 + sk - (s - 1)n]$$

by

$$\left[\frac{1 + sk - n}{1 + sk - sn}\right]. \tag{14}$$

With these conventions series (13) becomes

$$\begin{aligned} y = y_0 &+ \frac{b}{nc} y_0^{1+k} + \frac{b^2}{2!\,n^2c^2}[1 + 2k - n]y_0^{1+2k} \\ &+ \frac{b^3}{3!\,n^3c^3}\left[\frac{1+3k-n}{1+3k-3n}\right]y_0^{1+3k} + \frac{b^4}{4!\,n^4c^4}\left[\frac{1+4k-n}{1+4k-4n}\right]y_0^{1+4k} + \cdots \\ &+ \frac{b^s}{s!\,n^sc^s}\left[\frac{1 + sk - n}{1 + sk - sn}\right]y_0^{1+sk} + \cdots. \end{aligned} \tag{15}$$

If series (15) is convergent, it will furnish a root of the three-term equation

$$ay^n + by^k + c = 0$$

for each one of the $n$ values of $y_0$.

10. To test series (15) for convergency write the first $n$ terms in regular order in a row, underneath this row the succeeding $n$ terms and so on indefinitely. The terms of series (15) will now be arranged in $n$ columns as follows:

$$
\begin{aligned}
(16)\qquad & y_0 \qquad + \frac{b}{nc} y_0^{1+k} + \cdots + \frac{b^{n-1}}{(n-1)!\, n^{n-1} c^{n-1}} \left[ \frac{1+(n-1)k-n}{1+(n-1)k-(n-1)n} \right] y_0^{1+(n-1)k} \\
& + \frac{b^n}{n!\, n^n c^n} \left[ \frac{1+nk-n}{1+nk-n^2} \right] y_0^{1+nk} + \frac{b^{n+1}}{(n+1)!\, n^{n+1} c^{n+1}} \left[ \frac{1+(n+1)k-n}{1+(n+1)k-(n+1)n} \right] y_0^{1+(n+1)k} + \cdots + \frac{b^{2n-1}}{(2n-1)!\, n^{2n-1} c^{2n-1}} \left[ \frac{1+(2n-1)k-n}{1+(2n-1)k-(2n-1)n} \right] y_0^{1+(2n-1)k} \\
& + \frac{b^{2n}}{(2n)!\, n^{2n} c^{2n}} \left[ \frac{1+2nk-n}{1+2nk-2n^2} \right] y_0^{1+2nk} + \frac{b^{2n+1}}{(2n+1)!\, n^{2n+1} c^{2n+1}} \left[ \frac{1+(2n+1)k-n}{1+(2n+1)k-(2n+1)n} \right] y_0^{1+(2n+1)k} + \cdots + \frac{b^{3n-1}}{(3n-1)!\, n^{3n-1} c^{3n-1}} \left[ \frac{1+(3n-1)k-n}{1+(3n-1)k-(3n-1)n} \right] y_0^{1+(3n-1)k} \\
& \qquad \vdots \qquad\qquad\qquad\qquad\qquad \vdots \qquad\qquad\qquad\qquad\qquad \vdots \\
& + \frac{b^{sn}}{(sn)!\, n^{sn} c^{sn}} \left[ \frac{1+snk-n}{1+snk-sn^2} \right] y_0^{1+snk} + \frac{b^{sn+1}}{(sn+1)!\, n^{sn+1} c^{sn+1}} \left[ \frac{1+(sn+1)k-n}{1+(sn+1)k-(sn+1)n} \right] y_0^{1+(sn+1)k} + \cdots + \frac{b^{sn-1}}{(sn-1)!\, n^{sn-1} c^{sn-1}} \left[ \frac{1+(sn-1)k-n}{1+(sn-1)k-(sn-1)n} \right] y_0^{1+(sn-1)k} \\
& \qquad \vdots \qquad\qquad\qquad\qquad\qquad \vdots \qquad\qquad\qquad\qquad\qquad \vdots
\end{aligned}
$$

This rearrangement of the terms of series (15) into the $n$ columns of the table is permissible, inasmuch as throughout this investigation only absolute convergence is considered.

Cauchy's ratio test shows that each one of the $n$ partial series composed of the terms in each of the $n$ columns of the table is convergent when

$$\frac{b^n}{a^k c^{n-k}} < \frac{n^n}{k^k(n-k)^{n-k}}. \tag{17}$$

11. In like manner, if the algebraic functions defined by the equations

$$ay^n + by^k + cx = 0 \tag{2}$$

$$ay^n x + by^k + c = 0 \tag{3}$$

are expanded into power series in $x$ by Lagrange's theorem, and if $x$ is made unity in this power series, it is found that the resulting infinite series are convergent, provided

$$\frac{b^n}{a^k c^{n-k}} > \frac{n^n}{k^k(n-k)^{n-k}}. \tag{18}$$

12. If condition (18) is satisfied, equation (2) determines $n - k$ and equation (3) determines $k$ roots of the three-term equation

$$ay^n + by^k + c = 0.$$

Either condition (17) or condition (18) must be satisfied, unless

$$\frac{b^n}{a^k c^{n-k}} = \frac{n^n}{k^k(n-k)^{n-k}}. \tag{19}$$

If condition (19) is satisfied, Raabe's test shows that the series obtained from equations (1), (2), (3) are all convergent.

13. The convergency conditions for equations (1), (2), (3) may be written by following these directions:

($a$) To the left of the sign of inequality stands a fraction whose numerator contains the coefficient of the middle term of the three-term equation

$$ay^n + by^k + c = 0$$

and whose denominator contains the product of the coefficients of the end terms, the exponent of each coefficient being the difference of the exponents in the other two terms taken in order from left to right.

(*b*) The fraction to the right of the sign of inequality is obtained from the fraction to the left by replacing each coefficient by its exponent.

(*c*) The sign of inequality is $<$ when the term containing $x$ is between the other two terms; if the term containing $x$ is an end term the sign of inequality is $>$.

14. The following table exhibits the convergency conditions for the series obtained from equations (1), (2), (3) and the number of roots of the three-term equation

$$ay^n + by^k + c = 0$$

furnished by each one of these series.

$$(20)\quad \begin{array}{lll} (1)\ ay^n + by^kx + c = 0 & n & \dfrac{b^n}{a^kc^{n-k}} \leqq \dfrac{n^n}{k^k(n-k)^{n-k}}, \\ (2)\ ay^n + by^k + cx = 0 & n-k & \left\{ \begin{array}{l} \\ \dfrac{b^n}{a^kc^{n-k}} \geqq \dfrac{n^n}{k^k(n-k)^{n-k}}. \end{array} \right. \\ (3)\ ay^nx + by^k + c = 0 & k & \end{array}$$

The roots of the three-term equation can always be expressed in infinite series.

## III. The Four-term Equation.

15. In the four-term equation

$$ay^n + by^k + cy^l + d = 0$$

the two terms from which the factor $x$ is to be omitted can be selected in six different ways. This gives rise to the six equations:

$$ay^n + by^kx + cy^lx + d = 0 \tag{21}$$

$$ay^n + by^k + cy^lx + dx = 0 \tag{22}$$

$$ay^nx + by^k + cy^lx + d = 0 \tag{23}$$

$$ay^nx + by^k + cy^l + dx = 0 \tag{24}$$

$$ay^nx + by^kx + cy^l + d = 0 \tag{25}$$

$$ay^n + by^kx + cy^l + dx = 0 \tag{26}$$

Each one of these six equations defines $y$ as an algebraic function of $x$. The $y$ of equation (21) may be expanded into a power series in $x$ by any one of the three methods of articles 7, 8, 9. Using the symbol (14) and denoting $(-d/a)^{1/n}$ by $y_0$, this power series, when $x$ is made unity, becomes

$$
\begin{array}{llll}
(27)\ y = & y_0 & & \\
& +\dfrac{b}{nd}y_0^{1+k} & +\dfrac{c}{nd}y_0^{1+l} & \\
& +\dfrac{b^2}{2!\,n^2d^2}[1+2k-n]\,y_0^{1+2k} & +\dfrac{2bc}{2!\,n^2d^2}[1+k+l-n]\,y_0^{1+k+l} & +\dfrac{c^2}{2!\,n^2d^2}[1+2l-n]\,y_0^{1+2} \\
& +\dfrac{b^3}{3!\,n^3d^3}\left[\dfrac{1+3k-n}{1+3k-3n}\right]y_0^{1+3k} & +\dfrac{3b^2c}{3!\,n^3d^3}\left[\dfrac{1+2k+l-n}{1+2k+l-3n}\right]y_0^{1+2k+l} & +\dfrac{3bc^2}{3!\,n^3d^3}\left[\dfrac{1+k+2l-n}{1+k+2l-3n}\right]y_0^{1+k+2l}+\cdots \\
& +\dfrac{b^4}{4!\,n^4d^4}\left[\dfrac{1+4k-n}{1+4k-4n}\right]y_0^{1+4k} & +\dfrac{4b^3c}{4!\,n^4d^4}\left[\dfrac{1+3k+l-n}{1+3k+l-4n}\right]y_0^{1+3k+l} & +\dfrac{4b^2c^2}{4!\,n^4d^4}\left[\dfrac{1+2k+2l-n}{1+2k+2l-4n}\right]y_0^{1+2k+2l}+\cdots \\
& +\dfrac{b^5}{5!\,n^5d^5}\left[\dfrac{1+5k-n}{1+5k-5n}\right]y_0^{1+5k} & +\dfrac{5b^4c}{5!\,n^5d^5}\left[\dfrac{1+4k+l-n}{1+4k+l-5n}\right]y_0^{1+4k+l} & +\dfrac{5b^3c^2}{5!\,n^5d^5}\left[\dfrac{1+3k+2l-n}{1+3k+2l-5n}\right]y_0^{1+3k+2l}+\cdots \\
& \quad\vdots & \quad\vdots & \quad\vdots
\end{array}
$$

16. The infinite series composed of the terms of the left-hand column of the value of $y$ is convergent when

$$\frac{b^n}{a^k d^{n-k}} \leqq \frac{n^n}{k^k(n-k)^{n-k}}, \tag{28}$$

and if condition (28) is satisfied this infinite series furnishes the solution of the three-term equation

$$ay^n + by^k + d = 0. \tag{29}$$

It is found that each one of the infinite series composed of the terms of the respective columns of (27) is convergent when (28) is satisfied. It follows that (27) may be written

$$y = X_0 + \frac{c}{nd} y_0^{\,l} X_1 + \frac{c^2}{n^2d^2} y_0^{\,2l} X_2 + \frac{c^3}{n^3d^3} y_0^{\,3l} X_3 + \cdots, \tag{29}$$

where $X_0$, $X_1$, $X_2$, $X_3$, $\cdots$, stand for the sums of convergent series. If now $X$ is the largest of the numbers $X_0$, $X_1$, $X_2$, $X_8$, $\cdots$,

$$y \leqq X\left(1 + \frac{c}{nd} y_0^{\,l} + \frac{c^2}{n^2d^2} y_0^{\,2l} + \frac{c^3}{n^3d^3} y_0^{\,3l} + \cdots\right), \tag{30}$$

and this last value of $y$ is convergent when

$$\frac{c}{nd} y_0^{\,l} < 1. \tag{31}$$

Affecting both sides of this inequality by the exponent $n$, this convergency condition may be written

$$\frac{c^n}{a^l d^{n-l}} < n^n. \tag{32}$$

17. Conditions (28) and (32) are sufficient for the absolute convergence of (27). Condition (28) shows that the series which determines the roots of the three-term equation

$$ay^n + by^k + d = 0 \tag{29}$$

is found from

$$ay^n + by^k x + d = 0. \tag{33}$$

The columns of (27) after the first are the corrections which must be applied to the roots of the three-term equation (29) to obtain the roots of the four-term equation

$$ay^n + by^k + cy^l + d = 0$$

18. If the two terms in the second row of (27) are interchanged and the consequent changes are made throughout (27), the left-hand column in the resulting value of $y$ is convergent if

$$(34) \qquad \frac{c^n}{a^l d^{n-l}} \leqq \frac{n^n}{l^l (n-l)^{n-l}},$$

and the entire expression for $y$ is convergent if in addition

$$(35) \qquad \frac{b^n}{a^k d^{n-k}} < n^n.$$

Conditions (34) and (35) are sufficient for the absolute convergence of the new series for $y$.

Condition (34) shows that the series which determines the solutions of the three-term equation

$$(36) \qquad ay^n + cy^l + d = 0$$

is found from

$$(37) \qquad ay^n + cy^l x + d = 0.$$

This series is the left-hand column of the value of $y$.

Condition (35) shows that the series of corrections which must be applied to the roots of the three-term equation (36) to obtain the solution of the four-term equation

$$ay^n + by^k + cy^l + d = 0$$

is convergent.

19. From equation (21) by omitting in succession each of the terms containing $x$ are obtained the equations

$$(33) \qquad ay^n + by^k x + d = 0$$

$$(37) \qquad ay^n + cy^l x + d = 0$$

The convergency conditions (28) and (34) may be written from equations (33) and (37) respectively by following the directions (*a*), (*b*), (*c*) of article 13. The left-hand members of the conditions (32) and (35), together with the character of the signs of inequality, may be written from equations (37) and (33) respectively by following the same directions. The right-hand member of conditions (32) and (35) is formed by writing the difference of the exponents of the two terms of (21) which do not contain $x$ and giving this difference an exponent equal to itself. It will be found that when the sign of inequality is $>$ in convergency conditions corresponding to conditions (32) and (35) the right-hand member is the reciprocal of what it is when the sign of inequality is $<$.

20. In like manner two sets of conditions sufficient for the absolute convergence of the infinite series giving the roots of the four-term equation obtained from each one of the equations (21), (22), (23), (24), (25), (26) may be written.

The convergency conditions for all these infinite series may be taken from the following table, in which the signs of equality of the limiting conditions of convergence have been omitted.

| (38) | $\frac{b^n}{a^k d^{n-k}}$ | $\frac{c^n}{a^l d^{n-l}}$ | $\frac{b^{n-l}}{a^{k-l} c^{n-k}}$ | $\frac{c^k}{b^l d^{k-l}}$ | |
|---|---|---|---|---|---|
| (21) $ay^n+by^kx+cy^lx+d=0$ | $<$ | $<$ | | | $n^n$ |
| (22) $ay^n+by^k+cy^lx+dx=0$ | $>$ | | $>$ | | $(n-k)^{n-k}$ |
| (23) $ay^nx+by^k+cy^lx+d=0$ | $>$ | | | $<$ | $k^k$ |
| (24) $ay^nx+by^k+cy^l+dx=0$ | | | $>$ | $>$ | $(k-l)^{k-l}$ |
| (25) $ay^nx+by^kx+cy^l+d=0$ | | $>$ | | $>$ | $l^l$ |
| (26) $ay^n+by^kx+cy^l+dx=0$ | | | $<$ | $>$ | $(n-l)^{n-l}$ |
| | $\frac{n^n}{k^k(n-k)^{n-k}}$ | $\frac{n^n}{l^l(n-l)^{n-l}}$ | $\frac{(n-l)^{n-l}}{(k-l)^{k-l}(n-k)^{n-k}}$ | $\frac{k^k}{l^l(k-l)^{k-l}}$ | |

In this table the signs of the two inequalities which constitute the convergency conditions of the series obtained from the equations (21) to (26) are placed to the right of the respective equations. The left-hand member of each inequality is at the top of the column in which the sign of inequality stands. The right-hand member of one inequality must be taken at the bottom of the column in which the sign of inequality stands; the right-hand member of the second inequality is the expression at the right of the row in which the sign of inequality stands when the sign of inequality is $<$, when the sign of inequality is $>$ the right-hand member of the inequality is the reciprocal of this expression.

21. The following table exhibits one set of convergency conditions of the infinite series which give the roots of the three-term equation

$$ay^n + by^k + d = 0$$

together with the equations from which these series are derived and the number of the roots given by each series, and also the conditions sufficient for the absolute convergence of the series of corrections which must be applied to the roots of this three-term equation to obtain the roots of the four-term equation

$$ay^n + by^k + cy^l + d = 0.$$

| (39) | | $\frac{b^n}{a^k d^{n-k}}$ | $\frac{c^n}{a^l d^{n-l}}$ | $\frac{b^{n-l}}{a^{k-l} c^{n-k}}$ | $\frac{c^k}{b^l d^{k-l}}$ |
|---|---|---|---|---|---|
| I $ay^n + by^k x + d = 0$ | $n$ | $<$ | $<$ | | |
| II $ay^n + by^k + dx = 0$ | $n-k$ | $>$ | | $>$ | |
| $ay^n x + by^k + d = 0$ | $k$ | $>$ | | | $<$ |
| | | $\frac{n^n}{k^k(n-k)^{n-k}}$ | $n^n$ | $\frac{1}{(n-k)^{n-k}}$ | $k^k$ |

22. The substitution

(40) $$y = z^s,$$

where $s$ is a positive integer, transforms the four-term equation

$$ay^n + by^k + cy^l + d = 0$$

into the four-term equation

(41) $$az^{ns} + bz^{ks} + cz^{ls} + d = 0.$$

The table of convergency conditions for equation (41) corresponding to table (39) is

| (42) | | $\left(\frac{b^n}{a^k d^{n-k}}\right)^s$ | $\left(\frac{c^n}{a^l d^{n-l}}\right)^s$ | $\left(\frac{b^{n-l}}{a^{k-l} c^{n-k}}\right)^s$ | $\left(\frac{c^k}{b^l d^{k-l}}\right)^s$ |
|---|---|---|---|---|---|
| I $az^{ns} + bz^{ks} x + d = 0$ | $ns$ | $<$ | $<$ | | |
| II $az^{ns} + bz^{ks} + dx = 0$ | $ns-ks$ | $>$ | | $>$ | |
| $az^{ns} x + bz^{ks} + d = 0$ | $ks$ | $>$ | | | $<$ |
| | | $\left(\frac{n^n}{k^k(n-k)^{n-k}}\right)^s$ | $(sn)^{sn}$ | $\frac{1}{(sn-sk)^{sn-sk}}$ | $(sk)^{sk}$ |

The three-term equations

$$ay^n + by^k + d = 0$$

$$az^{ns} + bz^{ks} + d = 0$$

for all values of $s$ have the same convergency conditions.

If the inequality

$$\frac{c^n}{a^l d^{n-l}} < n^n$$

of table (39) is not satisfied, it is always possible to take $s$ sufficiently large so that the corresponding inequality

$$\frac{c^n}{a^l d^{n-l}} < s^n n^n$$

of table (42) will be satisfied.

In like manner, if the inequalities

$$\frac{b^n}{a^k d^{n-k}} > \frac{n^n}{k^k(n-k)^{n-k}}, \quad \frac{b^{n-l}}{a^{k-l} c^{n-k}} > \frac{1}{(n-k)^{n-k}}, \quad \frac{c^k}{b^l d^{k-l}} < k^k$$

of table (39) are not satisfied simultaneously, it is always possible to take $s$ sufficiently large so that the corresponding inequalities of table (42)

$$\frac{b^n}{a^k d^{n-k}} > \frac{n^n}{k^k(n-k)^{n-k}}, \quad \frac{b^{n-l}}{a^{k-l} c^{n-k}} > \frac{1}{s^{n-k}(n-k)^{n-k}}, \quad \frac{c^k}{b^l d^{k-l}} < s^k k^k$$

will be satisfied simultaneously.

To the convergency conditions of table (42) must be added the limiting convergency conditions obtained by replacing in the first column of inequality signs of table (42) each inequality sign by the equality sign.

It follows that it is always possible to determine $s$ so that all the roots of the four-term equation

(41) $$az^{ns} + bz^{ks} + cz^{ls} + d = 0$$

may be derived from the roots of the three-term equation

(42) $$az^{ns} + bz^{ks} + d = 0.$$

The roots of the four-term equation

$$ay^n + by^k + cy^l + d = 0$$

are found from the roots of equation (41) by substituting in

(40) $$y = z^s.$$

23. While table (42) shows the possibility of expressing all the

roots of equation (41) in infinite series, the method of article (22) requires the determination of the $ns$ roots of equation (41) to find the $n$ roots of the four-term equation

$$ay^n + by^k + cy^l + d = 0.$$

This method is therefore to be avoided in practice when possible.

The following table exhibits the conditions sufficient for the absolute convergence of the infinite series which give the roots of the four-term equation obtained from the four groups of equations. The series obtained from each group of equations determine all the roots of the four-term equation. The convergency conditions must be taken from this table as in article 20, and the limiting convergency conditions must be taken into account.

A less inclusive set of conditions sufficient for the absolute convergence of the series which give the roots of the four-term equation derived from the groups of equations of table (43) is obtained by taking the second member of each inequality from the bottom of the column in which the sign of inequality stands.

| (43) | | | $\frac{b^n}{a^kd^{n-k}}$ | $\frac{c^n}{a^ld^{n-l}}$ | $\frac{b^{n-l}}{a^{k-l}c^{n-k}}$ | $\frac{c^k}{b^ld^{k-l}}$ | |
|---|---|---|---|---|---|---|---|
| I | $ay^n+by^kx+cy^lx+d=0$ | $n$ | $<$ | $<$ | | | $n^n$ |
| II | $ay^n+by^k+cy^lx+dx=0$ | $n-k$ | $>$ | | $>$ | | $(n-k)^{n-k}$ |
| | $ay^nx+by^k+cy^lx+d=0$ | $k$ | $>$ | | | $<$ | $k^k$ |
| III | $ay^n+by^kx+cy^l+dx=0$ | $n-l$ | | $>$ | $<$ | | $(n-l)^{n-l}$ |
| | $ay^nx+by^kx+cy^l+d=0$ | $l$ | | $>$ | | $>$ | $l^l$ |
| IV | $ay^n+by^k+cy^lx+dx=0$ | $n-k$ | $>$ | | $>$ | | $(n-k)^{n-k}$ |
| | $ay^nx+by^k+cy^l+dx=0$ | $k-l$ | | | $>$ | $>$ | $(k-l)^{k-l}$ |
| | $ay^nx+by^kx+cy^l+d=0$ | $l$ | | $>$ | | $>$ | $l^l$ |
| | | | $\frac{n^n}{k^k(n-k)^{n-k}}$ | $\frac{n^n}{l^l(n-l)^{n-l}}$ | $\frac{(n-l)^{n-l}}{(k-l)^{k-l}(n-k)^{n-k}}$ | $\frac{k^k}{l^l(k-l)^{k-l}}$ | |

It is only when the convergency conditions of the groups I, II, III, IV, together with the corresponding limiting convergency conditions fail simultaneously that the use of equation (41) becomes necessary.

## IV. The Five-term Equation.

24. In the five-term equation

$$ay^n + by^k + cy^l + dy^m + l = 0$$

the two terms from which the factor $x$ is to be omitted can be selected in ten different ways. This gives rise to the ten equations:

$$ay^n + by^k x + cy^l x + dy^m x + l = 0 \tag{44}$$

$$ay^n + by^k + cy^l x + dy^m x + lx = 0 \tag{45}$$

$$ay^n + by^k x + cy^l + dy^m x + lx = 0 \tag{46}$$

$$ay^n + by^k x + cy^l x + dy^m + lx = 0 \tag{47}$$

$$ay^n x + by^k + cy^l + dy^m x + lx = 0 \tag{48}$$

$$ay^n x + by^k + cy^l x + dy^m + lx = 0 \tag{49}$$

$$ay^n x + by^k x + cy^l + dy^m + lx = 0 \tag{50}$$

$$ay^n x + by^k + cy^l x + dy^m x + l = 0 \tag{51}$$

$$ay^n x + by^k x + cy^l + dy^m x + l = 0 \tag{52}$$

$$ay^n x + by^k x + cy^l x + dy^m + l = 0 \tag{53}$$

Each one of these ten equations defines $y$ as an algebraic function of $x$ which may be expanded into a power series by any one of the methods of articles 7, 8, 9.

25. The terms of the power series expressing the value of the algebraic function defined by equation (44), using the symbol (14) and placing $y_0 = (-l/a)^{1/n}$, when $x$ is made unity, may be arranged as follows:

$$
\begin{array}{llll}
(54)\ y = & y_0 & & \\
& +\dfrac{b}{en}\,y_0^{\,1+k} & +\dfrac{c}{en}\,y_0^{\,1+l} & \\
& +\dfrac{b^2}{2!\,e^2n^2}\left[1+2k-n\right]y_0^{\,1+2k} & +\dfrac{2bc}{2!\,e^2n^2}\left[1+k+l-n\right]y_0^{\,1+k+l} & +\dfrac{c^2}{2!\,e^2n^2}\left[1+2l-n\right]y_0^{\,1+2l} \\
& +\dfrac{b^3}{3!\,e^3n^3}\left[\dfrac{1+3k-n}{1+3k-3n}\right]y_0^{\,1+3k} & +\dfrac{3b^2c}{3!\,e^3n^3}\left[\dfrac{1+2k+l-n}{1+2k+l-3n}\right]y_0^{\,1+2k+l} & +\dfrac{3bc^2}{3!\,e^3n^3}\left[\dfrac{1+k+2l-n}{1+k+2l-2n}\right]y_0^{\,1+k+2l}+\cdots \\
& \vdots & \vdots & \vdots \\
& +\dfrac{d}{en}\,y_0^{\,1+m} & & \\
& +\dfrac{2bd}{2!\,e^2n^2}\left[1+k+m-n\right]y_0^{\,1+k+m} & +\dfrac{2cd}{2!\,e^2n^2}\left[1+l+m-n\right]y_0^{\,1+l+m} & \\
& +\dfrac{3b^2d}{3!\,e^3n^3}\left[\dfrac{1+2k+m-n}{1+2k+m-3n}\right]y_0^{\,1+2k+m} & +\dfrac{3bcd}{3!\,e^3n^3}\left[\dfrac{1+k+l+m-n}{1+k+l+m-3n}\right]y_0^{\,1+k+l+m} & +\dfrac{3c^2d}{3!\,e^3n^3}\left[\dfrac{1+2l+m-n}{1+2l+m-3n}\right]y_0^{\,1+2l+m}+\cdots. \\
& \vdots & \vdots & \vdots
\end{array}
$$

26. The first group of terms of (54) is the infinite series which gives the solution of the four-term equation

$$ay^n + by^k + cy^l + l = 0$$

obtained from the equation

$$ay^n + by^k x + cy^l x + l = 0$$

provided the conditions

$$\frac{b^n}{a^k e^{n-k}} < \frac{n^n}{k^k (n-k)^{n-k}}, \quad \frac{c^n}{a^l e^{n-l}} < n^n,$$

are satisfied.

The second group of terms has the common factor

$$\frac{d}{en} y_0^m,$$

and the successive groups of terms respectively the common factors

$$\frac{d^2}{e^2 n^2} y_0^{2m}, \quad \frac{d^3}{e^3 n^3} y_0^{3m}, \quad \frac{d^4}{e^4 n^4} y_0^{4m}, \quad \cdots.$$

The convergency conditions of the successive groups of terms are identical with the convergency conditions of the first group. It follows that (54) may be written

$$(55) \qquad y = Y_0 + Y_1 \frac{d}{en} y_0^m + Y_2 \frac{d^2}{e^2 n^2} y_0^{2m} + Y_3 \frac{d^3}{e^3 n^3} y_0^{3m} + \cdots,$$

where $Y_0, Y_1, Y_2, Y_3, Y_4, \cdots$, represent the sums of convergent infinite series.

If $Y$ denotes the largest of the numbers $Y_0, Y_1, Y_2, Y_3, \cdots$,

$$(56) \qquad y \leqq Y\left(1 + \frac{d}{en} y_0^m + \frac{d^2}{e^2 n^2} y_0^{2m} + \frac{d^3}{e^3 n^3} y_0^{3m} + \cdots\right).$$

The series (56) is convergent provided

$$(57) \qquad \frac{d}{en} y_0^m < 1.$$

If both members of the inequality (57) are affected by the exponent $n$, condition (57) becomes

$$(58) \qquad \frac{d^n}{a^m e^{n-m}} < n^n.$$

The conditions sufficient for the absolute convergence of (54) are therefore

$$(59) \qquad \frac{b^n}{a^k e^{n-k}} < \frac{n^n}{k^k(n-k)^{n-k}}, \quad \frac{c^n}{a^l e^{n-l}} < n^n, \quad \frac{d^n}{a^m e^{n-m}} < n^n.$$

27. When the conditions (59) are satisfied the first group of terms of (54) gives the roots of the four-term equation

$$ay^n + by^k + cy^l + l = 0$$

expressed in the series obtained from the equation

$$ay^n + by^k x + cy^l x + l = 0$$

and the successive groups of (54) are the series of corrections which must be applied to the roots of this four-term equation to obtain the roots of the five-term equation

$$ay^n + by^k + cy^l + dy^m + l = 0.$$

28. If in the first row of (54) either of the terms

$$\frac{c}{en} y_0^{1+l}, \quad \frac{d}{en} y_0^{1+m}$$

is placed first and the consequent changes in (54) are made, the convergency conditions of the two new series are found to be

$$(60) \qquad \frac{b^n}{a^k e^{n-k}} < n^n, \quad \frac{c^n}{a^l e^{n-l}} < \frac{n^n}{l^l(n - l^{n-l}}, \quad \frac{d^n}{a^m e^{n-m}} < n^n;$$

$$(61) \qquad \frac{b^n}{a^k e^{n-k}} < n^n, \quad \frac{c^n}{a^l e^{n-l}} < n^n, \quad \frac{d^n}{a^m e^{n-m}} < \frac{n^n}{m^m(n-m)^{n-m}}.$$

In the limiting convergency conditions the signs of inequality in the first inequality of (59), in the second inequality of (60) and in the third inequality of (61) must be replaced by the equality sign.

The conditions sufficient for the absolute convergence of (54) may be written from equation (44) by the method stated in article 19.

In like manner the conditions sufficient for the absolute convergence of the series obtained from equations (45) to (53) may be written.

The convergency conditions for all these series may be taken from the following table. The convergency conditions are taken from the table by the method stated in article 20, except that the right-hand members of two inequalities must be determined from the expressions at the right of the row in which the sign of inequality stands.

| (62) | $\frac{b^n}{a^k e^{n-k}}$ | $\frac{c^n}{a^l e^{n-l}}$ | $\frac{d^n}{a^m e^{n-m}}$ | $\frac{b^{n-m}}{a^{k-m} d^{n-k}}$ | $\frac{b^{n-l}}{a^{k-l} c^{n-k}}$ | $\frac{c^k}{b^l e^{k-l}}$ | $\frac{d^k}{b^m e^{k-m}}$ | $\frac{c^{n-m}}{a^{l-m} d^{n-l}}$ | $\frac{d^l}{c^m e^{l-m}}$ | $\frac{c^{k-m}}{b^{l-m} d^{k-l}}$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| (44) | < | < | < | | | | | | | | $n^n$ |
| (45) | > | | | > | > | | | | | | $(n-k)^{n-k}$ |
| (46) | | > | | | < | | | > | | | $(n-l)^{n-l}$ |
| (47) | | | > | < | | | | < | | | $(n-m)^{n-m}$ |
| (48) | | | | | > | > | | | | > | $(k-l)^{k-l}$ |
| (49) | | | | > | | | > | | | < | $(k-m)^{k-m}$ |
| (50) | | | | | | | | > | > | > | $(l-m)^{l-m}$ |
| (51) | > | | | | | < | < | | | | $k^k$ |
| (52) | | > | | | | > | | | < | | $l^l$ |
| (53) | | | > | | | | > | | > | | $m^m$ |
| | $\frac{n^n}{k^k(n-k)^{n-k}}$ | $\frac{n^n}{l^l(n-l)^{n-l}}$ | $\frac{n^n}{m^m(n-m)^{n-m}}$ | $\frac{(n-m)^{n-m}}{(k-m)^{k-m}(n-k)^{n-k}}$ | $\frac{(n-l)^{n-l}}{(k-l)^{k-l}(n-k)^{n-k}}$ | $\frac{k^k}{l^l(k-l)^{k-l}}$ | $\frac{k^k}{m^m(k-m)^{k-m}}$ | $\frac{(n-m)^{n-m}}{(l-m)^{l-m}(n-l)^{n-l}}$ | $\frac{l^l}{m^m(l-m)^{l-m}}$ | $\frac{(k-m)^{k-m}}{(l-m)^{l-m}(k-l)^{k-l}}$ | |

29. The following table exhibits one set of conditions sufficient for the absolute convergence of the infinite series which give the roots of the four-term equation

$$ay^n + by^k + cy^l + l = 0$$

together with the equations from which these series are obtained and the number of roots given by each series, and also the conditions sufficient for the absolute convergence of the series of corrections which must be applied to the roots of this four-term equation to obtain the roots of the five-term equation

$$ay^n + by^k + cy^l + dy^m + l = 0.$$

| (63) | | $\frac{b^n}{a^k e^{n-k}}$ | $\frac{c^n}{a^l e^{n-l}}$ | $\frac{b^{n-l}}{a^{k-l} e^{n-k}}$ | $\frac{c^k}{b^l e^{k-l}}$ | $\frac{d^n}{a^m e^{n-m}}$ | $\frac{b^{n-m}}{a^{k-m} d^{n-k}}$ | $\frac{d^k}{b^m e^{k-m}}$ |
|---|---|---|---|---|---|---|---|---|
| I $ay^n+by^kx+cy^lx+e=0$ | $n$ | < | < | | | < | | |
| II $\begin{cases} ay^n+by^k+cy^lx+ex=0 \\ ay^nx+by^k+cy^lx+e=0 \end{cases}$ | $n-k$<br>$k$ | ><br>> | | > | <br>< | | > | <br>< |
| | | $\frac{n^n}{k^k(n-k)^{n-k}}$ | $n^n$ | $\frac{1}{(n-k)^{n-k}}$ | $k^k$ | $n^n$ | $\frac{1}{(n-k)^{n-k}}$ | $k^k$ |

30. The substitution

$$y = z^s, \tag{64}$$

where $s$ is a positive integer, transforms the five-term equation

$$ay^n + by^k + cy^l + dy^m + l = 0$$

into another five-term equation

$$ay^{ns} + by^{ks} + cy^{ls} + dy^{ms} + l = 0. \tag{65}$$

An examination of the table of convergency conditions for equation (65) corresponding to table (63), shows that it is always possible so to determine $s$ that the convergency conditions for the series obtained from the equation

$$ay^{ns} + by^{ks}x + cy^{ls}x + dy^{ms}x + l = 0 \tag{66}$$

or from the pair of equations

$$ay^{ns} + by^{ks} + cy^{ls}x + dy^{ms}x + lx = 0 \tag{67}$$

$$ay^{ns}x + by^{ks} + cy^{ls}x + dy^{ms}x + l = 0 \tag{68}$$

are satisfied. Hence it is always possible to determine all the roots of a five-term equation by means of series.

31. The method of article 30 requires the determination of the $ns$ roots of equation (65) in order to find the $n$ roots of the five-term equation

$$ay^n + by^k + cy^l + dy^m + l = 0.$$

The use of this method becomes necessary only when the convergency conditions of the seven groups of equations of the following table, together with the corresponding limiting convergency conditions fail simultaneously.

The convergency conditions must be taken from this table as in article 20.

A less inclusive set of congruency conditions may be taken from this table as in article 23.

(69)

| | | | $\frac{b^n}{a^k e^{n-k}}$ | $\frac{c^n}{a^l e^{n-l}}$ | $\frac{d^n}{a^m e^{n-m}}$ | $\frac{b^{n-m}}{a^{k-m} d^{n-k}}$ | $\frac{b^{n-l}}{a^{k-l} c^{n-k}}$ | $\frac{c^k}{b^l e^{k-l}}$ | $\frac{d^k}{b^m e^{k-m}}$ | $\frac{c^{n-m}}{a^{l-m} d^{n-l}}$ | $\frac{d^l}{c^m e^{l-m}}$ | $\frac{c^{k-m}}{b^{l-m} d^{k-l}}$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| I | $ay^n + by^k + cy^lx + dy^mx + ex = 0$ | $n$ | $<$ | $<$ | $<$ | | | | | | | | $n^n$ |
| II | $ay^n + by^k + cy^lx + dy^mx + ex = 0$ | $n-k$ | $>$ | | | $>$ | $>$ | | | | | | $(n-k)^{n-k}$ |
| | $ay^nx + by^k + cy^lx + dy^mx + e = 0$ | $k$ | $>$ | | | | | $<$ | $<$ | | | | $k^k$ |
| III | $ay^n + by^kx + cy^l + dy^mx + ex = 0$ | $n-l$ | | $>$ | | | $<$ | | | $>$ | | | $(n-l)^{n-l}$ |
| | $ay^nx + by^kx + cy^l + dy^mx + e = 0$ | $l$ | | $>$ | | | | $>$ | | | $<$ | | $l^l$ |
| IV | $ay^n + by^kx + cy^lx + dy^m + ex = 0$ | $n-m$ | | | $>$ | $<$ | | | | $<$ | | | $(n-m)^{n-m}$ |
| | $ay^nx + by^kx + cy^lx + dy^m + e = 0$ | $m$ | | | $>$ | | | | $>$ | | $>$ | | $m^m$ |
| V | $ay^n + by^k + cy^lx + dy^mx + ex = 0$ | $n-k$ | $>$ | | | $>$ | $>$ | | | | | | $(n-k)^{n-k}$ |
| | $ay^nx + by^k + cy^l + dy^mx + ex = 0$ | $k-l$ | | | | | $>$ | $>$ | | | | $>$ | $(k-l)^{k-l}$ |
| | $ay^nx + by^kx + cy^l + dy^mx + e = 0$ | $l$ | | $>$ | | | $>$ | | | $<$ | | | $l^l$ |
| VI | $ay^n + by^kx + cy^l + dy^mx + ex = 0$ | $n-l$ | | $>$ | | | $<$ | | | $>$ | | | $(n-l)^{n-l}$ |
| | $ay^nx + by^kx + cy^l + dy^m + ex = 0$ | $l-m$ | | | | | | | | $>$ | $>$ | $>$ | $(l-m)^{l-m}$ |
| | $ay^nx + by^kx + cy^lx + dy^m + e = 0$ | $m$ | | $>$ | | | | $>$ | | $>$ | | | $m^m$ |
| VII | $ay^n + by^k + cy^lx + dy^mx + ex = 0$ | $n-k$ | $>$ | | | $>$ | $>$ | | | | | | $(n-k)^{n-k}$ |
| | $ay^nx + by^k + cy^l + dy^mx + ex = 0$ | $k-l$ | | | | | $>$ | $>$ | | | | $>$ | $(k-l)^{k-l}$ |
| | $ay^nx + by^kx + cy^l + dy^m + ex = 0$ | $l-m$ | | | | | | | | $>$ | $>$ | $>$ | $(l-m)^{l-m}$ |
| | $ay^nx + by^kx + cy^lx + dy^m + e = 0$ | $m$ | | $>$ | | | | $>$ | | $>$ | | | $m^m$ |
| | | | $\frac{n^n}{k^k(n-k)^{n-k}}$ | $\frac{n^n}{l^l(n-l)^{n-l}}$ | $\frac{n^n}{m^m(n-m)^{n-m}}$ | $\frac{(n-m)^{n-m}}{(k-m)^{k-m}(n-k)^{n-k}}$ | $\frac{(n-l)^{n-l}}{(k-l)^{k-l}(n-k)^{n-k}}$ | $\frac{k^k}{l^l(k-l)^{k-l}}$ | $\frac{k^k}{m^m(k-m)^{k-m}}$ | $\frac{(n-m)^{n-m}}{(l-m)^{l-m}(n-l)^{n-l}}$ | $\frac{l^l}{m^m(l-m)^{l-m}}$ | $\frac{(k-m)^{k-m}}{(l-m)^{l-m}(k-l)^{k-l}}$ | |

## V. Conclusion.

32. In the algebraic equation of $t$ terms

$$f(y)=0$$

the two terms from which the factor $x$ is to be omitted can be selected in

$$\frac{t(t-1)}{2}$$

ways. Each one of the resulting equations defines $y$ as an algebraic function of $x$, and each algebraic function of $x$ can be expanded into a power series in $x$ by the methods used to obtain the corresponding expansions for the three-, four- and five-term equations. When $x$ is made unity in these power series the resulting series become the roots of the $t$-term equation and a table of convergency conditions for these series analogous to tables (20), (38), (62) can be set up. In fact, this table may be written mechanically by following the directions of article 19.

33. If in the $t$-term equation the substitution

$$y=z^s$$

is made, a table of convergency conditions analogous to tables (39), (63) can be set up, and the value of $s$ can be determined so that this table of conditions shows that it is possible to obtain all the roots of the transformed equation from the series derived either from the equation in which $x$ is omitted from the first and last terms, or from the two equations in which $x$ is omitted from the first and second, and from the second and last terms respectively. The roots of the given equation are then found from the roots of the transformed equation by substituting in

$$y=z^s.$$

34. Finally, tables of convergency conditions analogous to tables (43), (64) can be set up for the $t$-term equation, and it is necessary to use the transformed equation only when the convergency condi-

tions of all the groups of this table, together with the corresponding limiting convergency conditions, fail simultaneously.

35. It follows that all the roots of an algebraic equation of any number of terms, that is, of any algebraic equation, can be expressed in infinite series by the method of this investigation.

LEHIGH UNIVERSITY, BETHLEHEM, PA.,
April 2, 1908.

## *Stated Meeting May 1, 1908.*

Treasurer JAYNE in the Chair.

Dr. Martin G. Brumbaugh, a newly elected member, was presented to the chair, and took his seat in the Society.

Letters were read, accepting election to membership from

Martin Grove Brumbaugh, Ph.D., Philadelphia.
Walter Bradford Cannon, A.M., M.D., Boston, Mass.
James Christie, Philadelphia.
Edward Washburn Hopkins, Ph.D., LL.D., New Haven, Conn.
Josiah Royce, Ph.D., LL.D., Cambridge, Mass.
Jacob G. Schurman, Ph.D., Ithaca, N. Y.
Edward Anthony Spitzka, M.D., Philadelphia.
Robert Williams Wood, Ph.D., Baltimore.

MR. R. H. MATHEWS presented some "Notes on Australian Laws of Descent."

Professor Albert A. Michelson, of Chicago, was unanimously elected a Vice-President to fill the unexpired term of Professor George F. Barker, resigned.

## *Stated Meeting May 15, 1908.*

Curator DOOLITTLE in the Chair.

Letters were read accepting membership from

William Hallock, Ph.D., New York City.
Leonard Pearson, M.D., Philadelphia.
Charles Henry Smyth, Ph.D., Princeton, N. J.
John Robert Sitlington Sterrett, Ph.D., Ithaca, N. Y.
Ernest Nys, Brussels.

From Professor Albert A. Michelson accepting election to the Vice-Presidency to fill an unexpired term.

From the Committee of Organization of the Third Congrès International de Botanique, announcing that the Congress will be held at Brussels from May 14–22, 1910, and inviting the Society to be represented by delegates.

Dr. H. M. Chance read a paper on "The Origin of Bombshell Ore" (see page 135), which was discussed by Mr. Sanders, Mr. Jayne and Professor Doolittle.

# THE ORIGIN OF BOMBSHELL ORE.

By H. M. CHANCE.

(*Read May 15, 1908.*)

The term "bombshell" ore is applied by miners and iron-masters to hollow masses of limonite—brown hematite—which sometimes are round or oval but more commonly are of any irregular shape. The "bombs" may contain water, clay, sand, quartz, flint, pyrite, siderite, sandstone or decomposed slate, or may be entirely empty. Geologists usually speak of such ore as nodular or concretionary. A careful examination of the literature of ore deposits and especially of that relating to the genesis of limonite ores fails to disclose a satisfactory explanation of its origin of mode of formation. By many it is assumed to be similar in origin to silicious geodes, which are supposed to be formed by the deposition of silica or silicates upon the walls of cavities, while others describe it as of "concretionary" origin without attempting to explain the process of formation or the manner in which it has occluded the variety of materials which are found in the interior of different specimens from the same locality. That it is not of concretionary origin is evident upon even cursory consideration, for concretions are masses of material arranged in concentric layers around a central nucleus. The latter may be a grain of sand, a pebble, fossil, or any substance around which (as a core) the concretion forms, growing from the center by the successive addition of concentric rings. Concretions are perhaps merely symmetrical segregations.

The peculiarities of this ore are well described by Professor T. C. Hopkins, *Bull. Geol. Soc. Am.*, 1890, Vol. 11, p. 477, etc., as follows:

> "Nodular ore consists of irregularly rounded masses, varying in size from a fraction of a pound to several hundred pounds in weight. The masses are frequently hollow, but some enclose a rounded or sub-angular rock fragment, which is sometimes sandstone, . . . sometimes chert, sometimes slate, and sometimes clay. Some shells are filled with clay and sand,

and workmen report finding many of them filled with water. Some are filled with clay, which still retains the laminated structure and appearance of the original slate from which the clay was derived, furthermore, the slaty structure was found to extend through the ore shell, which showed, besides the plain lamination of slate, a faint concentric structure as well. . . . While only one shell was found still retaining the laminations of the clay, there were many others containing clay and sand. Some of the shells were but thin crusts, while others were quite thick, almost solid; some have a smooth, velvety or bright mammillated inner surface, frequently coated with manganese oxide. In some instances the lining of the shell is covered with many small stalactites of ore. . . . Many of the shells are lined with a dense fibrous layer, often an inch or more in thickness. . . . The thinner shells have all been broken, and we see only the fragments of them in the clay-ore masses. This shell form of ore . . . forms an appreciable part of the ore body in many cases. The small, irregular, nodular-like-pieces of ore, commonly knows as shot ore, are presumably closely related in origin to the shells. . . ."

The inner wall of many bombs consists of a hard, bright, brown or jet-black, glazed surface, curved, rounded or botryoidal. This is frequently described as a manganese coating, but is doubtless a film of iron or manganese silicate. Occasionally the interior or a part of the interior is lined with a layer of extremely hard, flinty, liver-colored iron silicate, or with quartz crystals or chalcedony, and the same silicate frequently forms a considerable portion of the body of the shell or of its outer layers, but generally the shell is composed of high-grade limonite, of a fibrous structure, especially in those layers forming the inner lining of the shell.

These peculiarities are satisfactorily accounted for neither by the theory that these ore masses owe their origin to concretionary action, nor by that which assumes the direct deposition of ferric hydrate upon the interior of rock (limestone?) cavities. They may, however, be explained by assuming that the bombs are the residual masses, remaining after oxidation, of iron sulphides or carbonates containing sand or clay or both in varying proportions.

If the material from which this ore is formed consists of sandstone, or of sandy slate, or of clay slate, impregnated more or less completely with pyrite or siderite, the formation of bombshells, containing just such materials as are found in these shells, may be readily explained, especially if the iron impregnation be in the form of pyrite or marcasite, that is, $FeS_2$.

If such sandstone or slate, is broken and fissured by faulting and crushing, and by the development of cleavage planes, oxidation by percolating waters will proceed along the joints or planes which form the channels through which these waters circulate, and in each fragment of the mineralized rock oxidation will commence upon the outside and progress towards the center.

In this way on outer skin or shell of limonite first forms on the outside of the fragment, for if the iron be present as pyrite or marcasite while some of it may be removed as ferrous sulphate, this salt, if formed, may immediately be oxidized and precipitated *in situ* as ferric hydrate. The sulphuric acid formed by the oxidation of the remaining molecule of sulphur will attack and decompose the clay of the gangue, removing the bases as sulphates in solution; the silicic acid also escaping in solution, or combining with iron oxides to form iron silicates, remains as an integral part of the ore.

If clay be present in large quantity a portion will remain undecomposed in the center of the bomb, together with all of the sand originally present in the gangue.

Hence, if the original pyritic material has a clayey (slate) gangue, bombs may form containing no residual matter, or containing more or less clay; if the gangue be sand and clay (arenaceous slate), the sand only, or sand and clay may remain; if the gangue be sand only, some of this will remain as an impurity in the limonite forming the body of the shell, and some as a partial filling of the interior of the bomb.

It is now well known that pyrite (or marcasite) oxidizing underground, whether by waters carrying free oxygen, or by waters containing no uncombined oxygen, or by reactions involving hydrolysis, does not behave in the same way as when oxidized by exposure to the air above-ground. One of the most common reactions above-ground is that in which sulphur is set free, often written:

$$FeS_2 + 4O = FeSO_4 + S,$$

but this rarely occurs beneath the surface, for the gossans of pyritic veins seldom carry free sulphur, although there are a few noted examples in which large deposits of sulphur are found between the surface and the unoxidized portions of such veins.

In the absence of oxygen, carbonates in solution may, as shown by Dr. N. H. Stokes, completely oxidize the iron of pyrite or marcasite thus:

$$8FeS_2 + 15Na_2CO_3 = 4Fe_2O_3 + 14Na_2S + Na_2S_2O_3 + 15CO_2,$$

and under proper conditions of temperature and pressure the ferric oxide thus formed may be deposited as hydrate; but these reactions do not satisfy the observed conditions and it seems more probable that oxidation near the surface has proceeded as indicated by some of the following reactions:

$$\begin{aligned}
&FeS_2 + H_2O + 7O = FeSO_4 + H_2SO_4;\\
&3FeS_2 + 8H_2O + 22O = Fe_2O_3,\ 3H_2O + FeSO_4 + 5H_2SO_4;\\
&2FeSO_4 + 5H_2O + O = Fe_2O_3,\ 3H_2O + 2H_2SO_4;\\
&2FeS_2 + 7H_2O + 15O = Fe_2O_3,\ 3H_2O + 4H_2SO_4;\\
&2FeS_2 + 4H_2O + 15O = Fe_2O_3 + 4H_2SO_4;\\
&2FeSO_4 + 2H_2O + O = Fe_2O_3 + 2H_2SO_4;\\
&6FeSO_4 + 3O = Fe_2O_3 + 2Fe_2(SO_4)_3;\\
&6FeSO_4 + 3H_2O + 3O = Fe_2O_3,\ 3H_2O + 2Fe_2(SO_4)_3;\\
&2Fe_2(SO_4)_3 + 2FeS_2 + 4H_2O + 12O = 6FeSO_4 + 4H_2SO_4.
\end{aligned}$$

The sulphuric acid having been formed in direct contact with the gangue, it is reasonable to suppose that it must at once attack any clay or other decomposable material, and the removal of the soluble silicates and silicic acid by transfusion through the walls of the bomb is readily pictured. It is, however, possible that the colloidal silicic acid may be retained, and further that it may perhaps often be set free in a gelatinous condition. This latter hypothesis may account for the frequent presence in such ores of a skeleton of amorphous silica which appears to completely ramify some parts of the limonite.

If the oxidation proceed according to these equations, the successive additions of layers of limonite to the interior of the shells is doubtless due to the further oxidation of the ferrous sulphate as above shown, the oxidation of the solution occurring at or in the wall of the shell where the solutions, in escaping by transfusion through the walls of the shell, are met by oxidizing waters transfusing towards the center of the shell. Under such conditions the ferric hydrate would be deposited in the pores of the shell or upon its inner surface.

In attempting to picture these reactions and their results, it is important to remember the extremely slow rate at which oxidation proceeds under such conditions. Even at the surface where decomposition is comparatively rapid, the oxidation of pyrite appears to progress at a very slow rate, perhaps not exceeding an inch or a few inches in depth in several hundred years.

If the iron be present as carbonate, a precisely similar series of reactions may be conceived, in which carbonic acid transposes the silicates, freeing silicic acid and removing the bases as soluble carbonates.

Other observers have noted the occasional presence of a central core of siderite or pyrite in bombshell ore, but have generally attributed the presence of such cores to concretionary action and replacement by sulphates (accompanied by reduction to sulphide) or carbonates in solution.

The foregoing theory, advanced to account for the origin of bombshell ore, is based upon a study of these deposits dating back to 1885—when the writer was personally engaged in mining brown-hematite ore—and upon examinations of many specimens which show more or less clearly the character of the original material from which such ore is formed. It will form an integral part of a broader statement, extending the application of this theory to the genesis of limonite ores, and including a discussion of the original sources of the iron, methods of mineralization, and subsequent decomposition and precipitation.

PROCEEDINGS
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# THE SIGN AND NAME FOR PLANET IN BABYLONIAN.

By MORRIS JASTROW, Jr.

(*Read April 25, 1908.*)

Kugler begins his valuable work on Babylonian astronomy[1] with a discussion of the ordinary name for planet in Babylonian, namely, *bibbu,* and for which the ideographic designation is Lu-Bat.[2] He

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[1] "Sternkunde und Sterndienst in Babel" (Münster, 1907), I., pp. 7–9.

[2] That this combination is used for planet in general follows from such passages as (1) Thompson, "Reports of the Magicians and Astrologers," No. 112 Rev. 7; 236 B Rev. 4, where Lu-Bat occurs with the plural sign to designate the planets in general; See also nos. 88 Obv. 4 and Rev. 1; 89 Rev. 6; 101 Obv. 5; 103 Obv. 6, Rev. 7; 163 Obv. 4; 167 Rev. 1; 172 Rev. 1 and 3; 175 Obv. 4; 200 Rev. 5; 216 Rev. 1; 218 Obv. 1; 218 A Obv. 5; 219 Obv. 1; 220 Obv. 1; 222 Obv. 1; 223 Obv. 1; 224 Obv. 3; 225 Obv. 4; 229 A Obv. 1, 2, 4; 232 Rev. 1; 234 Obv. 3; 234 A Rev. 1; 235 Obv. 11; 244 C Obv. 6, where Lu-Bat is used for planet in general. It is to be noted, however, that the only planets which are regularly designated by means of Lu-Bat are Mercury (Lu-Bat Gu-Ud) and Saturn (Lu-Bat Sag-Uš). So in the famous list of planets IIR 48; 50–54 a-b and IIIR 57, No. 6, 65–67, and Thompson, *l. c., passim,* though occasionally even in the case of these two planets the element Lu-Bat is omitted, *e. g.,* Thompson, *l. c.,* Nos. 105 Obv. 8; 215 Obv. 1; 217 Obv. 1; 223 Obv. 4; 228 Obv. 1; (Gu-Ud) and 167 Rev. 4 (Sag-Uš). Further references in Kugler, *l. c.,* p. 12. Occasionally also Mars is designated as Lu-Bat Dir instead of (il) Zal-Bat-(a-nu), so *e. g.,* Thompson No. 146 Rev. 4–6, and 195 Rev. 1–2, where in both cases a gloss Lu-Bat Dir = (il) Zal-Bat (-a-nu) furnishes the proof for the identification. In the later period (after c. 400 B. C.) Saturn is designated as GI and Mars as AN. See Kugler *l. c.,* p. 12, including the note on that page.

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accepts the interpretation proposed as long ago as 1890 by Jensen[3] for the ideographic compound as "frei weidendes, abseits weidendes Schaf." This view rests on the identification of the first sign Lu as "sheep," while the second is taken in the sense of "to remove,"[4] the combination thus expressing the movement of the planets, like sheep that wander away from the flock. That Jensen was right in his explanation of the first element as "sheep" follows from various considerations, among which the testimony of the lexicographical list IIR. 6, 4 c–d by itself, Lu-Bat = *bi-ib-bu*, is decisive, since in the same list Lu-Igi is explained as *lu-li-mu* (l. 8) "ram" or "bellwether" and Lu is the common ideogram for *immeru* the ordinary term for "sheep."[5] In addition we have the equation IIR. 39, No. 5, 62 a–b (*il*) *bi-ib-bu* = (*il*) Lu-Bat.

Jensen's explanation, however, of the second element is not satisfactory. In the first place the equation Bat = *nisû* ("to remove") does not represent the most common value of the ideograph in question, for the various meanings of which it seems more reasonable to start from the fundamental notion of "coming to completion,"[6] whence we have the further development in two directions: (1) "coming to an end" (gamâru, katû, Br. Nos. 1499, 1512, etc.), "closing up" (sakku, sikêru Meissner, Assyr. Ideogramme, Nos. 869–872); "removing" (nisû, Br. No. 1525); "growing old" (labâru, Br. No. 1515); "die" (mâtu, etc., Br. Nos. 1517–19, 1527, 1533); "set at rest" (pašâḫu, Br. No. 1528): (2) "Completion" in the sense of "fullness" and "vitality," consequently, "life" (balâtu, Br. No. 1494); "being" (bašû, Br. No. 1495); "blood"

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[3] Kosmologie der Babylonier, p. 99. Hommel (Aufsätze und Abhandlungen p. 379) thinks that the designation *bibbu* which he takes as "ram" is an allusion to the "solar" character of the planets, but this is even less plausible than Jensen's explanation.

[4] Cf. Brünnow, No. 1525 (Bat = nisû).

[5] See Muss-Arnolt, Assyr. Dict., p. 61 b. Note also that in the list IIR. 6, 5–8 we have the group bi-ib-bu, a-tu-du ("he-goat"), šap-pa-ru ("mountain-goat") and lu-li-mu.

[6] We must bear in mind as Thureau-Dangin, "Recherches sur l' Origine de l'Ecriture cuneiforme," No. 11, has pointed out, that two originally distinct signs have been confounded in Bat, so that all meanings associated, *e. g.*, with *pitû* (Br. No. 1529) must be referred to No. 278 (p. 45) and explained accordingly.

(dâmu, Br. No. 1503), and "rule" (bêlu, etc., Br. No. 1496; Meissner, No. 856), as manifestations of vitality and power as well as "strong" (ikdu, Meissner, No. 851), "protect" (emû, Meissner, No. 853), etc. The idea of "removing" falls, therefore, in the category of a secondary or tertiary derivative from the fundamental value of the sign BAT. In the second place, it is rather a violent transition from the sense of "removing" to that of "pasturing by itself" and the like. Nor does the metaphor introduced in the Babylonian creation epic[7] (Tablet VII., 111, ed. King) where the stars, or rather the gods, are compared to sheep under the guidance of Marduk strengthen the conclusion that the planets are sheep that "pasture aside" from the stars in general, since the passage does not refer specifically to the planets. This passage, as well as the others adduced by Kugler (*l. c.*, p. 7), merely justifies the interpretation of the first element in LU-BAT as "sheep." For the second element we must start from the much more common meaning attaching to the sign in question, namely, "dead" (*mîtu*). The Babylonians themselves had this equation in mind when they explained LU-BAT as *muš-mit bu-lim,* "causing cattle to die" (VR, 46, No. 1, rev. 41) even though this explanation is to be regarded as a fanciful one.[8]

Taking the two signs as they stand, the simplest explanation is to interpret them as "dead sheep" in the sense of a sacrificial animal. To the question which now arises, what connection is there between the planets and "dead sheep," the divination texts, I venture to think, furnish a satisfactory answer.

## II.

On the basis of recent researches,[9] we must distinguish in Baby-

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[7] See Kugler, *l. c.*, p. 7.

[8] Recognized as fanciful by Jensen, Kosmologie, p. 96. Kugler's attempt (*l. c.*) to reconcile this explanation with the interpretation offered in astrological texts whereby certain phenomena connected with the planets prognosticate death is very artificial and encounters a fatal objection from the consideration that the prognostication of death in one form or other, is a common interpretation of omens, indeed one of the commonest. See examples in Jastrow, "Religion Babyloniens und Assyriens," II,. pp. 261, 298, 328, 329, 331, 333, 343, etc.

[9] See Jastrow, *l. c.*, pp. 212 f., and various papers by the writer as, *e. g.*, "Signs and Names of the Liver in Babylonian" (Zeitschrift für Assyr. XX., p. 111 f.), "The Liver in Divination and the Beginnings of Anatomy" (University of Pennsylvania Medical Bulletin, January, 1908).

lonian-Assyrian methods of divining the future two classes: (1) what we may call voluntary divination, and (2) involuntary divination. The characteristic feature of voluntary divination lies in deliberately seeking out some object by means of which an answer to a specific question regarding the future or the outcome of an undertaking, a sickness or what-not is furnished. The signs furnished by the liver of an animal selected as a sacrifice belong to this category; likewise the observation of the flight of birds sent out for the purpose of securing omens, the throwing of arrows before the image of a deity and the like. Involuntary divination, on the other hand, is concerned with the attempt to interpret signs that *force* themselves on our notice, such as phenomena connected with the sun, moon, planets and stars, the movements of clouds, earthquakes and storms; the actions of animals—dogs, snakes, locusts, birds, etc., that one happens to encounter and all the unusual or significant happenings and accidents in human life, while dreams form a special subdivision in this class of involuntary divination. We might for the sake of convenience distinguish the signs furnished by voluntary divination as "omens" and those of involuntary divination as "portents," but however we may distinguish them, the recognition of these two distinct classes is fundamental to an understanding of the general subject of divination.

Confining ourselves to Babylonia and Assyria, the chief method of voluntary divination was the inspection of the liver of the sacrificial animal and the chief method of involuntary divination, the observation of phenomena of the heavens. The correctness of this thesis is shown by the wide scope of these methods as revealed in the texts themselves.[10] Both methods rest on a well-defined theory, the inspection of the liver on the basis of the primitive view that the liver was the seat of vitality, of the intellect, of both the higher and lower emotions—in short, the seat of the soul, as that term was popularly understood.[11] The deity in accepting the sacrificial animal identifies himself, as it were, with the animal, becomes

[10] See Jastrow, *l. c.*, II., p. 209 f.—especially note 1 on p. 210. See parts 11–12 of this work for "liver" omens and the forthcoming parts 13 and 14 for "astrological" omens.

[11] Jastrow, *l. c.*, pp. 213 f.

one with it and, accordingly, the liver of the animal reflects the mind and will of the god. If one can therefore read the liver correctly, one enters, as it were, into the workshop of the deity. The mind of the animal and the mind of the deity become for this specific occasion like two watches regulated to be in perfect accord.

The divining of the future through the observation of the phenomena in the heavens rests on the identification (or personification) of the gods with the sun, moon, planets and stars. The movements of these bodies, the changes in their aspects and the variations in their relationship to one another represent, as it were, the activity of the gods and since, according to the current theory, all happenings on earth are due to the gods or to one god or the other, a knowledge of what the activity in the heavens portends furnishes the means of foretelling what is to happen on earth. In time no doubt the theory was perfected, at least in the theological circles of Babylonia and Assyria, into a complete correspondence between occurrences on earth and the decision to bring about these occurrences by the manifested activity of the gods in the heavens; but even without the perfected theory, the repeated observation of the kind of happenings on earth coincident with conditions and phenomena in the heavens would have led to attaching importance to these conditions—both those of a usual order and those of a more or less unusual nature.

Of these two chief divisions of divination, it is evident that the inspection of the liver, connected as it is with a primitive view of that organ, can be accounted for as the distinct outgrowth of popular beliefs, whereas the divination through the phenomena of the heavens not only makes greater demands on scientific or pseudo-scientific knowledge but presupposes also a conception of world-philosophy which can hardly be termed popular. The personification of the sun and moon is, of course, an element in all primitive phases of belief, but the extension of such personification to the planets and stars belongs to a higher order of thought, since the bearings of those bodies on the life, happiness and fate of mankind are of a more remote and a more indirect character than in the case of the two luminaries; and when we come to the projection of practically all the activity of the gods on to the heavens, we have definitely passed beyond the intellectual range of popular fancy and have entered the domain of distinctly theological speculation. If the views of the school associated with the names of Winckler and Jeremias, that the entire Babylonian religion is under the sway of "astral" conceptions, turn out to be correct, it will also have to be recognized that the underlying "Weltanschauung" is a product of the schools rather than an expression of popular notions.[11a] I venture to think that one of the weaknesses of the "astral" theory, which has from other points of view so much in its favor, is this failure on the part of its promoters to recognize the essentially "learned" character of what according to them became the prevailing world-philosophy in the ancient Orient and which must for a long time at least have separated it sharply from the much lower plane of popular beliefs and fancies.

Be this as it may, the development of a method of divination, through elaborate observations of the movements and positions of sun, moon, planets and stars, it will be admitted, belongs to a later stage in the unfolding of religious rites than so primitive a method as the inspection of the liver of a sacrificial animal. The persistence of astrology among advanced cultures as in India and Persia and in western Europe[12] down to the threshold of modern times, whereas "liver" divination disappeared with advancing culture everywhere except among the Babylonians and Assyrians and the Greeks, Romans and Etruscans,[12a] clinches the argument in favor of divination through the liver as the earlier and more primitive method. If this be admitted, it would be reasonable to find in the

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[11a] See also Comont, "Les Religions Orientales dans le Paganisme Romain" (Paris, 1907), p. 197.

[12] See the summary by Jeremias, "Das Alte Testament im Lichte des Orients" (1 ed.), p. 7, note 1.

[12a] Roman divination is dependent upon Etruscan, while in the case of Greek divination it is still a question whether we are to assume direct influence from Babylonia or likewise through the mediation of the Etruscans. In either case we have only two systems of "liver" divination surviving among cultured nations—the Babylonian and the Etruscan; and further investigations may definitely confirm the view which on the surface seems plausible that "liver" divination among the Etruscans stands in some direct connection with Babylonian divination. If this be so, then the single cause to which the persistence of "liver" divination in certain quarters is to be ascribed is the elaboration of the complicated and ingenious system of interpretation which we owe to Babylonian priests. See Jastrow, II., pp. 215 and 320, note 3.

later method of divination through the heavens, traces of the earlier one, if not indeed some link directly connecting the two. Among the Etruscans we actually encounter such a link in the interesting circumstance that the famous "bronze liver" of Piacenza,[18] prepared like the Babylonian clay model of a liver[13a] as an object lesson for instruction in the temple schools, is divided off along the margin into sixteen regions, corresponding with the ordinary divisions of the heavens and that the forty Etruscan words with which the surface of the liver is covered are names of deities. Whether we accept Thulin's view,[14] who sees a direct relationship between the enumeration of the gods and the list and arrangement given by Martianus Capella, or follow Körte,[15] in either case the "liver" reproduces the recognized divisions of the heavens and through this combination the liver becomes, as it were, a microcosm reflecting the macrocosm. The much-discussed problem[15a] whether this remarkable object dating from about the third century B. C. is a "liver" or, as was first supposed, a "templum," thus resolves itself into the thesis that it is both. To use the words of Körte in his paper in summarizing the results of twenty-five years of study of this object:[16]

> "The liver as the seat of life according to the view of antiquity appears as a minature reproduction of the universe. As the latter, so the liver is divided into a right and left half,[17] a day division and a night division, the line of division corresponding to the line dividing the universe into east and west. As the vault of heaven, so the edge of the liver is divided into 16 regions in which the gods who furnish portents dwell."

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[18] See Körte, "Die Bronzeleber von Piacenza" (*Mitteil. d Kaiserl. Deutsch. Archæolog.-Instituts.*, XX., pp. 348–379), the latest and probably final word on the subject.

[13a] Cuneiform Texts, VI., Pl. 1–2 and photograph.

[14] "Die Götter des Martianus Capella und der Bronzeleber von Piacenza" (Giessen, 1906), pp. 31–59.

[15] Körte, *l. c.*, p. 367 f.

[15a] See the references in Körte, p. 349 f., to which Nicola Terzaghi, "La piu recente Interpretazione dei Mundus-Templum di Piacenza" (*Bolletino Storico Piacentino,* 1906, Maggio-Giugno) is to be added.

[16] Körte, *l. c.,* p. 362.

[17] Referring to the band on the reverse of the object. See the illustration in Körte's article, p. 356.

## III.

If, therefore, among the Etruscans we find the unmistakable proof of a direct link between the two classes of divination, we should be prepared to find a similar association in Babylonia and Assyria. I believe that the ordinary name and sign for planet in Babylonia points in this direction. While already in early days we find various animals and all kinds of products dedicated as offerings to the gods,[18] for purposes of divination the only animal set aside was the sheep. This follows not only from the fact that the famous clay model of a liver found near Bagdad is that of a sheep,[19] but from the specific references to sheep in "liver" divination texts *and to no other animal.*[20] The sheep thus becomes the animal of divination *par excellence,* and we can well suppose that the word itself should come to be used as synonymous with divination. Such a usage would be paralleled by the extension of the term *auspicium* in Latin, which from being an omen derived through "bird observation" was applied to any kind of an omen or portent, so that an inspection

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[18] See Thureau-Dangin, "Die Sumerischen und Akkadischen Königsinschriften" (Leipzig, 1907), pp. 16, 80, 84, 86, 88, 124, etc. I cannot here enter into a full discussion of the nature of sacrifices among the Babylonians and Assyrians but it may be proper to point out that in an elaborate ritual controlled by an extended priestly organization we must sharply differentiate between (1) offerings that constitute part of the income of the temples, (2) voluntary gifts, (3) sacrifices offered in connection with purification or expiatory rites and (4) sacrifices offered directly to and for the god. So far as I can see sacrifices of the latter kind were brought only when an answer to a specific question was desired, so that it would appear that divination forms the starting point for the development of the whole idea of sacrifice in the proper sense in Babylonia.

[19] CT, VI., Pl. 1. See Jastrow, *l. c.,* II., p. 218 note 1, where a reference should have been given to Stieda, "Ueber die aeltesten bildlichen Darstellungen der Leber" (Bonnet-Merkel, Anatomische Hefte XV., p. 697), who shows that it is (as also in the case of the bronze liver of Piacenza) the liver of a sheep and not of a goat—as had been supposed by some scholars.

[20] *E. g.,* CT, XX., 1, 1—in the opening line of the first tablet of a series dealing with "liver" divination; also Boissier, "Documents Assyriens relatifs aux Prèsages," p. 97, 11; 212, 27; also in the "omen" text CT., IV., Pl. 34, 9; in the omen report of the Cassite period (Clay, *Cassite Archives,* XIV., Pl. 4, Obv. 10, and lastly the constant mention of the "sheep" in the omens attached to Knudtzon, *Assyr. Gebete an den Sonnengott.* Note also the expression *bêl immeri* "owner of the sheep" (CT, XX., 33, 93 and Boissier, Documents, p. 96, 13). The addition of NITA to LU shows that a "male" sheep was selected for the purpose.

of the liver of an animal for the purpose of securing an "omen" was also designated as an *auspicium*.[21] Similiarly, in Greek the word ὄρνις, "bird," is used for any kind of an omen and my colleague, Professor Lamberton, has kindly called my attention to the interesting passage in the *Birds of Aristophanes* in which this usage finds a striking illustration. In the "Parabasis," after indicating all the blessings that accrue to men from the birds, the chorus turns to divination and continues as follows:[22]

"You consider all things a bird, whatever gives a decision through divination. With you a word is a 'bird,' and you call a sneeze a 'bird,' a sound a 'bird,' a sudden meeting a 'bird,' and an ass a 'bird.' Are we not clearly a prophetic Apollo to you?"

The sheep, being the animal of divination *par excellence* in Babylonia, would in the same way become the Babylonian term for an "auspicium" in general. If we assume that this use of the term lurks in the application of "sheep" as the designation of a planet, a satisfactory explanation can be found for the addition of the sign Bat to the sign for "sheep" which has more specifically the same force in the combination Lu-Bat as in the combination IIR. 27, No. 2, Obv. 46, c–d, Ur-Bat, *i. e.*, "dead liver" in the sense of the liver of a sacrificial lamb and hence as the equivalent of *ter-tu ša ḫa-še-e*, "omen through the liver."[23]

The combination Lu-Bat thus expresses more precisely than Lu alone the association of an "omen" with a "sheep," and we would be justified in rendering the combination as "sheep omen," and then through the association of ideas above pointed out, as a general term for "omen."[24]

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[21] See Pauly-Wissowa, "Real-Encyclopaedie," (new ed.), II., p. 2580 f.

[22] Ll. 719–22 (ed. Van Leeuwen, Leiden, 1893). Dr. R. G. Kent, of the University of Penna., also calls my attention to the interesting passage in Xenophon's Anabasis (III, 2, 9) where a "sneeze" as a good sign is spoken of as οἰωνός or "bird" in the general sense of an omen.

[23] On the word *ḫašû* for liver which may have been used in earlier days in place of *kabittu* see Jastrow, *l. c.*, II., p. 213, note 1, and p. 276, note 7.

[24] It is to be noted that at least in one passage in a "liver divination" the sign Bat is added to Lu-Nita "male sheep," namely Boissier, *Doc. Assyr.*, p. 212, 27, ultu libbi Lu-Nita Bat (u) têrtu (written Ur-Bat as in the passage IIR 27) tu-še-la-a, *i. e.*, "Out of a dead sheep thou shalt bring forth an omen," where the phonetic complement *u* added to Bat suggests the reading *mîtu* and where "dead sheep" is clearly the equivalent of "sacrificial sheep" or "omen sheep."

Now what was the purpose for which the movements of the planets were observed by the Babylonians? What other than to secure through such observation, signs by means of which the future could be divined? The planets were, primarily, regarded as "omens" and since, as has been above set forth, divination through the heavens follows in point of time divination through the liver of the sheep, we would expect conceptions and terms used in "liver" divination to be transferred to astrological divination. The use of the term "sheep" as the designation of the planets observed to secure omens, precisely as omens were furnished by means of sacrificial sheep, I, accordingly, take as an illustration of this dependence of astrology upon hepatoscopy, forming, as it were, the connecting link between the two. It may be noted in this connection that the interpretations given in astrological texts to signs observed are paralleled in the "liver" divination texts,[25] and there can be little doubt that they are transferred bodily from the latter and earlier class of texts to the former.

The explanation here proposed, according to which Lu-Bat as applied to the planets conveys the notion that they were regarded as "omens" or means of securing omens, throws a new light upon the statement in Diodorus[26] that the Babylonians commonly called the five planets ἑρμηνεῖς, *i. e.*, "interpreters," adding as a reason for the designation that the planets were regarded as "interpreting" for mankind the intention of the gods. Bouchè-Leclercq ("L'Astrologie Grecque," p. 40, note 3), recognizes that the term "interpreters" does not embody a Greek tradition, but the notice in Diodorus, so far from being, as he supposes, of "doubtful value," reflects the perfectly correct view that the planets were used as "omens"[27] and the term "interpreters" is evidently an attempt to

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[25] The interpretations in the "astrological" texts are in fact practically identical with those in "liver" divination, furnishing the same references to public events and differing merely in containing more references to crops, to prices of food and to famine. Cf., *e. g.*, Craig, "Astrolog.-Astronom. texts," Pl. 2, 3; 20, 22 with CT, XX., 26, Obv. 3; Boissier, Doc. Assyr., 7, 21; Craig 20, 31 with CT, XX., 32, 54; 99, 100 (where ilu = Nergal). Cf. Jastrow, *l. c.*, II., p. 342, note 11).

[26] Bibl. Histor., Book II. (ed. Dindorf), 30, 4.

[27] To be sure, what Diodorus says in addition why the planets and not also the other stars were regarded as "interpreters" is rather beside the

convey this idea. The term may, therefore, be regarded as a rendering of the Babylonian designation "sheep omen" in the general sense above pointed out.

The objection may be raised at this point, why should not the moon and sun, as playing an equally if not more important rôle in divination lore, likewise have been designated as Lu-Bat in the generic sense of an "omen" or "auspicium"? The answer is obvious. Sun and moon cults are such ingredient parts of early forms of religion everywhere and the dependence of human fortune, life, health and welfare upon these two luminaries is so direct that other factors were at work in the development of conceptions regarding these two deities than merely the observation of their movements and changing relationship to one another as a basis for determining what these deities were preparing for mankind. Their cult precedes their introduction into divination texts, whereas the planets were observed solely for purposes of divination. Since the influence of the latter on human life was a matter of speculation rather than of direct experience, the basic and primary motive for noting their movements was in connection with the view that, as representing gods, their movements indicated the activity of these gods in preparing the events that were to happen on earth. The old and long established names and designations for sun and moon were accordingly retained, whereas the new term chosen for the planets was ordinarily restricted to them. Occasionally, however, so, *e. g.*, III. R, 57, No. 6, 65–67, sun, moon and the five planets are summarized as seven Lu-Bat (pl.).

That the association of ideas did not, on the other hand, lead to the extension of Lu-Bat to the stars in general constitutes no valid objection to the thesis here propounded. In the divination texts the number of stars introduced, outside of the planets, is not large and their role is quite secondary,[28] and it is not until we reach the period when astronomy becomes more definitely differentiated as a science from astrology, when calculations are made and "planet" tables are

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mark; and shows that he no longer fully understood the force of the Babylonian designation which he here faithfully reproduces.

[28] In astrological texts proper as distinguished from astronomical tablets, the stars mentioned are chiefly certain ones belonging to the constellations of the ecliptic and which are frequently introduced as guides and indications for fixing the position of the planets, rather than as omens.

prepared independently of divination, that star-lore assumes larger dimensions. Besides, in securing omens the positions of the stars constitute a minor factor and are of value chiefly, if not exclusively, in relationship to phenomena connected with the planets—a condition which is specially applicable to the relationship between the planets and the constellations of the zodiac.

Attention has already been called to the fact that although Lu-Bat is commonly applied to any planet, there are only two planets—Mercury and Saturn—that regularly appear written with this compound ideograph,[29] the former being designated as Lu-Bat Gu-Ud,[30] the latter as Lu-Bat Sag-Uš, while Mars occasionally appears as Lu-Bat Dir.[31] The other planets appear in the lists IIR, 48, 48–54 ab and IIIR, 57, No. 6, 65–67, as (il) Šul-pa-Ud-Du-a (Jupiter) (il) Dil-Bat (Venus) and Zal-Bat-a-nu (Mars), with Mul = *kakkabu* interchanging with an = *ilu*. Moreover, the phonetic reading bi-ib-bu in the latter list for Lu-Bat Gu-ud points to Mercury as being the planet *par excellence*. Why should Mercury have been assigned to this preëminent position among the planets? It has been suggested to me[32] that the position of Mercury nearest to the sun may have led to its being looked upon as the chief planet for purposes of divination and it is perhaps not without significance that in Greek astrology Mercury, frequently designated as στίλβων, "shining,"[33] is closely associated with the sun, and indeed at times identified with Apollo.[34] Certainly, the peculiar conceptions connected with Mercury in the astrology of the Greeks and of other nations—whose dependence upon Babylonian beliefs and speculations is generally admitted—sharply separate that planet from his fellows. While the others, *e. g.*, are conceived as masculine or feminine, Mercury, and Mercury alone, is double sexed.[35] Qualities are heaped upon Mercury in profusion,

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[29] See above, p. 141, note 2.

[30] Generally read Gud-Ud but the reading Gu-Ud seems preferable.

[31] See above, p. 141, note 2.

[32] By my friend, Mr. H. H. Furness, Jr., whose suggestion commended itself to my colleague, Professor C. L. Doolittle, Director of the Flower Observatory (University of Pennsylvania).

[33] Bouché-Leclercq, "L'Astrologie Grecque," pp. 66 and 100.

[34] *Ibid.*, p. 100, note 5.

[35] *Ibid.*, p. 102. So also in modern astrology. See Ellen H. Bennett, "Astrology" (New York, 1897), p. 98.

in contradistinction to the other planets to whom generally a single dominant trait is given. Intelligence, thought, feeling, eloquence, artistic spirit are all associated with Mercury,[36] which thus becomes, as it were, the "soul" among the planets and it will not seem far-fetched to see in the fancy which makes Mercury the planet of revelation and of language[37] a trace of primitive views regarding the seat of vitality. In accord with this, we actually find Mercury assigned to the liver[38] as the organ of revelation, though in deference to later views of the liver as the seat of the affections specifically—and not of *all* intellectual life and of *all* emotions—Venus is sometimes identified with this organ.[39] To be sure, such associations of ideas have not as yet been encountered in Babylonian texts and therefore a certain reserve is called for. On the other hand, the dependence of Greek astrology on Babylonian conceptions, fancies and prototypes is so evident at every turn[40] that we are justified in assuming a large measure of identity between the two systems of divination, just as, on the other hand, modern astrology is full of conceits and notions that can be paralleled in ancient Greece, India and Persia.

Another factor that may have led to assigning to Mercury a specially prominent place among the planets for purposes of divination is the circumstance that by virtue of its close position to the sun and its small size, it makes its circuit in the short space of twelve weeks and four days, or 87.97 solar days. Hence, since the basis of divination in the case of the planets is largely bound up with their relative position to the sun—upper conjunction, ascent, culmination, standstill, descent, lower conjunction[41]—Mercury would present a far larger proportion of changes in any given time than any other planet. In the case of frequent observations, Mercury would thus play a more prominent part than the other planets whose movements except for periods of some duration would furnish less of moment

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[36] Bouché-Leclercq, p. 101; Bennett, p. 99.

[37] Bouché-Leclercq, pp. 312, 321, 323.

[38] *Ibid.*, p. 312 and 323.

[39] *Ibid.*, p. 321.

[40] See Bouché-Leclercq's summary, pp. 70–71.

[41] See the valuable discussion in Kugler, *l. c.*, p. 20 f., of the Babylonian equivalents for those terms.

to the observer, dependent upon the naked eye. But whatever the reasons, we can only conclude from the fact that Mercury is the "sheep" *par excellence* that it was at one time singled out as *the* planet of revelation and that, therefore, it was in all probability the first planet whose movements were observed for the purpose of securing through them a means of determining what events the gods were preparing to take place on earth.

The designation of Saturn as *lulimu,* "ram," I am inclined to regard of secondary origin, that is to say, dependent upon the application of *bi-ib-bu* to Mercury—the latter term taken no longer in the sense of an "omen" but already as a specific and distinguishing designation. As companion piece, therefore, to Mercury as a "sheep," Saturn was called a "ram" just as the designation of the seven Maši-stars by the determinative Lu ("sheep")[42] is a secondary extension from Lu-Bat, limited originally to the planets. Saturn presents in almost every respect a contrast to Mercury. It is infinitely larger[43] in bulk, at a great distance from the sun, the most regular of the planets and the slowest in its motion, taking 10,759 days or 29.46 years to pass around the sun. In Greek astrology a preëminent position is accorded to Saturn,[44] which is expressed, for example, by making the planet the head and "brain" of the planetary world—reflecting the later view which placed the seat of the soul in the head,[45] while the association of Saturn with Mercury

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[42] Kugler, *l. c.,* p. 7.

[43] Jupiter alone is larger.

[44] Bouché-Leclercq, *l. c.,* p. 94 f. It is to be noted that Saturn is in Babylonian astrology called "the star of the sun" (as Diodorus, II., 30, also says)—which reminds one that Mercury (see above, p. 152) was identified with the sun in Greek astrology; the same appears to have been the case with Saturn. See Kugler, *l. c.,* p. 8.

[45] *Ibid.,* p. 95. The soul was placed successively (*a*) in the liver, (*b*) in the heart and (*c*) in the brain. "Liver" divination is the outward expression corresponding to the first stage. The addition of the "heart" (and then of other organs) to the "liver" in the examination of the sacrificial animal—as among the Romans—is a concession to the second stage, while phrenology is an expression—outside of the official cult—of the third stage. See Jastrow, "Divination through the Liver and the Beginnings of Anatomy" (*University of Pennsylvania Medical Bulletin,* January, 1907). In a special paper on "The Liver as the Seat of the Soul" I propose to treat in detail of these successive views.

crops out in the belief which makes the history of the world begin with the reign of Saturn and end with that of Mercury.[46] The prominence of Saturn in Babylonian-Assyrian astrological texts is in accord with this association with Mercury as a second Lu-Bat *par excellence.*[46a]

In modern astrology Saturn continues to play a particularly conspicuous rôle[47]—all of which points to its having been the first planet to become, by the law of contrasts, associated with the original "source" of divination among the planets—Mercury.

Lastly, a word regarding the ideographic designations of these two "sheep"—Mercury and Saturn. Kugler,[48] following in part Jensen,[49] proposes to take the element Gu-Ud in Lu-Bat Gu-Ud as *ḳarradu ša urri*,[50] "warrior of the light," because shortly after his appearance in the East day triumphs over night. The explanation seems forced and it is hardly likely that a circumstance like this should have suggested a name for a planet. In view of the fact that Mercury and Saturn are the two planets more particularly designated as Lu-Bat, it is more reasonable to see in Lu-Bat Gu-Ud and Lu-Bat Sag-Uš descriptions of characteristic features. For Sag-Uš, fortunately, the equivalent, *ka-a-ma-nu*,[51] has been definitely ascertained and the meaning "regular" is also beyond doubt. The name was clearly given to the planet because of the slow and regular motion which is its distinguishing feature. Mercury, on the

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[46] Bouchè-Leclercq, pp. 187, 498 f.

[46a] The statement of Diodorus (*l. c.*) that Saturn was regarded by the Babylonians as the most important for purposes of divination may correctly reflect a later stage when Saturn assumed the preëminent place once occupied by Mercury.

[47] Bennet, *l. c.*, p. 93.

[48] Kugler, *l. c.*, p. 10. On p. 218 he prefers the rendering "full of light" (as Hommel, Aufsätze, p. 381, does) but the two ideas ("full" in the sense of "strong" and "warrior") are correlated.

[49] "Kosmologie," p. 131, who takes Gud-Up as a single term = *ḳarradu* "warrior" (Br. 5742). It is always to be born in mind that we are to substitute Mercury for Mars throughout Jensen's volume—now that it has been definitely ascertained that Gud-Ud = Mercury and not Mars and Zal-Bat (a-nu) = muštabarru mutânu = Mars not Mercury.

[50] Gud = ḳarradu and Ud = urru (Br. 7798)—though ûmu = "day" would suggest itself as more probable.

[51] See Jensen, *l. c.*, p. 114. Cf. כיון in Amos 5, 26.

other hand, is marked by its rapid and irregular course and I accordingly propose the equation Gu-Ud = *šaḫâtu*—a common value of the compound ideogram in "liver" divination texts in the sense of "hinder, check, restrain."[52]

Assuming the adjective formation *šahtu* from this stem, the "checked" one as the designation of this planet would form a companion piece to *kaimanu*, the "regular" one. In contrast to *kaimanu* "regular," the designation *šaḫtu* would, naturally, convey the notion of a body checked and restrained and therefore "irregular" in its motion.[53]

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[52] Cf. Jastrow, II., p. 366, note 9.

[53] The gloss in Hesychius according to which *βελέβατος* is in Babylonian the "fire" star cannot be explained as Jensen "Kosmologie," p. 97, proposes, since he starts from the false assumption—since abandoned by him—that *bibbu*—the Lu-Bat *par excellence* is Mars, whereas it is Mercury. That *βελέβατος* designates Mars is however no doubt correct and since the common ideographic designation for Mars is Zal-Bat—the addition of a-nu being a phonetic complement to suggest the phonetic reading *muštabarru mutânu*, "the one satiated with death"—the correction of *βελέβατος* to *ζελέβατος* suggests itself as a simple solution of the problem.

# FURTHER RESEARCHES ON THE PHYSICS OF THE EARTH, AND ESPECIALLY ON THE FOLDING OF MOUNTAIN RANGES AND THE UPLIFT OF PLATEAUS AND CONTINENTS PRODUCED BY MOVEMENTS OF LAVA BENEATH THE CRUST ARISING FROM THE SECULAR LEAKAGE OF THE OCEAN BOTTOMS.

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*(Read April 24, 1908.)*

## I. General Considerations on the Physics of the Earth, with Especial Reference to the Secular Leakage of the Oceans and the Resulting Development of Mountains, Plateaus and Islands.

§ 1. *Introductory Remarks.*—In three papers recently communicated to the American Philosophical Society held at Philadelphia and since published in the proceedings of that Society,[1] the writer has treated at some length of the cause of earthquakes, moun-

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[1] 1. "The Cause of Earthquakes, Mountain Formation and kindred phenomena connected with the Physics of the Earth," Proc. Am. Philos. Soc., 1906.

2. "On the Temperature, Secular Cooling and Contraction of the Earth, and on the Theory of Earthquakes held by the Ancients," Proc. Am. Philos. Soc., 1907.

3. "The New Theory of Earthquakes and Mountain Formation as illustrated by Processes now at work in the Depths of the Sea," Proc. Am. Philos. Soc., 1907; issued in March, 1908.

The following shorter articles have also appeared:

4. "Outline of the New Theory of Earthquakes," *Popular Astronomy,* April, 1908.

5. "How the Mountains were Made in the Depths of the Sea," *Pacific Monthly,* Sept., 1908.

tain formation and kindred phenomena connected with the physics of the earth. In the course of these three memoirs many important questions are considered, and it seems to be rendered highly probable that six great classes of phenomena, not heretofore closely associated, depend on a single physical cause, namely, the secular leakage of the ocean bottoms, and the resulting movement of molten rock beneath the earth's crust. The six classes of phenomena traced to a single physical cause are: (1) world-shaking earthquakes; (2) the activity of volcanoes; (3) mountain formation; (4) the formation of islands and plateaus; (5) seismic sea waves; (6) the feeble attraction of mountains and plateaus long noticed in geodesy.

The first of the memoirs printed by the American Philosophical Society deals with the problem of earthquakes in its general aspects, and sets forth grounds for the theory that these six classes of phenomena are directly connected and dependent on a single physical cause; the second examines the question of the earth's temperature, secular cooling and contraction, and endeavors to show that the traditional theory of the changes noticed on the earth's surface is not well founded; while the third seeks to demonstrate the more important conclusions reached in the first memoir, by an appeal to processes now at work in the depths of the sea, the meaning of which apparently is so plain as to admit of no possible doubt.

The change in the point of view necessitated by the considerations brought forth in these papers is so remarkable as to be worthy of the attention of all who are interested in the grand science of natural philosophy. And we therefore propose to consider in this paper the physical basis of the theory of ocean leakage, the folding of mountain ranges and the uplift of plateaus and continents produced by movements of lava beneath the crust, together with the historical aspects of the problems of the physics of the earth. Heretofore the nature of the forces which have folded mountain ranges and their relationship to those slow movements which have raised whole continents have been equally mysterious and bewildering to the investigator. Accordingly any light which may be shed on this difficult subject will no doubt be exceedingly welcome to those who are interested in the progress of the physical sciences.

As the leakage of the oceans seems to be clearly proved by the movements noticed in earthquakes, especially where mountain formation is now going on in the depths of the sea, and the seismic disturbances are therefore accompanied by the sinking of the sea bottom, as shown by the seismic sea waves which follow the earthquakes, it seems legitimate to appeal to these movements of molten matter beneath the earth's crust as the only available means of demonstrating the porosity and other physical properties of layers of granite twenty miles thick. Owing to the restricted conditions of human life, no experiments on such a grand scale can ever be attempted in our laboratories, however great the facilities at our command; and our only means of ascertaining the truth with regard to the theory of ocean leakage is by careful observation in the great laboratory of nature. The leakage of the oceans involves three important questions: (1) The porosity of thick layers of matter such as those composing the earth's crust; (2) the penetrability of the crust under steady fluid pressure, by which the capillary forces are made to aid the molecular forces producing penetration of the fluid; and (3) the accumulation of stresses depending on the formation of steam in the layers just beneath the earth's crust.

The conditions existing in nature can scarcely be approximated in our laboratories, on account of the limitations of the forces at our command, but so far as experiments throw light on these great questions, the evidence tends to confirm the theory of ocean leakage. The well-known experiments of Daubrée, showing that under the action of capillary forces hot water will penetrate a layer of sandstone against a strong counter pressure of steam, and by entering a cavity actually increase the steam pressure on the further side, has been justly held to afford evidence of the leakage of the earth's crust, and of the probable mode of volcanic activity. If such action is possible in a minute way, it may easily operate on a vastly greater scale to produce the shaking of the crust in earthquakes, together with the uplift of mountains and the occasional outbreak of volcanoes.

Now if the rock of the earth's crust is at all as porous as we generally think, the constant pressure of the vertical column of water, often miles deep, resting on the ocean bed must tend to force the fluid deeper and deeper into the bowels of the earth. A study of what takes place on our earth under the observed conditions constitutes therefore one of the grandest problems in natural philosophy.

Indeed it may be said that the great laboratory of nature has magnificent experiments constantly going on. All that we need to do is to interpret these experiments correctly. The best way to do this is to select phenomena in which the processes are so clear as to be free from doubt; after we have found the law of the phenomena in cases which are beyond question, we may then generalize and interpret other phenomena, in which the relations are not so obvious. By gathering principles and laws from cases which are entirely clear, and working by degrees to understand those which are more obscure, we may finally arrive at the true processes even when the operations of nature are quite hidden from our view.

Laws thus established by observation in the great laboratory of nature will obviously hold true of like experiments in the minute physical laboratories designed by man; and by noting the phenomena of the globe we may extend our knowledge of the universal properties of matter under various physical conditions often more extreme than those ordinarily witnessed at the surface of the earth.

§ 2. *Heretofore the ocean bottoms have been assumed to be water-tight.*—The earth's crust is made up chiefly of sedimentary, igneous and granitic rocks, and soil produced by the decomposition of the various kinds of rock under the action of water and the atmosphere. Nearly all of the sedimentary rocks are quite leaky, and moreover they absorb a great deal of moisture from the air; the formation of artesian wells and of natural springs depends primarily upon the percolation of water through rocks and layers of soil of various kinds. The leaky character of the sedimentary rocks is well known and has been generally recognized. But these rocks exist only near the surface, and do not extend more than a very few miles deep; consequently they could admit the water to but a slight depth into the earth's interior. Below the sedimentary rocks lies the mass of granite which makes up by far the greater part of the earth's crust. The granitic rocks, such as granite, andesite, diabase, etc., are by no means so penetrable as the sedimentary rocks, and hence water has more difficulty in passing through them. And as the layers of this material composing the earth's crust are about fifteen miles deep, it has been generally held that water would have difficulty in making its way down into the heated layers just beneath the crust.[1] Indeed it has been practically assumed that the ocean bottoms are water-tight, in spite of the great fluid pressure constantly exerted by the mere depths of the water over a large part of the bottom of the sea. This fluid pressure in many places is great enough to throw a column of water to the free surface, over five miles high; and it operates not only from day to day, year to year, but also from century to century, age to age. If granite is at all penetrable by water, is it therefore any wonder that a gradual secular leakage should go on, and at length, by a kind of slow perspiration of the stone, give rise to sufficient accumulation of steam beneath the crust to produce a swelling of the saturated mass, and require a readjustment of the overlying rocks?

Now it happens that by nature all the granitic rocks are crystalline, and thus somewhat coarse-grained in structure; so that they absorb water from the ground and moisture from the air. The crystalline structure permits penetrability to a greater degree than would fine-grained and very hard rocks such as agate; but no rock has such fine pores as the metals, and especially vitreous bodies like glass, to which agate is an approximation. And as all the metals are proved by experiment to be leaky under great fluid pressure, and glass is shown to obey the same law, it obviously follows that all rocks are leaky under great fluid pressure. Consequently under the incessant pressure of the oceans water must make its way into the heated layer just beneath the earth's crust.

Heretofore the possibility of earthquakes cracking the ocean bottom has been generally recognized, but it has been held that

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[1] This statement is perhaps too positive, for Sir William Ramsay, the celebrated British Chemist and Physicist, writes me that he has long believed that the ocean bottom leaks and that the formation of minerals takes place chiefly in the bed of the sea. Undoubtedly this view will come to be generally accepted. Similar views seem to be held by Lord Rayleigh, Sir Wm. Huggins, Arrhenius and many other eminent physicists.

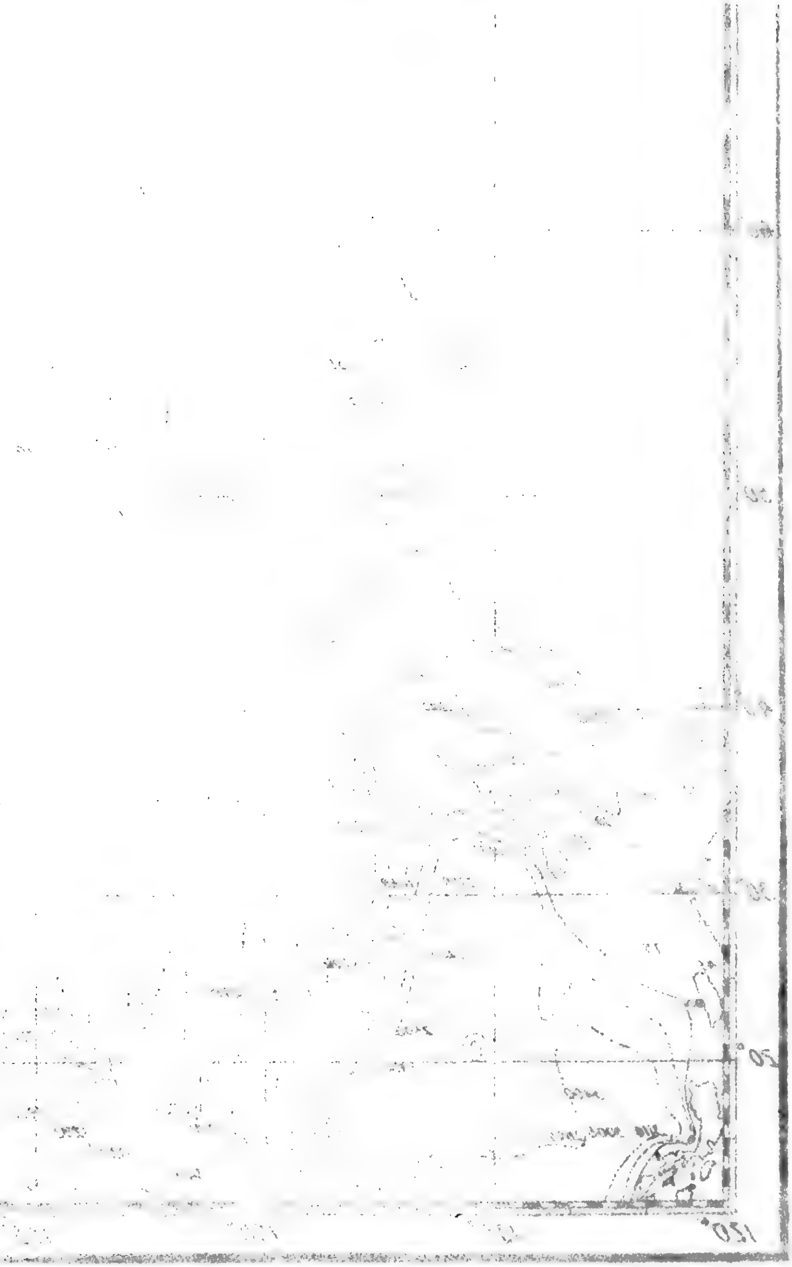
crevices thus formed would not extend over five or six miles deep before they would be closed by the effects of pressure, which naturally increases rapidly as we descend into the earth. The belief has therefore prevailed that although the bed of the sea might be rent by an earthquake, it would immediately close up again, and water would thus be prevented from entering the bowels of the globe.

It scarcely seems to have occurred to investigators to consider the effects of the constant hydrostatic pressure resulting from the depth of the sea, in forcing the water slowly through the fifteen miles of granite composing the earth's crust. A crevice is small, and would let in but little water when closed up quickly; but the whole sea bottom is large, and unless it is really water-tight, even a slow leakage over a large area would at length develop stresses beneath which would necessitate a readjustment of the overlying blocks of the crust. This readjustment is ordinarily called an earthquake.

Moreover the great abundance of submarine earthquakes has been largely overlooked by previous investigators. It is the secular effect of the constant pressure of the oceans and of capillary forces in promoting the downward movement of the water which has been generally lost sight of.

But if we admit on the basis of experimental evidence that water can penetrate thin layers of granite, the question naturally arises: Can it also penetrate a layer of granite fifteen or twenty miles thick? It seems obvious that it can, because for small or moderate pressures water is nearly incompressible and would not sensibly increase in density as it went down into the globe. The fluid which passed through the upper layer of granite would therefore keep on descending, under the increasing fluid pressure from above, and at length the whole layer would be saturated, and perspiring below with a steady leakage which would give rise to tremendous steam power in the underlying molten rock. Thus great stresses due to slow accumulation of steam would develop in the layer just beneath the crust, and this would give rise to earthquakes and mountain formation.

Among the practical men of science to whom the problem of ocean leakage was submitted, we might name some of the most



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eminent of living physicists. While disclaiming especial authority to pass upon such a question, they expressed the opinion that it was very improbable that the ocean bottom could be water-tight, unless the nature of the rock was greatly modified by pressure, which could hardly be the case in the first twenty miles of the earth's crust, where the pressure does not exceed 8,600 atmospheres.

Whatever doubt might attach to this solution of the problem, from an experimental standpoint, where positive knowledge is greatly lacking, seems to be dispelled by the phenomena noticed in the sea bottom in various places, which show that lava is expelled from beneath the sea and pushed under the adjacent land. The phenomena noticed in the laboratory of nature thus prove the leakage of the ocean from an observational standpoint, because they admit of no other interpretation.

§ 3. *The Theory of Water-tightness of the Ocean Bottoms Disproved by the Expulsion of Lava from under the Sea.*—Just south of the Aleutian Islands, a long, narrow and deep trench just parallel to this chain has been dug out by the expulsion of lava from beneath the sea. The nature of this trough is illustrated by the accompanying Map.

It will be seen that the island chain adjacent to the trough dug out in the sea bottom is really a mountain range under water, with only occasional peaks projecting above the water as islands. In fact the Aleutian Islands are a continuation of the Alaskan Mountains which are part of the Rocky Mountain System, and the range here continues into the sea. If therefore the Aleutian Islands are mountains now in process of formation in the sea, it would seem to follow logically that the Rocky Mountains and Andes, from Alaska to the straits of Magellan, were formed in the same way. What then is the process at work forming the Aleutian Islands?

It is evident that the deep trench south of the islands has been dug out by the expulsion of lava from under the sea and its injection under the Aleutian ridge; this is accomplished by earthquakes, and the process is still in full operation at the present time. This region is a well-known breeding-ground for world-shaking earthquakes and seismic sea waves. Several islands have been uplifted since 1783, and one or more new volcanoes have broken out within the historical period. The seismic sea waves following the earthquakes which affect this region indicate that the sea bottom often sinks after these disturbances. In other words, when lava is expelled from under the trench and pushed under the adjacent ridge, the bottom gives down to secure stability. The processes now going on have been at work through immense ages, and have thus dug out the trough parallel to the Aleutian Islands, and at the same time elevated this ridge, till it is now partly above the water, thus constituting the chain of islands.

In like manner the great earthquake at Yakutat Bay, farther east, September 3–20, 1899, which was so carefully investigated by Tarr and Martin (*Bulletin of the Geological Society of America*, May, 1906) raised the coast for about 100 miles; the maximum elevation being 47⅓ feet. Subsidence also occurred in a few places. Such a vast movement of the coast indicates an enormous expulsion of molten rock from beneath the sea under the land. It is these subterranean movements beneath the earth's crust which shake down cities and devastate whole countries. During the earthquake at Yakutat Bay the shaking was so terrible that persons could not stand on their feet; avalanches slid down the mountains, and glaciers were carried into the sea. This is the true nature of earthquakes, and one need not therefore be surprised at the devastation produced. The force which pushes lava under the land, overcoming the weight of the crust, naturally destroys cities and all the frail works of man built upon the surface.

§ 4. *Physical Experiments on the Porosity of Matter.*—Modern science presents many illustrations of the *porosity* of matter. In fact so many experiments illustrate *porosity* that it is difficult to find proof of the general property of *impenetrability* cited by Newton in the "Principia," except under the narrow limitations that the matter in question remains cold and the forces to which it is subjected are small. With increasing fluid pressure and rising temperature all matter is leaky; and in general a rise of temperature expands and thus augments the penetrability and porosity of all substances. *We may therefore say that all matter is porous and leaky under great fluid pressure, and impenetrability does not exist except* *under very restricted conditions, so that it is not a general property of matter as was once supposed.*

In the early days of physical science the demonstration of the porosity of such dense bodies as gold, silver and lead was considered a great achievement. In 1661 some academicians at Florence, repeating an earlier experiment of Bacon with a spherical shell of lead, filled a hollow sphere of solid gold with water, and, after sealing it hermetically, flattened the figure of the spherical shell in a hydrostatic press so as to diminish the volume. Under this deformation of the sphere the water was forced through the walls of solid gold and formed in drops on the outside. Corresponding experiments were made with spheres of silver, lead, and other metals, with analogous results. Modern engineering presents innumerable illustrations of the porosity and leaky character of structures made of the hardest bodies. Under great pressure all pipes and pistons leak, and put a limit to the applications of hydrostatic pressure.

In 1883 Amagat forced mercury through plates of solid steel three inches thick, under a pressure of about 4,000 atmospheres. This is the highest pressure hitherto applied in physical experiments, and yet all rocks are subjected to such pressure at a depth of only ten miles below the earth's surface. In the measurement of ocean depths it has been found that empty hollow glass balls with walls half an inch thick sent down with the deep sea apparatus come up more and more completely filled with water, according to the depth of the sea and the duration of the experiment. As glass is the most impervious of solid bodies, this leakage, which it shows under the external application of fluid pressure from the deep sea, is a good illustration of what happens to the bed of the ocean, which is constantly subjected to this pressure. No rock is anything like so impervious as glass, and consequently a general leakage of the ocean bottom inevitably takes place. The water which first enters the bed of the sea will keep on descending till it comes into contact with rock at high temperature, which produces and readily absorbs steam. When the rock becomes saturated with steam it swells and requires more space, and this finally brings on an earthquake. Hence also the preponderance of great earthquakes under the sea and the almost total absence of these disturbances far inland.

§ 5. *Important Criterion for the Nature of the Movement Beneath the Earth's Crust furnished by Seismic Sea Waves.*—In the paper on the "Cause of Earthquakes" we divided seismic sea waves into two general classes: the first, due to the sinking of the sea bottom, and characterized by a withdrawal of the water after the earthquake, to be followed later by the return of a great wave; the second, due to the uplift of the bottom, and characterized by the sudden rise of the sea without any previous withdrawal from the shore. Both classes of these waves exist in our seas, but those of the first class are the most dangerous and the most important. Most of the great historical inundations by the sea have been due to waves of the first class. The phenomena usually noted are: first, a terrible earthquake; second, after a short interval, the sea is noticed to be slowly draining away, laying bare the bottom, where it ordinarily is deep enough to anchor ships; third, after an interval of an hour or so, the sea is seen to be returning as a mighty wave, carrying everything before it, and thus washing the ships inland and stranding them high and dry; fourth, having once swept the shore, the sea again withdraws and lays bare the harbor as before, and after about the same interval again returns as a second great wave. This periodic movement of the sea may be kept up for quite a while, and sometimes quiet is not restored for a day or two.

Among the many well-known historical sea waves of the first class which might be mentioned, we shall cite only a few typical cases: As that which overwhelmed Helike in 373 B. C. (see the paper on the "Temperature of the Earth," § 23, pp. 269–272, and Addendum, pp. 291–298); the wave at Callao in 1746; the wave following the Lisbon earthquake in 1755; the waves of Arica, 1868, and Iquique, 1877; the wave on the Japanese coast in 1896. In all these cases the water first withdrew from the shore; not suddenly, but slowly, as in the draining away of a tide, though somewhat more rapidly; this of course indicated that the sea bottom had sunk, and the water was draining away to fill up the depression in the level caused by the drop of the bottom. When the currents meet at the center an elevation is produced by their mutual impact, and when this collapses under gravity the first great wave comes ashore. The elevation then subsides into a depression as at first, and the currents again flow in and force up the level a second time; and with the second collapse another wave is sent ashore; and so the oscillation of the sea continues, sometimes for a day or two before it finally quiets down.

Now these sea waves of the first class furnish an exceedingly important criterion as to the nature of what is going on beneath the earth's crust. The sinking of the sea bottom often happens in the deep trench south of the Aleutian Islands, and repeated drops of this kind have obviously produced the deep trough parallel to these islands. For it is observed that the earthquake usually raises one or more of the islands to the north, when the sea bottom sinks to the south. Now the islands could not be upraised unless something was pushed under them, and the bed of the trough could not sink down unless it was in some way undermined. Accordingly it follows that molten rock is expelled from beneath the bed of the trough to the south and pushed under the adjacent islands to the north, which are thus uplifted. The bed of the sea often sinks during the earthquake arising from this subterranean movement, and then the water withdraws from the shore and afterwards returns as a great seismic sea wave. It will be observed that the subcrustal movement is from the sea towards the land, because steam accumulates under the ocean, but scarcely at all under the land.

Thus these seismic sea waves become very important criteria for determining whether the sea bottom has sunk; and if it has sunk we know that lava was expelled from under the sea and pushed under the land. Seismic sea waves therefore may be regarded as *very delicate levels,* for determining the movement of the sea bottom; and from the nature of this movement we can often decide what the effect of the earthquake has been. Moreover these waves enable us to tell with certainty that the chief function of earthquakes is the elevation of the land along the coast by the expulsion of lava from beneath the bed of the sea. It is not too much to say that the true nature of earthquakes and their function in the uplift of mountains and plateaus could not be certainly made out except for the exceedingly important criterion furnished by seismic sea waves.

§ 6. *Additional Phenomena Noticed near the Aleutian, Kurile and Japanese Islands, and the Antandes.*—South of the Aleutian chain, as just remarked, a well-known earthquake belt parallels these islands, and the seismic disturbances occurring there are frequently followed by seismic sea waves of the first class. Soon after a great earthquake the water is seen to be withdrawing from the shore, and after a short interval of time it again returns as a mighty wave sweeping everything before it. Many volcanoes have broken out in these islands and several new islands have been uplifted within the historical period. The Russians long ago connected the earthquakes with the volcanoes in the Aleutian Islands. In later years the exact survey of the sea bottom has shown that it is sunk down into a narrow trough right under the earthquake belt. Just parallel to the trough the islands form a real mountain ridge under water, with only a few of the highest points projecting above the surface as islands. The uplift of these islands therefore denotes the uplift of mountain peaks, some of which have become volcanoes.

Now if the earthquakes are accompanied by the uplift of islands and the sinking of the sea bottom, as shown by the seismic sea waves, it follows that the uplift of the ridge is connected with the sinking of the adjacent sea bottom. As the ridge is just contiguous to the trench, and the earth is terribly shaken every time these disturbances occur, it seems to indicate that matter is expelled from under the trench and pushed under the ridge; so that the ridge is elevated and the trench sinks down correspondingly. This could not occur without the bodily transfer of matter beneath the earth's crust, and the shaking of the earth is due to this expulsion of lava from under the trench, and its injection under the ridge. This is the only possible explanation of the observed elevation of the ridge and the sinking of the trench. In this way the trough near the Aleutian Islands has been gradually dug out. Similar troughs have been formed by earthquakes near the Kurile and Japanese Islands, as we know by the observed depth of the sea, the lay of the earthquake belt parallel to these islands, and the occurrence of the seismic sea waves, showing that the sea bottom sinks after the earthquakes by which the region is afflicted. If the islands of Japan were dug off and thrown into the Tuscarora Deep, they would about fill it up.

Therefore all these islands were formed by the expulsion of lava from under the sea, and the subsequent sinking of the sea bottom has given rise to the deep troughs now found in that part of the ocean.

In the same way there is an earthquake belt between Samoa and New Zealand, and the sea bottom is sunk down into a deep trough, parallel to a ridge on the west, on the opposite side of the trench from the ocean. This ridge is a new mountain range 1,200 to 1,500 miles long, now forming on the west of the Pacific, just as the Andes were once formed on the east. Lava is being expelled from under the trench and pushed from the ocean towards the ridge on the west. This is developing into a new mountain range, which we shall call the *Antandes,* because it is being formed opposite to the Andes, on the other side of the Pacific, and in the same manner as the mighty mountains in South America were in earlier geological time. In the course of immense ages the Antandes will rise above the water as a mighty chain on the west of the Pacific just like the Andes on the east.

*These phenomena in the sea bottom show the real process of mountain formation at various stages of its progress, and prove to us that most of the folding observed in our mountain ranges now on land really took place in the bed of the sea, long before the whole range was raised above the water.* For this sinking and upheaval of adjacent portions of the sea bottom would crumple the rocks exactly as they are observed to be in all mountain ranges; and moreover the several parallel ranges so often observed would result from the development of several parallel troughs, all of which are eventually uplifted. It will be observed that the expulsion of lava is always from the sea towards the land, and this shows that the sole cause of the movement is the leakage of the ocean. It thus follows that mountains, plateaus, and islands are uplifted by earthquakes depending on the leakage of the oceans, and by nothing else.

§ 7. *The Andes with their high Plateaus Merely a Vast Wall Erected by the Pacific.*—It may sound strange to say that the cordillera of the Andes is a vast wall erected by the Pacific Ocean along its border; but to the navigator who traverses the shore from Panama to Cape Horn such a description will seem most appropriate.

FIG. 1. Relief Map of South America. (From Frye's Complete Geography, by permission of Ginn & Co., Publishers.) Notice that the Andes are a mighty wall erected by the Pacific Ocean along its border. Professor Charles Burkhalter, Director of the Chabot Observatory, Oakland, kindly suggested the use of these relief maps, which are well suited for bringing out the leading characteristics of the different continents.

Throughout the length of the continent the mountains are everywhere parallel to the coast, and run at nearly a constant distance from the shore. The Andes are not always a simple chain, but they are narrow relatively to their height, as compared to the other mountains. In many places there are two or more ranges with narrow plateaus between. These plateaus are so interwoven with the mountains themselves that we may feel sure they were formed together and represent a part of one general movement. Unless this were so it is impossible to believe that so many narrow and high plateaus would be enclosed between mountain walls on either side. The eastern cordillera is less volcanic than the western, and the eastern slope is believed by Professor Solon I. Bailey of Harvard College Observatory, who has exceptional opportunities for judging of these mountains, to be two or three times steeper than the western slope.

If we suppose a sea trough was first dug out in the elevation of the eastern range, and eventually when deep sediments had accumulated in the trough, the western edge of it was folded up to form the western range, and the trough itself became the plateaus, we shall have very nearly a true picture of how the Andes were formed. The full details of this process cannot be given now, but there is no doubt that the Andes are a vast wall erected by the Pacific along the edge of the continent. This origin of these mountains is also indicated by the earthquakes observed within historical time; for the coast has been again and again upraised by these disturbances, while the sinking of the sea bottom, indicated by the accompanying seismic sea waves, shows that the bed of the ocean is being undermined by the expulsion of lava under the land. The shells, fossils, and other evidences of marine life now found at altitudes as high as 15,000 feet show that the uplifting at present going on is but a part of the greater uplift of past geological ages; so that the great movement which formed these mountains and plateaus is identical with the earthquake disturbances noticed within historical time.

§ 8. *The uplift of mountains and plateaus around the margins of the Pacific, and of islands in the interior, with innumerable submarine eruptions everywhere, is nature's way of indicating leakage* *through twenty miles of crust.*—The peculiar position of the sea bottom between a molten globe and the overlying ocean is such that any disturbance of the bottom, as in a volcanic eruption, would naturally excite our suspicions that the crust had leaked and brought the water into contact with the underlying ball of fire. The situation of the overlying ocean, with the fire so close beneath, is much the same as that of the water above the furnace of a boiler, in which steam is developed; and if one had the molten globe for a furnace and the ocean for a reservoir of water, leakage would develop steam on a grand scale, and give rise to mighty experiments exactly resembling earthquakes and volcanic eruptions. Some of these disturbances might take the form of uplifts of the crust into islands, mountains and submarine volcanoes, others near the edges of the sea would cause lava to push out under the land and raise the coasts.

Now the Pacific Ocean is everywhere surrounded by high mountains, as if the lava had been pushing out at the margins of the sea. And throughout the interior a vast number of islands are raised up in deep water, and every part of the ocean is from time to time disturbed by terrible earthquakes. One must therefore admit that the ocean has the aspect which might be expected to result from a leakage of the ocean bed. Moreover the Pacific is surrounded nearly everywhere by volcanoes, which emit chiefly vapor of steam. If it is shown that mountains are formed by earthquakes, chiefly in the expulsion of lava under the land, and some of the mountains break out into volcanoes, then there will obviously be a connection not only between earthquakes and volcanoes, but also between the vapor of steam emitted from these smoking mountains and that formed under the ocean by the leakage of the bottom.

It is this intimate connection between all the related phenomena which tells so powerfully in favor of the view that the leakage of the ocean takes place through a layer of rock twenty miles thick. The height of the mountains and plateaus is but a small fraction of the thickness of the crust, and movement in the underlying layers therefore usually gets relief without breaking through. The crust of the globe is thick enough to offer great resistance to uplift, so that the steam saturated lava usually adjusts itself beneath without a surface eruption. Yet where the crust is sharply upheaved as in mountains, volcanoes sometimes break out. But it is obvious that earthquakes are the more general, volcanoes the more special phenomena; and that both are connected with mountain formation, and depend on the sea for their continued activity.

§ 9. *On the Structure of Granite as a Typical Crystalline Rock of the Earth's Crust.*—Granite has a thoroughly crystalline structure, and is an admixture of feldspar, mica, and quartz. The mica is in the form of minute shingles, or snowflakes, embedded in the non-crystalline matrix of quartz, which encloses the other elements. The feldspar is chiefly orthoclase. The two chief ingredients, quartz and feldspar, form a granular aggregate made up of grains of fairly equal size, varying all the way from several inches in diameter to a structure so fine as to be inseparable to the naked eye.

> "Many granites contain irregularly shaped cavities (miarolitic structure), in which the component minerals have had room to crystallize in their proper forms, and where beautifully terminated crystals of quartz and felspar may be observed. It is in these places also that the accessory minerals (beryl, topaz, tourmaline, garnet, orthite, zircon and many others) are found in their best forms. Not improbably these cavities were somewhat analogous to the steam holes of amygdaloids, but were filled with water or vapour of water at high temperature and under great pressure, so that the constituents could crystallise under the most favorable conditions. Among the component minerals of granite, the quartz presents a special interest under the microscope. It is often found to be full of cavities containing liquid, sometimes in such numbers as to amount to a thousand millions in a cubic inch and to give a milky turbid aspect to the mineral. The liquid in these cavities appears usually to be water, either pure or containing saline solutions, sometimes liquid carbon-dioxide" (p. 143). (Sir A. Geikie, "Geology," p. 204.)

The cavities in crystalline rock such as granite may contain either gas or liquid matter, and sometimes both. Professor Tilden's researches have shown that the included gases (hydrogen, carbon dioxide, carbon monoxide, marsh gas, nitrogen, and water vapor) may exceed many times the volume of the rock itself. The cavities have all manner of forms, branching, oblong, curved, oval, spherical and negative crystalline shapes, and are often so numerous as to give a turbid aspect to the mineral. The intersecting planes of the crystalline granite frequently present real fissures more or less filled with liquid. Obviously capillary forces may here attain great importance, and fluid entering the rock would be absorbed into these spaces with irresistible power. Geikie remarks that the cavities in quartz have all sizes from the coarse pores visible to the naked eye to minute spaces less than 1/10,000 of an inch in diameter, which can be seen only under high magnifying power.

Now it is worth while to remember that small as are the least cavities and fissures which we can see with the microscope, they are very large and coarse compared to the molecular structure of a fluid such as water or of a solid like glass. It is useful to remember that the limit of naked eye vision is about 1/250 of an inch, and of the most powerful microscope about 1/100,000 of an inch. The microscope therefore increases our power of vision about 400 times. (Cf. Prof. A. A. Michelson's "Light Waves and their Uses," p. 30.)

§ 10. *On Lord Kelvin's Determination of the Size of Atoms.*—In order to form a clear conception of the physical constitution of the matter composing the crust of the globe, we must recall the lines of research by which Lord Kelvin has determined the size of atoms.

1. By determining the work done or heat produced in bringing thin plates of zinc and copper together. The observed amount of heat evolved when the plates are made of given thickness and afterwards imagined to be thinner and thinner, limited only by the condition that the mass shall not be melted, under the heat of combination, which is not indefinitely great even when brass is produced by fusing zinc and copper, but corresponds to the mutual attraction of a number of plates not more numerous than 100,000,000 to the millimeter; hence it follows that the molecules are at least 1/1,000,000,000 cm. and probably more than 1/400,000,000 cm. in diameter. Lord Kelvin concluded that "Plates of zinc and copper 1/300,000,000 of a centimeter thick, placed close together alternately, form a near approximation to a chemical combination if indeed such thin plates could be made without splitting atoms." He fixed 1/1,000,000,000 of a centimeter as the minimum diameter of the atoms found in this way. It is to be remembered here that 2.54 centimeters = 1 inch.

2. By the study of Newton's rings on soap bubbles as they become thinner and thinner, the thickness of the film being reckoned from the known wave-length of the reflected light. Unless the film materially weakened when a certain limit is attained, it could not be stretched beyond a certain thickness without volatilizing, if

maintained at the same temperature; for as it expands it cools, and the heat that would have to be supplied to it would be more than sufficient to vaporize it. Now it is found by observation that the intensity of the surface tension of the film of water falls off before the thickness is reduced to 1/200,000,000 cm., and hence there probably are but few molecules in that thickness.

3. By the phenomenon of dispersion in the wave theory of light. Cauchy showed that dispersion of colors implied a granular structure in refracting media, and that the grains could not be indefinitely small, but must exceed 1/10,000 of the shortest wave length; and to produce the observed effect Lord Kelvin concluded that the number of molecules in a wave length would have to be from 200 to 600. Nobert ruled lines on glass at the rate of 40,000 to the centimeter,[2] or about two to the wave length of blue light (about 4/100,000 centimeter); and as this left the ruled surface capable of reflection, the number of molecules in the ridges between the grooves must have been sufficient to give solid body to the sculptured mass, and thus not less than several hundred to the wave length. If the mean free path in a solid like glass be 25 times the diameter of the atom itself, this will make the diameter of the atoms of the order of 1/400,000,000 of a centimeter.

4. By calculating the length of the average free path of a molecule in a gas, according to the kinetic theory. Loschmidt in 1865, Stoney in 1866, and Lord Kelvin in 1870, independently reached similar results, namely, for the average free path about 1/100,000 of a centimeter, and for the diameter of the gaseous molecule about 1/500,000,000 of a centimeter.

These four methods of estimating the diameter of atoms thus agree very closely among themselves; and moreover a similar result on the average distance of molecules deduced by entirely different

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[2] Referring to Nobert's lines Maxwell says: "A cube, whose side is the 400th of a millimetre, may be taken as the *minimum visible* for (microscopic) observers of the present day. Such a cube would contain from 60 to 100 million molecules of oxygen or nitrogen" (cf. The article "Atom," Encyclopedia Britannica, ninth edition, p. 42). If there be 400 molecules in a line the length of the edge of the cube just considered, the cube would contain 64,000,000, which agrees with Maxwell's estimate. A line equal to the wave length of blue light would thus contain 250 molecules.

considerations was obtained by M. Lippmann, in a paper read to the Paris Academy of Sciences, October 16, 1882.

In his "Popular Lectures and Addresses" (vol. 1, p. 224) Lord Kelvin condenses his conclusions as follows:

> "The four lines of argument which I have now indicated lead all to substantially the same estimate of the dimensions of molecular structure. Jointly they established, with what we cannot but regard as a very high degree of probability, the conclusion that, in any ordinary liquid, transparent solid, or seemingly opaque solid, the mean distance between the centres of contiguous molecules is less than the 1/5,000,000 and greater than the 1/1,000,000,000 of a centimeter.
>
> "To form some conception of the degree of coarse-grainedness indicated by this conclusion, imagine a globe of water or glass, as large as a football,[1] to be magnified up to the size of the earth, each constituent molecule being magnified in the same proportion. The magnified structure would be more coarse grained than a heap of small shot, but probably less coarse-grained than a heap of footballs."

§ 11. *On the Molecular Constitution of Matter and on the Penetrability of Solids by Fluids.*—In his address on "Mathematical Physics" at the St. Louis Congress of Arts and Sciences in 1904, Poincaré speaks of the porosity of matter as follows:

> "The astronomical universe consists of masses, undoubtedly of great magnitude, but separated by such immense distances that they appear to us as material points; these points attract each other in the inverse ratio of the squares of their distances, and this attraction is the only force which affects their motion. But if our senses were keen enough to show us all the details of the bodies which the physicist studies, the spectacle thus disclosed would hardly differ from the one which the astronomer contemplates. There too we should see material points separated by intervals which are enormous in comparison with their dimensions, and describing orbits according to regular laws. Like the stars proper, they attract each other or repel, and this attraction or repulsion, which is along the line joining them, depends only on distance." (Cf. *Bulletin of the American Mathematical Society,* February, 1906, p. 241; authorized translation by Professor J. W. Young.)

Professor Sir G. H. Darwin's recent presidential address to the British Association for the Advancement of Science at Cape Town, 1905, was devoted largely to the discovery of electrons. After treating of these subatomic corpuscles he adds:

> "I have not as yet made any attempt to represent the excessive minuteness of the corpuscles, of whose existence we are now so confident; but, as an introduction to what I have to speak of next, it is necessary to do so.

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[1] Or say a globe of 16 centimeters diameter.

To obtain any adequate conception of their size we must betake ourselves to a scheme of threefold magnification. Lord Kelvin has shown that if a drop of water were magnified to the size of the earth the molecules of water would be of a size intermediate between that of a cricket ball and of a marble. Now each molecule contains three atoms, two being of hydrogen and one of oxygen. The molecular system probably presents some sort of analogy with that of a triple star; the three atoms replacing the stars, revolving about one another in some sort of a dance which cannot be exactly described. I doubt whether it is possible to say how large a part of the space occupied by the whole molecule is occupied by the atoms; but perhaps the atoms bear to the molecule some such relationship as the molecule to the drop of water referred to. Finally, the corpuscles may stand to the atom in a similar scale of magnitude. Accordingly, a threefold magnification would be needed to bring these ultimate parts of the atom within range of our ordinary scales of measurement. . . .

"The community of atoms in water has been compared with a triple star, but there are others known to the chemists in which the atoms are to be counted by fifties and hundreds, so that they resemble constellations."

Such general discussions by these illustrious physicists, Kelvin,[1] Poincaré and Darwin, are not to be construed too literally, and yet they clearly indicate the general belief among the foremost men of science that the spaces between the particles of matter are immense in comparison with the dimensions of the particles themselves.

From Lord Kelvin's discussion of the size of atoms treated in the above section, we have seen that the diameters of these bodies is of the order of 1/500,000,000 of a centimeter, or 1/1,270,000,000 of an inch. The average space between the molecules being 1/100,000 of a centimeter, or about 5,000 times the diameter, is of the order of 1/254,000 of an inch. This is decidedly below the

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[1] In a well-known paper on gravitating matter, Lord Kelvin compares the stars of the Milky Way to the atoms of a bubble of gas. For a giant for whom our suns would be what atoms are to us, the stars would be beyond the reach of the keenest vision and the Milky Way appear to behave as a gaseous medium. M. Poincaré has discussed the problems of the universe from this point of view in an address to the Astronomical Society of France (*Bulletin Astronomique de la Societé Astronomique de France,* April, 1906; an excellent translation in *Popular Astronomy* for October, 1906). It is remarkable that Democritus, founder of the atomic theory among the Greeks (460–360 B. C.), should also have recognized that the Milky Way is composed of a mass of stars too dense to be seen separately by the unaided vision (cf. "Aristotle's Meteorology," Lib. I., Ch. VIII., Sec. 4). Thus Lord Kelvin's conceptions do not differ greatly from those of Democritus of Abdera, though the modern theories are much better established than the atomic theories were among the Greeks.

limit of resolution of the microscope which has been estimated by Michelson at 1/100,000 of an inch.

Now in our discussion of the constitution of granites we found that the *visible pores* in the quartz matrix have all diameters down to less than 1/10,000 of an inch, and thus practically to the lowest limit visible in the microscope. These visible pores thus evidently connect directly with the smaller invisible spaces which separate the molecules. As the diameters of the molecules in water vapor are only about 1/5,000 of the spaces between them, the triple atom of hydrogen and oxygen constituting water or water vapor would have ample facilities for penetrating a spongy and cavernous mass like granite with innumerable holes frequently of large size but always at least equal to the average free path. If the water or vapor were under pressure, so as to condense the fluid and thus increase the number of vibrations of a molecule per second, the rate of penetration of the fluid obviously would be much augmented.

And since granite not only is filled with pores of these various sizes, but also everywhere more or less cleft by planes of crystalline structures which are not really tight, but full of fissures and thus inviting the penetration of the fluid by the full power of capillary forces, we see that water would necessarily penetrate it at a fairly rapid rate. At the same time the influence of capillarity in such a structure is so great that although water might enter and slowly pass through it, even the development of steam pressure beneath the layer would not force the fluid back, because the steam pressure is nullified an infinitely small distance from where it is exerted, on account of capillary resistance; yet the fluid may keep on descending under the suction of the capillary forces so long as the supply from above is not cut off.

Upon these physical grounds it seems clear that there must be a secular leakage of the ocean bottoms, and a corresponding development of steam beneath the earth's crust. The steam expands the rock in which it is absorbed and in seeking release thus brings on earthquakes and mountain formation.

Even if the pressure due to depth should tighten up the structure of the rock in the lower layers of the crust, it would not be able to obliterate the leakage depending on the pores and crystalline structure. It is evident that at depths such as twenty miles the downward movement of the fluid would continue, though very slowly. Hence the leakage of the oceans is extremely gradual, and the recurrence of earthquakes visibly delayed after relief has once been obtained. Thus while the tightness of the earth's crust due to the grain of the rock and the pressure to which it is subjected in the lower parts does not prevent ocean leakage, it makes the process so slow and gradual as to afford considerable protection to life upon our planet.

## II. ON THE PHYSICAL STATE OF THE EARTH'S INTERIOR, ON THE AVERAGE RIGIDITY OF THE GLOBE AS A WHOLE, AND ON THE SUBSTRATUM OF PLASTIC MATTER BENEATH THE CRUST WHICH IN EARTHQUAKES BEHAVES AS FLUID.

§ 12. *On the Theory of a Fluid Globe Held by the Older Geologists, and on Hopkins' Argument for Solidity Based on the Phenomena of Precession and Nutation.*—In the early part of the nineteenth century it was generally believed by geologists that the earth was a liquid globe covered by a rocky crust much thinner in proportion to the diameter than the shell is to that of an egg. This supposed liquid interior had been suggested by the streams of molten lava often observed to issue from volcanoes, and by the igneous rocks so abundantly poured forth in many places. The theory of a fluid globe seemed to be confirmed by the observed increase of temperature downward, which would give rise to molten rock at a depth of some twenty miles. The mountains and other phenomena traceable to dislocations of the crust could all be explained by a solid layer of this thickness, and the natural inference was that the great central nucleus remained liquid. The consolidation of the globe was ascribed to the progress of secular cooling, from the primitive state of high temperature assumed by Laplace in the nebular hypothesis postulated for explaining the origin of the solar system.

The older geologists had not adequately considered the effects of pressure in augmenting the solidity of the globe as we go downward; for since pressure raises the melting point of solids, the matter of the nucleus, though highly heated, might be solid if the pressure be great enough to prevent fusion under the prevailing temperature. In order to throw light upon this question, Hopkins of Cambridge, England, took up the problem in 1839 (*Phil. Trans.*, 1839; "Researches in Physical Geology," 1839–1842), and sought to prove from the observed phenomena of precession and nutation that the earth could not be composed of a thin shell some twenty miles thick, filled with liquid. He concluded that the crust could not be less than 800 to 1,000 miles thick, and that the globe might even be solid to the center, except some small vesicular spaces here and there filled with molten rock.

In 1868 this subject was examined by the eminent French astronomer, Delaunay, who published a paper on "The Hypothesis of the Interior Fluidity of the Globe" (C. R. Acad. des Sci., Paris, July 13, 1868), in which he threw doubt on the views of Hopkins, and suggested that if the earth's nucleus were a mass of sufficient viscosity it might behave as if it were solid, and hence concluded that the observed phenomenon of precession and nutation did not necessarily exclude a fluid nucleus.

§ 13. *Lord Kelvin's Earliest Studies on the Precession of a Spheroid Containing Liquid.*—Lord Kelvin had already taken up the problem of the internal state of the earth in 1862, and considered the effects of a fluid nucleus enclosed in a thin shell when the whole mass was subjected to tidal strains. As the shell must yield under these strains the land would be carried up and down with the superjacent sea, and if such yielding occurred it ought to be sensible to observation. But since the sensible obliteration of the tides had not been observed, he naturally inclined to the view of Hopkins that the earth is effectively rigid and behaves as a solid globe.

In reply to Delaunay's criticism Lord Kelvin pointed out that if the French astronomer had worked out the problem mathematically he could not fail to see that the hypothesis of a viscous and quasi-rigid interior "breaks down when tested by a simple calculation of the amount of tangential force required to give to any globular portion of the interior mass the precessional and nutational motions which, with other physical astronomers, he attributes to the earth as a whole." (*Nature*, February 1, 1872.) On making this calculation Lord Kelvin found that the earth's crust down to depths of hundreds of kilometers must be capable of resisting a tangential stress of nearly 0.1 of a gramme weight per square centimeter; this would rapidly draw out of shape any plastic substance which could be properly called a viscous fluid. "An angular distortion of 8″ is produced in a cube of glass by a distorting stress of about ten grammes weight per square centimeter. We may therefore safely conclude that the rigidity of the earth's interior or substance could not be less than a millionth of the rigidity of glass without very sensibly augmenting the lunar nineteen yearly nutation." (*Nature,* February 1, 1872, p. 258.)

Notwithstanding these early criticisms of Delaunay's paper, Lord Kelvin subsequently concluded that the phenomena of precession and nutation do not decisively settle the question of the earth's internal fluidity. Yet the semiannual and lunar fortnightly nutations may be considered to disprove absolutely the existence of a thin rigid shell full of liquid. If the fluid were arranged in successive layers of equal density, the only nutational or precessional influence exerted upon it would depend on the non-sphericity of the shells. "A very slight deviation of the inner surface of the shell from perfect sphericity would suffice," according to Lord Kelvin, "in virtue of the quasi-rigidity due to vortex motion, to hold back the shell from taking sensibly more precession than it would give to the liquid, and to cause the liquid (homogeneous or heterogeneous) and the shell to have sensibly the same precessional motion as if the whole constituted one rigid body." (Sir W. Thomson, British Assoc. Report, 1876, Sections, p. 5.)

It will be seen from this discussion that the argument from precession and nutation is only in part conclusive. If the fluid had a viscosity approaching high rigidity for rapidly acting forces, or it were subjected to such pressure that the particles in confinement acquired the properties of a solid, there would evidently be no sensible deviation from the precession and nutation appropriate to a cold solid globe.

§ 14. *On Lord Kelvin's Researches on the Earth's Rigidity Based on the Analysis of the Tides.*—The state of the earth's interior had early engaged the attention of Lord Kelvin, for the propagation of heat through the crust was before him as early as

1846. ("De Motu Caloris per Terræ Corpus," read before the faculty of the University of Glasgow in 1846; also a "Note on Certain Points in the Theory of Heat," February, 1844, published in the *Cambridge Mathematical Journal,* and reprinted in the "Mathematical and Physical Papers of Sir W. Thomson," 1882, Vol. I, Art. X.)

In a paper "On the Rigidity of the Earth" published in the *Philosophical Transactions of the Royal Society* for May, 1862, Lord Kelvin pointed out that if the matter of the earth's interior yielded readily to the tidal forces arising from the attraction of the sun and moon, the crust itself would respond to these forces in much the same way as the waters of the sea; and the corresponding movements of the crust would mask or largely reduce the height of the oceanic tides calculated for a rigid earth. By actual analysis of long series of tidal observations Kelvin and Darwin subsequently found the observed fortnightly tide to have very nearly its full theoretical height, and hence concluded that our globe as a whole possesses a very high effective rigidity. (Cf. Thomson and Tait's "Natural Philosophy," Vol. I, part II, § 832–847; also the article "Tides," Encyclopedia Britannica, ninth edition, § 44.)

Owing to the great importance of this work on the rigidity of the earth, we must trace the successive steps in the advancement of our knowledge. The assumption that the earth is made up of a liquid nucleus covered with a thin crust stiff enough to maintain its figure against the tide-raising forces of the sun and moon would imply that the crust has a degree of strength and rigidity not possessed by any known substance. It was therefore inferred by Lord Kelvin as early as 1862 that the crust might be 2,000 to 2,500 miles thick, in order to resist distortion under the tide-producing forces arising from the sun and moon.

> "If the crust yielded *perfectly,* there would be no tides of the sea, no rising and falling relatively to the land, at all. The water would go up and down with the land, and there would be no relative movement; and in proportion as the crust is less or more rigid the tides would be more or less diminished in magnitude. Now we cannot consider the earth to be absolutely rigid and unyielding. No material that we know of is so. But I find from calculation that were the earth as a whole not more rigid than a similar globe of steel the relative rise and fall of the water in the tides would be only

two-thirds of that which it would be were the rigidity perfect; while, if the rigidity were no greater than that of a globe of glass, the relative rise and fall would be only two-fifth of that on a perfectly rigid globe.

"Imperfect as the comparison between theory and observation as to the actual height of the tides has been hitherto, it is scarcely possible to believe that the height is only two fifths of what it would be if, as has been universally assumed in tidal theories, the earth was perfectly rigid. It seems, therefore, nearly certain, with no other evidence than this afforded by the tides, that the tidal effective rigidity of the earth must be greater than that of glass. This is the result taking the earth as a globe uniformly rigid throughout. That a crust fifty or a hundred miles thick could possess such preternatural rigidity, as to give to the mass, part solid and part liquid, a rigidity as a whole, equal to that of glass or steel is incredible; and we are forced to the conclusion that the earth is not a mere thin shell filled with fluid, but is on the whole or in great part solid." (Paper read to Geological Society of Glasgow, February 14, 1878; Kelvin's "Popular Lectures and Addresses," Vol. II, pp. 317–318.)

In his presidential address to the Mathematical and Physical section of the British Association at Glasgow, September 7, 1876, Lord Kelvin remarked of the earth's crust that "were it of continuous steel and 500 kilometers thick, it would yield very nearly as much as if it were india rubber to the deforming influences of centrifugal force and of the sun's and moon's attractions." "The solid crust would yield so freely to the deforming influence of sun and moon that it would simply carry the waters of the ocean up and down with it, and there would be no sensible rise and fall of water relatively to the land." ("Popular Lectures," Vol. II., pp. 251–2.)

Lord Kelvin's final conclusion was that "the earth as a whole is certainly more rigid than glass, but perhaps not quite so rigid as steel."

§ 15. *Darwin's Researches on the Tidal Method of Evaluating the Earth's Rigidity.*—As the natural successor of Lord Kelvin in the researches on the physics of the earth, Professor Sir G. H. Darwin took up the problem of the earth's internal physical condition and confirmed and extended these conclusions by several important lines of inquiry. Darwin's researches on the bodily tides of viscous and semi-elastic spheroids and on the oceanic tides upon a yielding nucleus tended to strengthen the argument for a high effective rigidity so decidedly that he concluded that "no very considerable portion of the interior of the earth can even distantly approach the fluid condition."

But whilst Darwin's researches confirmed Kelvin's conclusions as to the great effective rigidity of the earth, yet a more critical examination of the method for calculating the fortnightly tide led to the conviction that Laplace's argument is regard to the effects of friction was unsatisfactory. That friction would greatly effect the motion of the water in slow ocean currents within a few days was seen to be untenable. In consequence of this defect it turned out that long period tides as short as a fortnight would not enable the physicist to evaluate the rigidity of the earth, though the 18.6 yearly tide, depending on the revolution of the Moon's nodes, if it can be determined by observation, will eventually give the desired result. The height of this 18.6 yearly tide, however, is only one third of an inch at the equator, and great accuracy will be required for its detection.

Acting on the old belief Darwin compared the lunar fortnightly and monthly tides observed for 33 years at various Indian and European ports, with the equilibrium theory, and found that the tide-heights were about two thirds of the theoretical height. Accordingly he remarks: "On the whole we may fairly conclude that, whilst there is some evidence of a tidal yielding of the earth's mass, that yielding is certainly small, and the effective rigidity is at least as great as that of steel." (Thomson and Tait's "Nat. Phil.," Vol. 1, Part II, § 848.)

This was written prior to the discovery of the theoretical defect in the method of calculating the height of tides with periods not exceeding a fortnight in duration; yet even after the discovery of this defect it was still possible to infer that tides of long period in oceans such as ours must conform much more nearly to the equilibrium laws than do the tides of short period. "Whilst, then, this precise comparison with the rigidity of steel falls to the ground, the investigation remains as an important confirmation of Thomson's conclusion as to the great effective rigidity of the earth. . . . It appears by numerical calculation on viscous and elastico-viscous tides that in order that the oceanic semi-diurnal tide may have a value equal to two thirds of the full amount on a rigid globe, the stiffness of the globe must be about twenty thousand times as great as that of pitch at freezing temperature, when it is hard and brittle." (Sir G. H. Darwin, article "Tides," Ency. Brit., §§ 44–45.)

§ 16. *On the Rigidity of the Earth as found by Comparing the*

*Observed Period of the Polar Motion Arising in the Variation of Latitude with the Theoretical Eulerian Period Calculated for a Rigid Earth.*—The detection of the variation of latitude by Küstner at Berlin in 1890–91 and the subsequent discussion by Chandler of long series of observations showing that the movement of the pole in the body of the earth has a period of some 427 days, instead of the 305 days long ago inferred from Euler's theory of the rotation of a rigid spheroid, led Professor Newcomb to point out that this observed prolongation of the theoretical Eulerian period indicates some yielding of the matter of the globe under the stresses to which it is subjected by the movement of the pole, and would afford a new method of evaluating the earth's rigidity. In his well-known paper on the "Dynamics of the Earth's Rotation" (*Monthly Notices, R. A. S.,* March, 1892) Newcomb showed that the results already obtained decidedly confirmed Darwin's conclusion that the rigidity of the globe as a whole is comparable to that of steel.

The essential point in Newcomb's explanation is that when the pole changes its position in the body of the globe, the distribution of centrifugal force shifts with respect to the solid earth, which is thus put into a state of stress and must yield to the forces acting upon it, like any other elastic solid body; the periodic deformation of the earth's figure operating to lengthen the period of the free nutation, by an amount depending on the average rigidity of the whole earth.

The continued investigation of the variation of latitude carried out at the various international latitude observatories by Albrecht and others confirms this observational result, and the subject has also been examined theoretically by Darwin, Hough, Larmor and others; so that the validity of the method suggested by Newcomb is generally recognized.

In 1896 Mr. S. S. Hough treated of the problem in a very thorough manner in his well-known paper, "On the Rotation of an Elastic Spheroid" (Phil. Trans., A, 1896). He considered chiefly the case of an incompressible homogeneous spheroid, and was enabled to show by rigorous methods that the rigidity of the earth in all probability slightly exceeds that of steel.

In a remarkable paper "On the Period of the Earth's Free

Eulerian Precession," read to the Cambridge Philosophical Society, May 25, 1896, Professor Larmor showed how to estimate the effect of the elastic yielding of a rotating solid on the period and character of the free precession of its axis of rotation, and again confirmed the high effective rigidity of the earth from another point of view.

The observed prolongation of the Eulerian period is thus fully explained by the imperfect rigidity of the earth's mass, and the high rigidity thus deduced has naturally strengthened the earlier conclusions of Kelvin and Darwin drawn from the study of the long period tides of the sea.

This investigation, like those already cited, gives us only an average effect for the earth as a whole, but does not tell us the law of the distribution of rigidity within the globe. If this law of distribution of rigidity could be found, even approximately, it would be of great interest, because we could then see in what part of the globe the principal part of the yielding takes place; and this would give us a much better understanding of the internal constitution of our planet than heretofore has been considered possible.

§ 17. *Rigidity of the Earth Calculated from the Theory of Gravity, on the Hypothesis that the Distribution of Rigidity in the Globe is Everywhere Proportional to the Pressure.*—It has not been supposed by previous investigators that a method could be devised for deducing the rigidity of a body like the earth from the theory of gravity; but in 1905 it occurred to the present writer that such a method could be found if we could adopt a suitable hypothesis for the variation of the rigidity with the pressure. Previous investigations of the internal state of the heavenly bodies had justified the law of Laplace as giving an excellent approximation to the law of density for the earth and the rest of the encrusted planets; and the monatomic law had been found most satisfactory for the sun and fixed stars (cf. *A. N.*, 4053). These laws enable one to obtain the pressure at every point of the radius of the heavenly bodies. For in several ways Laplace's law of density is fairly well established for the earth, and on equally good grounds the density of the sun is believed to conform essentially to the monatomic law.

From a study of the laws of density, pressure and temperature within the heavenly bodies it appeared to me (as it had independently appeared to Arrhenius five years before) that matter under these extreme conditions must be essentially gaseous; and as it is above the critical temperature, it is made to behave in confinement as an elastic solid. Now in all gaseous masses the density is proportional to the pressure so long as the gas remains perfect; and the gas does not cease to be perfect when the temperature is above the critical value, though it may acquire in confinement the property of an elastic solid if the pressure be great enough to bring the molecules within a distance at which the molecular forces become effective in spite of the high temperature. Thus while the property of rigidity in cold solids depends wholly on molecular forces which prevent deformation, this property for gaseous matter in confinement under such pressure that it acquires the property of an elastic solid, is due wholly to the pressure. The molecular forces giving effective rigidity must increase in proportion to the pressure, or in a higher ratio.

If according to hypothesis the matter is made solid by pressure, then the molecular forces resisting deformation in the imprisoned matter thus solidified cannot resist deformation in a less degree than the direct proportion to the pressure on which the solidification depends. And any ratio higher than the direct proportionality to the pressure would most likely depend on the temperature. Now the temperature in the earth is supposed to be everywhere such as to make the density conform essentially to Laplace's law; and the pressure resulting from this law of density gives the matter everywhere the property of an elastic solid, and therefore its molecular properties must correspond to the physical state determined by the laws of density and pressure.

It is of course conceivable that some parts of the globe might be relatively more rigid than is required to give solidity, but the effect of this would only increase the average rigidity of the earth as a whole. And since seismological and other observations seem to show that the globe is solid throughout, except a thin layer just beneath the crust, the hypothesis of a rigidity proportional to the pressure will give a true minimum value of the earth's rigidity.

Now on the hypothesis that the density follows Laplace's law, the pressure throughout the earth's mass is given by the formula (cf. *A. N.*, 4104)

$$p=\frac{3x}{2(\sigma_1 g)q^2}[(\sigma g)^2-(\delta g)^2], \qquad (1)$$

where $r$ is the radius of the earth, $g$ mean gravity, $q$ the constant for Laplace's law, 2.52896 radians = 144° 53′ 55″.2, $\sigma$ the density at any point, $\delta$ the density at the surface, and $\sigma_1$ the mean density.

To render this expression available for integration throughout the sphere occupied by the earth's mass, we must put for $\sigma^2$ its value

$$\sigma^2=\sigma_0^2\frac{\sin^2(qx)}{q^2x^2},$$

and for $\delta^2$ its value

$$\delta^2=\sigma_0^2\frac{\sin^2 q}{q^2},$$

corresponding to the surface where $x=1$. Thus we obtain

$$p=\frac{3(\sigma_0 g)^2 r}{2(\sigma_1 g)q^2}\left[\frac{\sin^2(qx)}{q^2x^2}-\frac{\sin^2 q}{q^2}\right]. \qquad (2)$$

For the total pressure throughout a sphere of radius $\rho=rx$, $r$ being the external radius, and $x=(\rho/r)=$ fraction of the radius, we have

$$\begin{aligned}P&=\int_0^x p\cdot 4\pi r^2x^2\cdot r\,dx\\&=\frac{3(\sigma_0 g)^2\cdot r4\pi r^3}{2(\sigma_1 g)q^4}\left(\int_0^x\frac{\sin^2(qx)}{x^2}x^2dx-\sin^2 q\int_0^x x^2dx\right),\end{aligned} \qquad (3)$$

which by integration becomes

$$P=\frac{3(\sigma_0 g)^2 r4\pi r^3}{2(\sigma_1 g)q^4}\left(\frac{qx-\sin(qx)\cos(qx)}{2q}-\sin^2 q\frac{x^3}{3}\right). \qquad (4)$$

As our integration is to include the whole sphere of the earth, we put $x=1$, and then we have

$$P=\frac{3(\sigma_0 g)^2\cdot r4\pi r^3}{2(\sigma_1 g)q^4}\left(\frac{q-\sin q\cos q}{2q}-\frac{\sin^2 q}{3}\right). \qquad (5)$$

The total volume of the earth is $(4/3)\pi r^3$, and hence the average pressure per unit of area on all concentric spherical surfaces is

$$R=\frac{P}{\frac{4}{3}\pi r^3}=\frac{3}{4\pi r^3}\int_0^x p\cdot 4\pi r^2x^2\cdot rdx$$
$$=\frac{9(\sigma_0 g)^2\cdot r}{2(\sigma_1 g)q^4}\left(\frac{q-\sin q\cos q}{2q}-\frac{\sin^2 q}{3}\right). \qquad (6)$$

If $r$ is expressed in meters, the mean pressure or mean rigidity $R$ comes out in kilograms per square meter. To reduce the result to atmospheres we divide by 10,333. The result for the earth is $R=748{,}843$ atmospheres, about the rigidity of wrought iron.

This method takes no account of the earth's solid crust, and is therefore too small; moreover viscosity increases within the earth, owing to the rise of temperature downward. We give hereafter an approximation to the increase of rigidity by determining the mean rigidity of the earth's *matter,* as distinguished from that of the *various layers* composing the globe, just found by the above analysis.

To find the mean rigidity of the earth's *matter* we must consider not only the pressure but also the density or mass per unit volume of the imprisoned matter in each layer. The result represents a mean rigidity in which every elementary spherical shell composing the globe is allowed a weight proportional to its mass, which is multiplied by the pressure to which it is subjected.

The theory of the determination of the mean rigidity of the earth's matter is as follows:

$$P'=\int_0^x p\cdot 4\pi r^2x^2\cdot rdx\cdot\sigma=4\pi r^3\sigma_0\int_0^x p\cdot x^2dx\frac{\sin(qx)}{qx}. \qquad (7)$$

Substituting for $p$ its value from (2), we get

$$P'=\frac{3(\sigma_0 g)^2\cdot r\cdot 4\pi r^3\sigma_0}{2(\sigma_1 g)q^5}\left(\int_0^x\frac{\sin^3(qx)x^2dx}{x^3}-\sin^2 q\int_0^x\frac{x^2\sin(qx)dx}{x}\right), \qquad (8)$$

$$=\frac{3(\sigma_0 g)^2\cdot r\cdot 4\pi r^3\cdot\sigma_0}{2(\sigma_1 g)q^5}\left(\int_0^x\frac{\sin^3(qx)qdx}{qx}-\sin^2 q\int_0^x\frac{x\sin(qx)qdx}{q}\right). \qquad (9)$$

The integral of this last term is $-\sin^2 q\,\frac{\sin(qx)-qx\cos(qx)}{q^2}$.

The value of the first integral is most conveniently found by quadrature, table for which is given in *A. N.*, 4104, p. 379. Dividing out the mass, or volume of the sphere by the density, we have

$$R' = \frac{P'}{\frac{4}{3}\pi\sigma_1 r^3} = \frac{3\int_0^x p \cdot 4\pi r^2 x^2 \cdot r dx \cdot \sigma}{4\pi\sigma_1 r^3} \tag{10}$$

$$= \frac{9(\sigma_0 g)^2 \cdot r \cdot \sigma_0}{2(\sigma_1 g) q^5 \sigma_1}\left(\int_0^x \frac{\sin^3 (qx) q dx}{qx} - \frac{\sin^2 q}{q^2}[\sin (qx) - qx \cos (qx)]\right).$$

On putting $qx = 144° \, 53' \, 55''.2$, the value of the integral is found by quadrature to be 0.9592502, and when the rest of the formula is reduced to numbers we have (*A. N.*, 4104):

$$R' = 1028702 \text{ atmospheres.}$$

The rigidity of nickel steel is taken to be 1,000,000 atmospheres. It thus appears from this calculation that the average rigidity of all the earth's matter somewhat exceeds that of nickel steel. The actual rigidity of the earth almost certainly lies between the limits thus established, namely $R = 748{,}843$, based on the rigidity of the layers deduced from the pressure to which they are subjected, and $R' = 1{,}028, 702$, derived from the product of the mass of each layer by the pressure acting upon it.

In the paper, "Researches on the Rigidity of the Heavenly Bodies," *A. N.*, 4104, the rigidity of the earth is discussed as follows:

> "When one considers the effects of the enclosing crust and the viscosity of the whole earth, which must be assumed to increase towards the centre, owing to the increasing density and rising temperature of the imprisoned matter, it seems not improbable that the actual effective rigidity of our globe may be nearer the upper limit than the lower, and probably we shall not be far wrong in concluding that it is approximately equal to that of nickel steel.
>
> "Leaving aside the consideration of the effects of the solidified crust, it is evident from the nature of the forces at work that most of the yielding of our globe, due to the periodic action of small forces, is in the outer layers; and in general the yielding in any concentric layer may be taken to be inversely as the pressure to which the imprisoned matter is subjected. *It is remarkable that the curve of pressure as we descend in the earth becomes therefore also the curve of effective rigidity for the matter of which the earth is composed.* Thus the rigidity of the matter at the earth's center probably is at least three times that of nickel steel used in armor plate; as we approach the surface the effective rigidity constantly exceeds that of nickel steel until we come within less than 0.4 of the radius from the surface, where the pressure is less than 1,000,000 atmospheres.

"To imagine a mechanical substitute for the earth's constitution, without the introduction of pressure, suppose an alloy of adamant to give the material at the centre of such a globe, of the same size but devoid of gravitation, a hardness three times that of armor plate. The outer layers as we approach the surface must then be supposed softer and softer, until it is like armor plate at a little over 0.6 from the center, and finally a very stiff fluid near the surface. In addition to this arrangement of its effective internal rigidity the actual earth is enclosed in a spheroidal shell of solid rock analogous to granite. One can easily see that tidal forces applied to all the particles of such an artificial armored sphere would produce but very slight deformation, because of the enormous effective rigidity of the nucleus.

"The principal uncertainty in this result arises from the admissible variations in the assumed Laplacean distribution of density within the earth. Both Radau and Darwin (cf. *Monthly Notices,* Roy. Astron. Soc., December, 1899) have pointed out that considerable variations in the internal distribution of density are possible without invalidating the well-known argument drawn from the phenomenon of the precession of the equinoxes; yet on physical grounds it seems clear that pressure is the principal cause of the increase of density towards the earth's centre. And since this does not vary greatly for moderate changes in the law of density, the principle of continuity shows that the actual law of density within the earth cannot depart very widely from that of Laplace. The above value of the theoretical rigidity of the earth may therefore be taken as essentially accurate, and I think no doubt can remain that the rigidity of our earth as a whole considerably exceeds that of steel. The original conclusions of Kelvin and Darwin are therefore confirmed by the present dynamical considerations based upon the theory of universal gravitation."

In this connection we should remember that the experimental rigidity of steel is 808,000 and of glass 235,000 atmospheres. The calculated rigidity of all the matter within the globe, found by considering not only all the layers, but also the density in each layer, is found to be 1,028,702 atmospheres. Now the average rigidity must be greater than 750,000, because the stiffness of the crust and increase of viscosity downward is neglected in the gravitational method. In fact this method is not applicable to the outermost layers, because the pressure there is much less than the rigidity, and only becomes equal to the rigidity at a depth of something like one tenth of the radius, where the pressure is 320,295 atmospheres.

According to the experiments of Milne and Gray the rigidity of granite is about one sixth that of steel; and as steel has a rigidity of 808,000 atmospheres, that of granite is about 135,000 atmospheres, or a little more than one half that of glass. We may therefore take the outer layers of our globe to have a rigidity about half that of glass, and assume that at a depth of 0.1 of the radius it becomes nearly 2.5 times as great as it is at the surface.

Whether it becomes at a depth of twenty miles less than it is at the surface we cannot tell, but such a decrease is not impossible, perhaps not improbable; because at this depth the molten rock moves in earthquakes, and yet in confinement it must have a very sensible rigidity, though probably not more than half that of granite.

Accordingly, it looks as if the rigidity at the surface is about half that of glass, at a depth of 20 miles about one half that at the surface, and at the depth of 40 miles nearly the same, but increasing below that depth and at 160 miles again equal to that at the surface, and at a depth of 400 miles considerably larger yet, or about 1.4 times that of glass. Increasing below this depth according to the pressure, it becomes at the center over 3 times that of nickel steel used in armor plate. The rigidity of steel is attained at a little over 0.3 of the depth to the center of the earth. If this be the distribution of rigidity in the earth, the curve of rigidity is as follows:

This postulated fall in the rigidity just beneath the crust is probable for several reasons:

1. The temperature increases quite rapidly as we go downward, while the pressure increases proportionately more slowly, so that a depth would be reached at which the matter would become a plastic if not a viscous fluid.

2. The eruption of volcanoes and lava flows on a vaster scale show that a molten layer underlies the crust, and occasionally is forced to the surface.

3. This underlying molten rock moves in world-shaking earthquakes, and frequently is expelled from beneath the sea under the land to form mountain ranges along the coast.

4. We may prove this expulsion of lava by the observed seismic sea waves which indicate a sinking of the sea bottom, and by the simultaneous uplift of mountains and coasts.

From these considerations it follows that the earth is most nearly liquid just beneath the crust, and has the greatest rigidity at the center. As the plastic or quasi-viscous layer beneath the crust is thin, and possessed of considerable rigidity, *it too remains quiescent* *except when set in motion by the dreadful paroxysms of an earthquake.*

In tidal and other observations the earth therefore behaves as a solid, and the rigidity of the earth inferred by Kelvin and Darwin is confirmed. Yet a layer of plastic matter or quasi-viscous fluid exists just beneath the crust, and when disturbed by earthquakes gives rise to the development of ridges in the crust called mountains, chiefly by the expulsion of lava from under the sea.

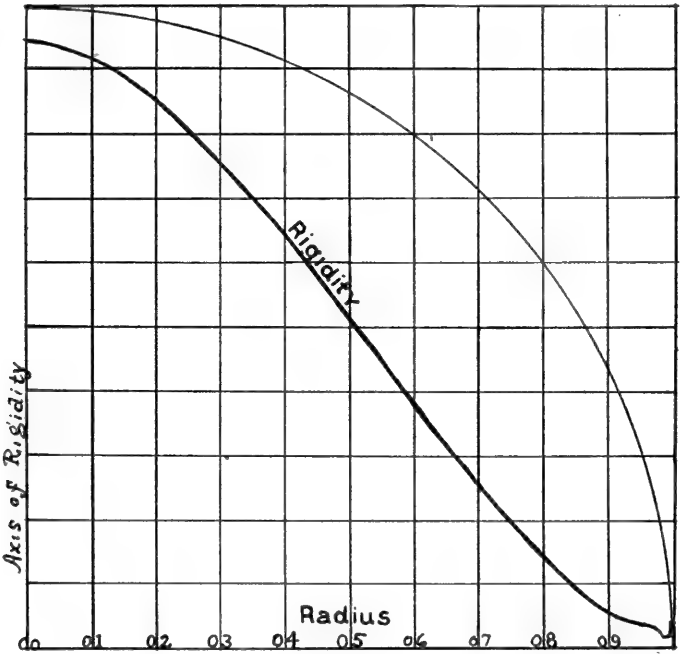

FIG. 2. Curve of Rigidity for the Earth, showing the plastic layer just beneath the crust.

§ 18. *Wiechert's Researches on the Interior Constitution of the Earth and on the Plastic or Viscous Layer which he Infers to Exist Just Beneath the Crust from Oscillations of Long Period Noticed in Seismic Vibrations.*—Professor E. Wiechert, of Göttingen, has devoted much attention to the problem of the constitution of the earth's interior. He long ago reached the conclusion that the great interior nucleus probably is a mass of iron covered with a thick shell of stony material. In the paper which he recently presented to the International Seismological Association in session at the Hague, September 21–26, 1907, he estimates the depth of the stony layer as 1,500 kilometers, which is nearly one fourth of the earth's radius.

This view that interior of the earth is metallic has been entertained by many eminent physicists, including Lord Rayleigh; but it is beset with many difficulties. We shall here mention three of the principal objections:

1. If this constitution of the earth be admitted, the curve of density will have a sudden break at a depth of about one fourth of the radius; and, as the pressure increases rapidly as we go downward, it seems improbable that the density of the outer layer could remain uniform and then change suddenly at a depth of one fourth of the distance to the center. Such discontinuity in nature seems highly improbable for the density, since there probably is no sensible discontinuity in the laws of pressure and temperature.

2. If the central nucleus is metallic, it follows that the denser elements have separated from the rest of the mass. As the matter has been essentially solid and highly rigid, owing to the pressure, ever since the globe attained anything like its present dimensions, this sinking would not be possible, because the resistance to the motion would be much too great. Thus owing to resistance to motion arising from rigidity we can not admit a separation of the denser from the lighter elements of such a globe. If the metals were all so deep down, it would be hard to account for the veins found in the crust by any kind of eruptive process, since the globe is never fissured to a depth of anything like one fourth of the radius.

3. If in addition to these mechanical objections we recall that deep down the pressure is so great as to cause an interpenetration of all the elements, whatever be the temperature, but especially under the high temperature known to prevail in the interior of the globe, so that no aggregation or crystallization of substances would be possible, and the nucleus would therefore be a magma of all the elements, it becomes inconceivable that the metals could separate from the stony elements by sinking, while the latter floated to the

surface. Even if the globe were a liquid mass of very small viscosity, it is clear that such a separation of the elements could not take place.

Finally it is to be recalled that recent experiments with radium have shown the probable transmutation of some of the metals, as when Sir Wm. Ramsay caused sulphate of copper to be partially degraded into lithium. If this can occur for one or two metallic elements, it may eventually be possible for many and perhaps all of the metals. Our knowledge of these transformations is still in its infancy, and we can not yet ascertain how minerals and metallic veins have arisen; but it is impossible to believe that the material has come up from a pure supply at a depth of 1,500 kilometers. It is much more probable that the metallic elements have been developed by differentiation and transformation from an original magma, and that the whole interior of our planet is still a magma. Differentiation of the elements appears to develop under conditions met with in the crust, but nowhere else.

Accordingly we are obliged to dissent from the constitution of the globe outlined by Professor Wiechert; but in the matter of the existence of a layer of plastic or fluid material just beneath the crust, which he infers from the long seismic vibrations with periods of about eighteen seconds, we are in hearty accord with him. This is definitely proved by the phenomena noticed in earthquakes, as more fully set forth hereafter. It is the expulsion of lava from under the margins of the sea which produces world-shaking earthquakes and the upheaval of mountains along the sea coasts.

§ 19. *On Sir G. H. Darwin's Researches on the Stresses in the Interior of the Earth Due to the Weight of Continents and Mountains.*—We have seen that the earth behaves as a solid at all depths, unless it is in the thin layer just beneath the crust, in which movements take place during earthquakes. The theory of an elastic solid shows that when such a body is stressed the state of stress is completely determined when the amount and direction of the three principal stresses are known. No limit is imposed on these stresses by theory, but in practice nature fixes a limit, beyond which the elasticity breaks down, and the solid either flows or ruptures by breaking.

In the "Nat. Phil.," Vol. I, part II, § 832, Lord Kelvin and Professor Tait remark that

> "The precise circumstances under which elastic bodies break have not hitherto been adequately investigated by experiment. It seems certain that rupture cannot take place without difference of stress in different directions. One essential element therefore is the difference between the greatest and least of the three principal stresses. How much the tendency to break is influenced by the amount of the intermediate principal stress is quite unknown. The difference between the greatest and least stresses may however be taken as the most important datum for estimating the tendency to break. This difference has been called by Mr. G. H. Darwin (to whom the investigation of which we speak is due) the 'stress-difference.'"

Stress-difference is a term which when applied to matter within the earth denotes the tendency to flow. For rupture is not possible when the matter is in confinement under such pressure and at high temperature. Now if the earth were homogeneous, as assumed in Darwin's inquiry, the inequalities of surface due to the mountains, plateaus, and continents would give rise to a stress-difference in the underlying layers; and Darwin showed that the stress-difference would increase with the depth, being at the center, for inequalities of the type represented by harmonics of the second order, eight times what it is at the surface.

If the earth were not effectively solid throughout, a flow ought to take place either near the surface or at greater depth; and thus the inequalities of surface would disappear. But the plateaus and mountains do not sink in, and this fact proves that the globe is not fluid, and even that the plastic or viscous layer just beneath the crust is quite stiff. As we have seen that the rigidity increases very rapidly towards the center, we easily see why movement should not occur at great depth, since the rigidity there exceeds that of any known substance, and at the centre is about three times that nickel steel used in armor plate.

In the paper on the "Temperature of the Earth" we have shown from the evidence of stability afforded by geological pinnacles millions of years old, that no movements of deep seated character occur within the earth. This evidence supports the view that the earth is effectively solid, and has behaved as such since the consolidation of the crust.

As the rigidity increases so rapidly towards the center of the earth, flow ought not to take place at those depths; and the absence of any evidence of deep seated movements among the ruins wrought by geological time in turn supports the theory of rigidity depending on the pressure.

Darwin's hypothesis of homogeneity is only a rough approximation to the truth, and Laplace's law would no doubt give a much more exact representation of the density and the resulting stress-difference in the earth. But this suggested change of data would not greatly modify the general conclusions already stated.

§ 20. *The Theory of Isostacy.*—A more important difference might arise from the theory of isostacy, the applicability of which to the earth seems to be becoming better established by recent researches. In this view the crustal inequalities seen at the surface are compensated for by lighter or greater densities beneath, according as the crust is elevated or depressed, so that for a certain thickness of crust equal blocks have equal mass, however unequal the level of the blocks at the surface.

The recent investigations by the U. S. Coast Survey indicate that the depth of complete compensation for the United States and outlying stations is about 71 miles. No doubt a depth of something like this extent would hold true for the entire globe. If this view be admissible, it will follow that all inequalities of the crust cease to be effective at depths greater than 71 miles, and no stress-differences depending on plateaus and mountains would exist in the globe except in the layers just beneath the crust. There would thus be no stresses in the deep interior depending on the weight of continents and mountains.

This theory of isostacy is confirmed by the theory of mountain formation developed in the paper on the "Cause of Earthquakes," which shows clearly that these elevated ridges are underlaid by material lighter than the average rock of the crust. On the one hand, therefore, if stress-differences exist deep down, no movement can take place, owing to rigidity; on the other, if the theory of isostacy be admissible, no stress-differences can exist except in the outer layers of the globe, within 71 miles of the surface.

*We conclude therefore that in no case could movements occur* *except in the layer just beneath the crust.* These superficial movements are called earthquakes, and are caused chiefly by the leakage of the oceans. Observations show that the depth of such disturbances in all cases is less than 40 miles. This accords with the theory of isostacy, and confirms the conclusions drawn from that theory that all surface inequalities are compensated for at but a slight depth.

§ 21. *Uplifts along the Andes show that the mountains are not sinking under their own weight.*—In Professor Sir G. H. Darwin's paper on the stresses in the earth, above cited, he has also considered harmonics of high order, corresponding to the case of a series of parallel mountains and valleys, which thus corrugate a mean level surface with an infinite series of parallel ridges and furrows. Here the stress-difference depends only on the depth below the surface, and is independent of the position of the point considered with respect to ridge and furrow. Taking a series of mountains 13,000 feet (about 4,000 meters) above the valley bottoms, formed of granite of density 2.8, he shows that the maximum stress-difference is $4 \times 10^5$ grammes weight per square centimeter (about the tenacity of cast tin). And when the mountain chains are 314 kilometers apart, making the ridges about 78 times wider than they are deep, the maximum stress-difference is reached at a depth of 50 kilometers below the surface, or at a depth of 12½ times the height of the mountains above the valleys. Thus for mountains of the height of our average ocean depth, the maximum tendency to flow would be at a depth of about 31 miles. (Cf. "Nat. Phil.," Vol. I, Part II, § 832.)

If earthquake shocks were due to such flowage the mountains would be gradually reduced in height. Instead of this settling occurring, mountains like the Andes are still rising, as we may infer from the fact that after an earthquake the adjacent sea coast often is elevated and higher than before; while the sinking of the adjacent sea bottom, indicated by the accompanying seismic sea wave, shows that the bed of the sea was undermined by the expulsion of the material pushed under the land and mountains. *This state of fact emphatically contradicts the view that these great seismic disturbances are due to the flowage beneath the crust arising from the* *weight of continents and mountains.* Neither the uplift of mountains about the sea coasts, nor the earthquakes occurring in these regions can be explained by flowage beneath the crust, because the movement is positive rather than negative, as required by this theory.

Whilst the investigation of Professor Sir George Darwin therefore does not give us a clue to the observed movements, it is nevertheless very valuable as furnishing an indirect confirmation of the present theory that mountain formation depends on the sea. Observation shows that the movements are positive, and as the theory of flowage indicates that they should be negative, we may infer that whatever be the stress-differences existing beneath the earth's crust, the movements thus produced are insensible compared to those depending on the expulsion of lava from under the sea by world-shaking earthquakes.

## III. The New Physical Theory of Earthquakes and Mountain Formation Based on the Secular Leakage of the Ocean Bottoms.

§ 22. *On the Plastic and Perhaps Viscous Layers Just Beneath the Earth's Crust.*—We have now examined at length the arguments in regard to the constitution of the earth's interior, and have shown that although as a whole the earth is solid, owing to the pressure to which the matter is subjected, there is a plastic layer just beneath the crust which in earthquakes is made to flow and behave almost as a viscous fluid. In this layer just beneath the crust either the pressure is not great enough to produce entire solidity, with the existing temperature, or else the solid is made to flow by the breaking down of the elasticity under the action of the earthquake forces, which are powerful enough to disturb the whole world.

Although the matter in this substratum appears to have some rigidity, it seems probable that it has not the requisite elasticity to behave as a perfect solid. We know that the layer must be nearly solid, because, if it were not so, there would be a greater tendency of the mountains to subside than actually is observed. The stress-difference in the layers just beneath the crust must be very considerable; and yet this plastic matter is so stiff that it does not flow and allow the mountains and plateaus to sink in.

Now earthquake disturbances are often complex, and consist in horizontal and vertical movements combined. We have seen that in the long run the uplifting tendency predominates, because it is in this way that the mountains and plateaus have arisen. Nevertheless there are numerous cases in which subsidences take place, and these settlements often seem to be somewhat gradual, as if the substratum was slowly yielding and flowing under the stresses to which it is subjected. These gradual subsidences, of the class that was observed by Darwin and Fitzroy at Conception in 1835, seem to afford convincing evidence that the layer beneath the crust is certainly plastic, perhaps viscous.[4] The yielding of the layer beneath the crust is shown not only in movements noticed in earthquakes, when lava is expelled from under the sea and pushed under the land; but also in the subsidences which the sea trenches experience after earthquakes. These subsidences have folded the rocks seen in mountain ranges now on land; and although most of such subsidence is due to the undermining of the troughs by the expulsion of lava, it seems likely that some very gradual yielding also takes place. The layer under the crust is therefore certainly plastic, when partially undermined, and probably so, independent of the undermining, if it is subjected to great forces, as in world-shaking earthquakes, where mountains are in process of upheaval. If the matter is also viscous, the viscosity must be very high. With the matter imprisoned beneath the earth's crust it is difficult if not impossible to distinguish between plasticity and true viscosity, because, if the fluid is very stiff, it would behave almost as a solid. And the tests heretofore afforded by earthquakes are not decisive. This view of the substratum just beneath the crust is not essentially different from the theory held by Arrheniüs with regard to the interior of the earth as a whole. But this layer is the only part of the interior in which movements may be observed, and even here movements would not take place but for the steam developed beneath the crust by the secular leakage of the oceans. It may be that the future study of these movements will some day

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[4] We follow Sir George Darwin in "distinguishing viscosity, in which flow is caused by infinitesimal forces, from plasticity in which permanent distortion or flow sets in when the stresses exceed a certain limit." (Letter to Sir A. Geikie, January 9, 1884.)

enable us to decide whether the substratum is plastic only, or truly viscous.

§ 23. *Substratum Everywhere Quiescent Except when Disturbed by Earthquakes.*—The fact the large areas of the earth's surface in such dry countries as Sahara, our Western Plateaus, and the interior of Australia, are quite free from earthquake disturbances, shows what would happen everywhere but for the presence of surface water, and especially the leakage of the crust depending on the sea. The quiescence of the substratum in interior regions remote from the sea shows that under normal conditions this layer is quite inert. It is only set in motion by the vapor of steam which slowly develops stresses in the rocks of the crust and finally brings on earthquakes. It might be plastic enough to yield slightly under sufficiently great forces, but the loading and unloading due to meteorological and geological causes going on in nature are not great enough to have any appreciable effect, as we may infer from the universal quiescence of inland areas, especially in desert countries.

It seems to be true, however, that when the crust is broken and upheaved, in the formation of mountains near the sea coast, some slow yielding takes place beneath. Yet at present any changes of a creeping nature can not be entirely separated from those depending on the expansion and expulsion of lava from under the sea; and we can only feel sure of the inert character of the substratum, except where disturbed by water vapor entering from without. Along the sea coasts the stresses in the crust are constantly changing, and the crust blocks yielding more or less to the stresses acting upon them; it is only when *sudden yielding* occurs that we experience a shock, and the greatest earthquakes are characterized by molten rock adjusting itself beneath the crust. It is probable that much yielding takes place which is exceedingly gradual and produces no disturbances sensible to ordinary observation. In dry regions remote from the sea there are no shocks, and therefore also no gradual yielding of the crust; hence the substratum is inherently and naturally quiescent except when disturbed by external forces.

§ 24. *Mountain Formation in the Sea and on the Land.*—In the paper on the "New Theory of Earthquakes and Mountain Formation," we have cited certain cases of mountain formation now going

FIG. 3. Relief Map of North America. (From Frye's Complete Geography, by permission of Ginn & Co., Publishers.) This map illustrates beautifully the recession of the sea since the formation of the Rocky Mountains, which were at one time the eastern border of the Pacific Ocean.

on in the depths of the sea, and directly connected with mountain systems spread out on the land. Thus we have shown that the Aleutian Islands are a branch or part of the Rocky Mountains still remaining in the depths of the sea. As this part of the chain is now being uplifted by the ocean, we get a very clear conception of how the whole Rocky Mountain system was formed. We are fortunate therefore to find a part of a great mountain chain still unfinished, with one end under water and the main body of the system high and dry along the edge of the continent.

Now no one believes[1] that mountain formation takes place far inland, because the mountains generally follow the coast, and moreover at present the process is found to be most active *in the sea,* as in the region of the Aleutian Islands and the Antandes. This geographical distribution of mountain-making is therefore a most powerful argument for the new theory. Moreover it is generally recognized that the Rocky Mountains in the United States are a good deal older than the Andes in South America; and as the relative ages bear some relation to the distances from the sea, the mountains on land give the same indication as those still in the depths of the sea. The recession of the sea goes on at very unequal rates in different parts of the world, yet the present positions of the mountains show that the older mountains are generally remote from the ocean. The present theory is therefore confirmed by the lay of the older as well as of the younger mountain systems; and by the situation of the mountains on land as well as of those now being formed in the depths of the sea. All the mountain phenomena of the globe are thus shown to be consistent. But as direct observation of mountain formation witnessed with our own eyes is the most convincing of all evidence, it is fortunate that we are able to cite numerous cases of mountain ranges now developing in the sea. By the study of the sinking going on where trenches are developing, we see how the wrinkles and valleys were produced in mountain systems now at a considerable distance from the ocean. Since the sea recedes from the mountains in the course of geological ages, it follows that more and more land is constantly rising above the water,

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[1] Compare § 42 of this paper, where Leconte's views are quoted at length. He held that mountain ranges are formed on lines of thick sediment along the shores of continents.

and the continents growing larger. The mountains are formed by earthquakes, and earthquakes are due to the sea, which thus makes more and more land for the development of the higher forms of life upon the globe.

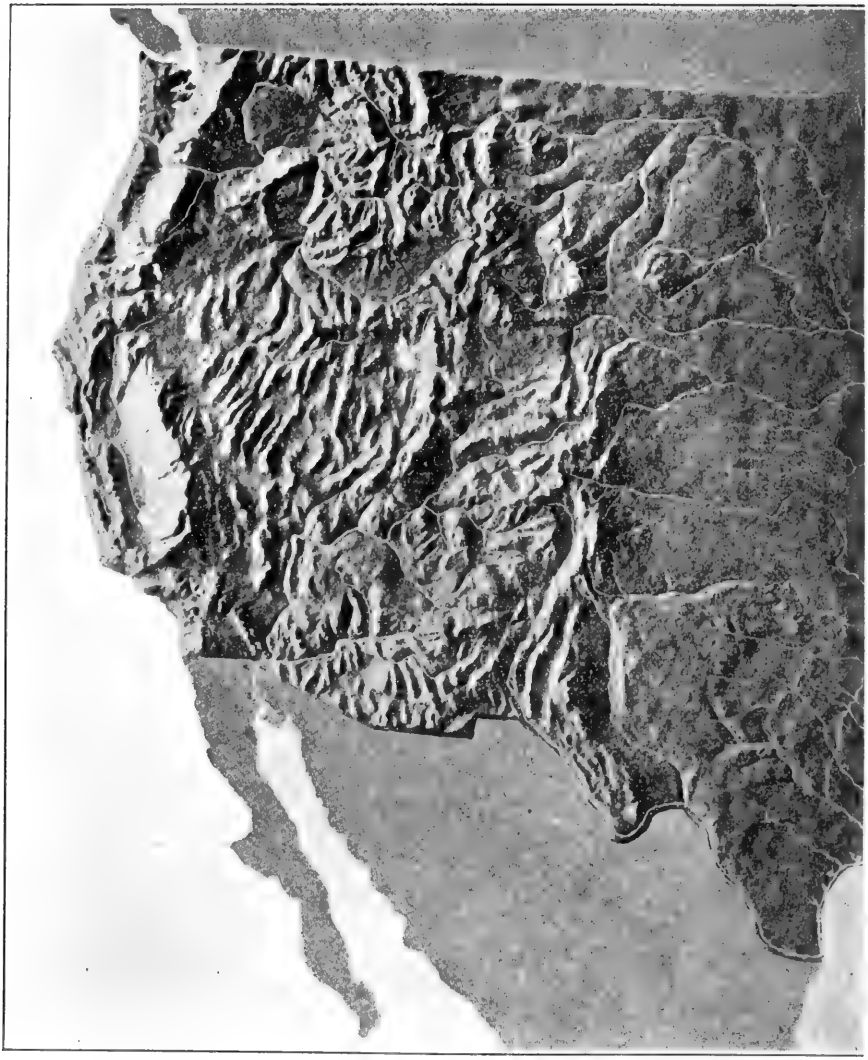

FIG. 4. Relief Map of the United States. (From Frye's Complete Geog- especially how the great plateau west of the Rocky Mountains has been

§ 25. *The Origin of Faults in the Earth's Crust.*—It has long been recognized that faults in the earth's crust are often displaced by earthquakes. Now earthquakes are mainly submarine or follow the borders of the continents. Here the mountain ranges have de-

raphy, by permission of Ginn & Co., Publishers.) The reader should notice crumpled in the uplift from the sea, which has receded westward 1,000 miles.

veloped or are now developing, and in general the faults run along the sea coasts and into the sea, where mountain formation is in progress. Thus it is clear that faults arise from the stresses and movements of the crust produced by earthquakes and mountain formation, and therefore from the secular leakage of the ocean bottoms.

Sometimes the faults move but little, at other times they give rise to conspicuous changes of level; and where vast down-throws or uplifts have occurred certain types of mountains arise from normal faulting. The more horizontal movements of faults arise mainly in the trenches along the sea coasts, which produce the folding seen in mountain chains. The vertical movements are more general, and are especially conspicuous in elevated plateaus, like those of our western states.

In his "Report on the Geology of the High Plateaus of Utah," Washington, 1880, Major Dutton gives a description of some of the most magnificent faults in the world. On page 45 he indicates the dependence of these faults on the ancient shore line of the Eocene lake, thus:

> "It yet remains to speak of another interesting relation of the later system of faults. They have throughout preserved a remarkable and persistent parallelism to the old shore line of the Eocene lake, following the broader features of its trend in a striking manner. The cause of this relation is to me quite inexplicable, so much so, that I am utterly at a loss to think of any subsidiary facts which may be mentioned in connection with it and which can throw light upon it."

What puzzled Major Dutton most was the raising of the area of the lake; but as the whole region was uplifted by the sea in later times this phenomenon was in no way remarkable. The rocks in such disturbed regions have been broken and folded into a series of troughs and arches or thrown into domes and basins, and probably no two adjacent areas retained their relative levels throughout. His observation, however, confirms the present theory that faulting is generally parallel to the ancient sea shore, and therefore produced originally by the oceans.

The conspicuous character of the vertical movement of the crust blocks in the region of the Great Basin led several American geologists to suggest that vertical forces had operated in the uplift of these plateaus. As the whole region has been raised from the sea by the injection of the land with lava pushed under the crust from beneath the sea, it is evident that the crust blocks ought to be displaced unequally in different places, and hence the various types of faulting observed.

It should be remarked, however, that in the elevation of a plateau a mile high, only a layer of lava a mile deep needs to be injected. If three miles high, the layer would have to be three miles thick; but even this maximum height is only about one seventh of the thickness of the crust; and hence eruptions would not usually occur in these uplifts. The plateaus are all of small height compared to the thickness of the earth's crust, beneath which the movement of molten rock takes place.

If some faults should thus be widely opened, lava flows of vast extent, like those in Utah and Oregon, might be expected to occur. We cannot give the details of the cracks which produced these gigantic outflows, but it is evident that they depended on the opening of immense faults. Now the faults are produced and moved by earthquakes, and earthquakes are due to the leakage of the oceans. It follows therefore that the most immense lava flows ought to take place near the sea; and this seems to be true both in North America and in Asia, where the outflow in the plateau of Deccan has always excited the wonder of the naturalist.

That all the faults of the earth's crust depend on the sea and are produced by world-shaking earthquakes, is clearly indicated by the geographical distribution of these cracks in the crust. If any other cause, such as the secular cooling of the globe, were at work, we should find a relatively greater predominance of faults far inland, which is contrary to observation, especially in dry countries.

*It is remarkable that geologists have referred so many phenomena to faulting, but have made little or no attempt to explain faulting itself.* In the present theory referring the origin of faults to the expulsion of lava from under the sea we have for the first time a satisfactory and consistent view of these phenomena. Faults evidently arise mainly from the motion of lava in earthquakes, by which the overlying rocks of the crust are broken, and often displaced along the line of fracture.

When the crust is thus rent into blocks, some of them are reduced to small size, and eventually raised up, as in the vertical walls of granite now seen in Smyth's channel, southern Chile, the Straits of Magellan, Yosemite Valley, California, and the fiords of Norway. These precipitous walls of granite could be pushed up only by vertical forces, in earthquakes. It is noticeable that no such isolated masses are found towering up in the plains of Kansas, the desert of Sahara, and other inland regions far from the oceans. The origin of faults and fault movements must therefore be sought in the leakage of the oceans and in the resulting relief, which takes place in the sea bottoms and along the borders of the continents.

§ 26. *On the Uplift of the Great Plateaus of the World and on the Gradual Elevation of the Continents.*—For reasons already amply set forth in § 7, the process involved in the formation of the Andes is clear and beyond dispute. Now it happens that the Andean plateaus, such as those of Quito, Caxamarca, Cuzco and Titicaca, are generally included between the eastern and western ranges of the Andes, and were evidently uplifted by the same forces which formed the mountains themselves. Accordingly it is clear that a plateau such as that of Titicaca was therefore uplifted by the expulsion of lava from under the sea.

If now we pass from the Andes to the Himalayas, we shall find that in like manner those great mountains of Asia were uplifted principally by the Indian Ocean. The plateau of Thibet in the Himalayas of Asia corresponds exactly with that of Titicaca in the Andes of South America; and as the latter was formed with the Andes, so also the plateau of Tibet was formed with the Himalayas. This seems absolutely clear and incontrovertible. And a similar mode of development must be ascribed to the table lands to the east and west of Tibet, so that the principal plateaus of Asia, Tibet and Iran, are clearly the work of the sea.

The highest part of these plateaus is Tibet, with an average elevation of about 15,000 feet, and a width of about 500 miles at the highest part. At the middle it is somewhat wider, and to the west it narrows into Little Tibet, less than half the width of Tibet proper. It is evident that great Tibet was uplifted chiefly by movements from the direction of the bay of Bengal; this is shown by the lay of the mountain chains south of Tibet, and by the great earthquake belt still persisting in the valleys of the Ganges and Brahmaputra.

In the case of North America the plateaus are broader and correspondingly lower than those of South America and Asia. But if the sea gave rise to the uplifts connected with the Andes and Himalayas, can anyone doubt that the plateaus of North America are due to the same cause? The *total volume* of the North American

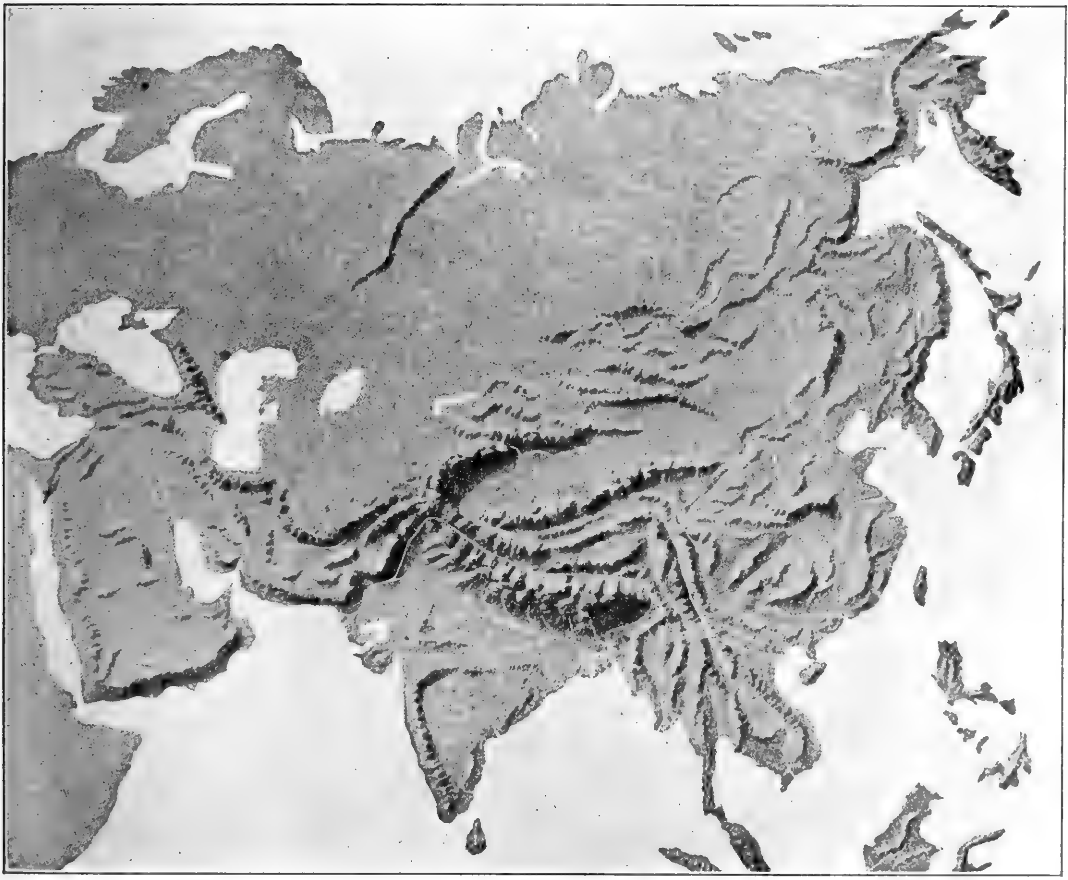

FIG. 5. Relief Map of Asia. (From Frye's Complete Geography, by permission of Ginn & Co., Publishers.) The mountains along the east coast illustrate the successive stages in the recession of the Pacific Ocean. At some future time the border of the continent will extend to the string of islands running from Kamchatka to the Philippines, the shallow seas of Japan and China becoming inland valleys.

FIG. 6. Relief Map of Africa. (From Frye's Complete Geography, by permission of Ginn & Co., Publishers.) The reader should notice how the highest mountains along the east coast face the Indian Ocean, which is a continuation of the Pacific.

plateau is comparable with that in Asia, and it is easy to see how the relief of the Pacific on our side may have taken the form of a table-land of greater width but smaller height. The numerous parallel mountain chains west of the Rocky Mountains show the nature of the mighty forces at work, and prove that this uplift was the work of the Pacific Ocean.

§ 27. *The forces which have raised the mountains and plateaus of the globe are identical with those which have raised the continents above the sea, and all these forces depend on the leakage of the oceans.*—The geological evidence of the slow operation of the forces which have uplifted the plateaus and mountains shows the immeasurable ages during which they have been at work. Sometimes large portions of a continent have risen for a time, and again slowly subsided, and thus have arisen the phenomena noted in the sedimentary rocks studied in geology. These gentle movements often are without violent earthquake shocks, because the yielding is very gradual, and the crust is slowly raised up and down without breaking. It is only where the expulsion of lava from under the sea is rapid and violent that breaking develops at such rate as to form mountain chains and plateaus. The uplift of a plateau also requires a large amount of material. Where the process is gentle and gradual a whole continent may be slowly uplifted, and this process evidently has raised the low broad plains above the water. *The cause of epeirogenic and of orogenic movements is everywhere one and the same.* The movements take different forms according to the suddenness with which the forces act; but both depend on the leakage of the oceans, and not at all on the secular cooling of the globe, the effect of which is insensible.[1]

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[1] Since this was finished the writer has carefully recalculated the shrinkage of the earth's radius in 2,000 years, and finds that it can not exceed 1.5 inches. This takes no account of the increase of the interior heat of our globe due to radio-activity. If this latter effect were taken into account probably there would be no shrinkage whatever. Quite independently of these effects, however, there is an actual expansion of the globe due to the leakage of the oceans.

In the same way it is found, by the application of Fourier's theory of heat to the cooling at the surface, that the total shrinkage in the *length* of a continent such as North or South America, assumed to be equal to the terrestrial radius in length, is less than 1.5 inches. This again takes no

Such an inference seems justified by the study of the mountains and plateaus of the world, and also by the movement of the strand line which Professor Suess has so carefully traced in every country. Almost everywhere the level of the sea has been lowered in recent geological time.

During his travels in South America, Darwin recorded many observations to show that Patagonia and the whole end of the continent south of the La Plata had been recently elevated above the sea; and he mentions a channel in the Andes quite a distance north of the Straits of Magellan which gave evidence of the former passage of the sea through it. In view of these well-established facts, can any one doubt that the Straits of Magellan will eventually become dry and Tierra del Fuego be added to Patagonia? This whole region shows vast walls of rock towering vertically thousands of feet above the sea; evidently they were uplifted by earthquake forces from beneath, sometimes working quietly, and again spasmodically.

As surely as Calabria in Italy has been uplifted from the Mediterranean, by that sea, just so surely has the southern end of South America been raised up by the southern ocean. And if an end of a continent can be upraised, obviously whole continents can be uplifted. Accordingly in the leakage of the oceans and the relief taking place under the land which bounds them we have the true cause of continent-making.

Some original inequalities of surface may have existed after the detachment of the moon from the consolidating globe, but these have since been enormously increased by the effects resulting from the leakage of the oceans. As the earth gets older, the lithosphere becomes more diversified, and the face of the earth more and more wrinkled.

The situation of the great plateaus of the world facing the largest oceans gives a clear indication of the nature of the forces at work

account of radium, the effect of which would be to diminish this calculated shrinkage, or do away with it entirely. By such comparisons as these, placed along side of the large horizontal and vertical movements noticed in earthquakes near the sea, which sometimes amount to from 30 to 50 feet at a single disturbance, we see the utter untenability of the old theories heretofore current in works on geology and the related sciences. Note added July 28, 1908.

Fig. 7. Relief Map of Australia. (From Frye's Complete Geography, by permission of Ginn & Co., Publishers.) The reader should notice how the largest mountains along the east coast face the Pacific Ocean.

FIG. 8. Relief Map of Europe. (From Frye's Complete Geography, by permission of Ginn and Co., Publishers.) The reader should notice how the principal mountain chains face the Mediterranean and the Atlantic. There is a trough in the sea bottom off the Scandinavian coast to which Professor Schiaparelli has called attention.

by which these mighty uplifts have been produced. The complex folding of the mountains to the east of Tibet shows that the Pacific aided the Indian Ocean in producing this great uplift, but we cannot yet determine the relative importance of the parts played by the two oceans.

§ 28. *On the Origin of the Alps and on the Extreme Crumpling and Folding which They Exhibit.*—The remarkable crumpling and folding noticed in the Alps has long been a matter of surprise and wonder to the naturalist. This phenomenon has always presented great difficulty to those who have attempted to explain the origin of the Alps. In the paper on the "Cause of Earthquakes" (§§ 14, 16, 18, 23) we have outlined the theory of how the Alps were formed by the sea, and criticised the old theories as totally inadequate to account for the observed crumpling. We propose here to develop the new theory a little further, and to show how it accounts for all the facts observed in a range such as the Swiss Alps, which are generally recognized as about the most complex system of mountains known upon the globe. If the new theory will explain the Swiss Alps, it will obviously explain any other mountain system in the world. The test of the theory as applied to the Alps may therefore be regarded as an *experimentum crucis*.

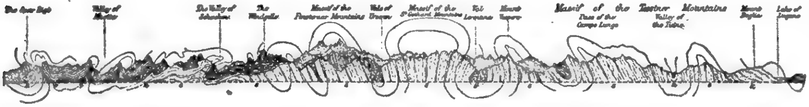


FIG. 9. Complex Folding. Section Across the Alps from the Neighborhood of Zürich toward Como; about 110 miles. (Heim and Prestwich.)

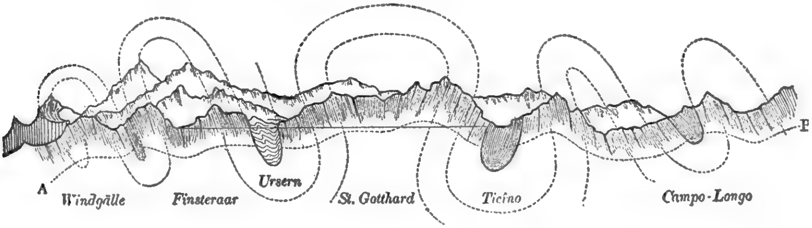


FIG. 10. Section through the Alps, Showing the Effects of Complex Folding. (From Heim's Gebirgsbildung.) The line of the St. Gotthard Tunnel and the plane of equal temperature, *AB*, beneath it, are compiled from F. Giordano, in *Bollettino del R. Comitato Geologico d'Italia,* Vol. XI., 1880, pp. 408–50.

The accompanying figures exhibit: (1) A general section of the Alps from Zürich to Lake Como (Heim and Prestwich), and (2) a section on a larger scale of a portion of the central Alps (from *Heim's Gebirgsbildung*) with fan-shaped folds and inversion of strata on the two sides. It can hardly be assumed that these illustrations are extremely accurate, but no doubt they are free from large errors in exhibiting the general character of the folding, which gives here and there fan-shaped structures with overturned dips at the sides.

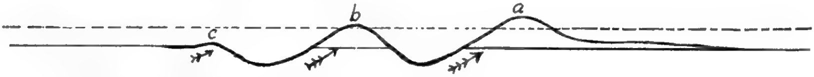
Now the explanation of such structures is the most difficult problem heretofore presented to the geologist. They exhibit conspicuous lateral and vertical movements which cannot well be accounted for by the contraction theory. A shortening of about 74 miles (Heim) in the folding, which has amounted to 50 per cent. of the whole span of crust (Leconte), can not be accounted for, on the old theory, without assuming that the crust is loose from the globe, so that a vast amount of slack could be brought forward and concentrated in the folds at one point, in the Swiss Alps. This is clearly unthinkable. On the other hand, the cone of matter underlying the Alps with vertex at the center of the earth could not be sufficiently condensed to give the required slack in the overlying crust without increasing the density of the cone by 50 per cent., which could easily be detected by geodetic observations, owing to the resulting deviations of the plumb line. Accordingly we may feel sure that the matter under the Alps not only is not denser than the average, but actually lighter, by an appreciable amount. The crumpling of the Alps cannot therefore be due to condensation beneath these mountains.

How then did the folding arise?

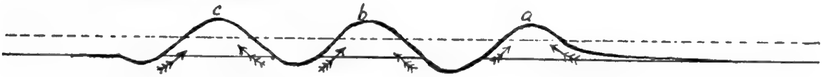
If we cut a section across the Aleutian Islands perpendicular to the chain and the parallel trench lying to the south, we shall have a figure something like that shown in figure 1 of the following plate. Now in the paper on the "Cause of Earthquakes" (§ 16) we have shown how the undermining of the sea bottom sinks the trough down deeper and deeper, and as the expulsion of lava continues it eventually becomes easier to fold up the side of the trough towards the ocean (at *b*) and make another range of mountains parallel to the first. And there is nothing to prevent the process from being repeated several times. When several successive ranges of mountains are thus developed in the process of expulsion under the margin of the sea, it is easy to see that the central range may finally be driven upward and flared out at the top exactly as in the Alps. Thus all this movement occurs in the sea, and eventually the range becomes like that now seen in Switzerland, as depicted by Heim, of Zürich.

1. *Mountain Range rising in the Sea.*

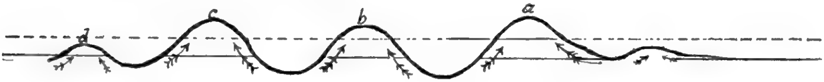
2. *Double Range forming.*



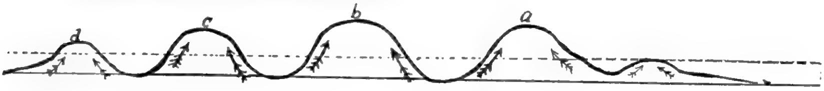
3. *Triple Range beginning.*



4. *Movement from both sides.*



5. *Movement from both sides continued.*



6. *Whole Mountain Range rising from the sea.*

7. *Rising from the sea continued, giving fan-shaped structures and overturned dips.*

FIG. 11. Illustration of Formation of Complex Range, such as the Swiss Alps. The bending of the crust has caused it to pull apart at the top and bottom of the folds, where it is largely covered by sedimentary deposits and filled by molten rock from beneath, so that the breaks do not show at the surface, unless erosion has laid bare parts of the underlying structure. In these figures the thickness of the crust is less than half the width of the folds; and for clearness the depth of the sea is exaggerated.

As the movement continues the central range rises upwards, while its flanks sink down on either side, and thus the fan-shaped structure develops, so as to give overturned dip and inversion of strata once deposited horizontally in the bed of the sea.

This is a perfectly simple and direct explanation of one of the most mysterious phenomena heretofore encountered by naturalists.

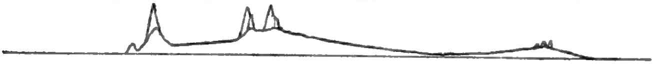
The new theory of mountain formation is proved to represent a real law of nature by phenomena now witnessed in the Aleutian Islands, Japan and elsewhere. The fact that it perfectly accounts for the perplexing phenomena seen in the Swiss Alps, shows that they too were formerly under the sea, and were uplifted by the same force now at work in the Aleutian Islands and the Antandes.

Accordingly it is not remarkable that Professor Suess should, without knowledge of the *true cause,* describe the uplift of the Alps from the sea in words which are almost prophetic ("Face of the Earth," Vol. II, p. 552):

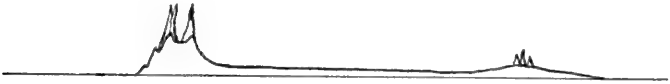
> "As a result of *tangential thrusts,* the sediments of this Sea (Mediterranean) were folded together and driven upward as a great mountain range, and the Alps have therefore been described as a compressed sea."

Without overestimating the significance of this result, it seems clear that neither parallel ranges nor fan-shaped structures with inverted dips will hereafter present any further difficulty to the geologist. Now that the true laws of such phenomena are known, it will be exceedingly interesting to work out the details of all the great mountain systems with which the earth is adorned.

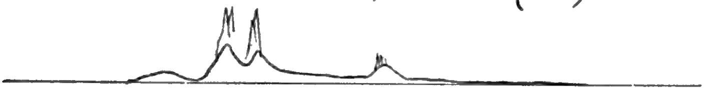
§ 29. *All Complex Folding now seen in Mountain Ranges Originated in the Sea.*—It is scarcely necessary to add that all the complex folds now seen in mountain ranges were produced in the sea by the repetition of trenches dug out by earthquakes. The folds were frequently broken apart at both top and bottom, by the earthquake movements, and thus the folded crust is not shortened by anything like so much as has been supposed. Moreover where the fan-shaped structures and overturned dips appear, the two sides were never joined together by an arch above, as represented in the above figures by Heim, but were quite separated before the range arose to any considerable height. Accordingly it follows that erosion has not worn off anything like so much of the top of the range as the theory of a rounded arch would require. Thus we may not only explain the folds of the Alps, but also recognize that the folds both above and below were less extensive than was formerly supposed; and this greatly simplifies the labor of the geologist in restoring the former structure of mountain chains as they appeared before they were greatly eroded.



Section of North America, East to West (Dana).



Section of South America, East to West (Dana).



Section of Asia, North to South (Dana).

Section of Africa, North to South (Dana).

Section of Africa East to West (Dana).

Fig. 12. Sections of the Continents, and of the Alps and Himalaya on the same Scale. (Gen. Strachey.)

The process of undermining the sea bottom in the expulsion of lava arising from the leakage of the ocean, has given rise to all the important folds of the earth's crust. Thus arose all the complicated folds in the Alps, Andes, Alleghenies and other mountain ranges. And wherever we see these folds sea trenches once existed, and the crust was pushed hither and thither by earthquakes, raising ridges and undermining the troughs, till the rocks were crumpled and folded as we find them to-day. *The simplicity of this cause, and the easy way in which we pass from the living troughs now being dug out in the sea to fossil troughs long since dead and now far inland give a genuine paleontological interest to the science of mountain formation.* What has long been mysterious and nearly inexplicable is now as clear as any theorem in geometry.

§ 30. *Application of the New Theory to the Allegheny Mountains.*—The Allegheny Mountains in Pennsylvania and Virginia are very remarkable for the great extent of the folds, and it seems worth while to dwell a moment on the mode by which these folds were produced. We have seen that they all arose in the sea, and by a repetition of the earthquake process of digging out trenches along the ancient shore line. As we shall see in Part V, § 41 of this paper, Professor James Hall so long ago as 1857 announced to the American Association in session in Montreal that the enormous thickness of the formations along the Appalachian Chain in the United States was due to the prolonged accumulation of sediments over a sinking sea bottom, at the margin of the continent, where the marine currents allowed the material to deposit.

Obviously if sea trenches were dug out by earthquakes they would become the basins for the accumulation of a vast amount of detritus. And when several trenches were successively dug out in the sea bottom by earthquakes depending on the Atlantic, would not the resulting folds give us the Allegheny, Tuscarora and Blue Ridge Mountains of Pennsylvania and Virginia? The famous Shenandoah Valley in Virginia is nothing but an ancient sea trough; and Pennsylvania has many such valleys originally formed in the depths of the sea. This is clearly indicated by the beautiful parallelism of the mountain ranges.

It is noticeable that the sea trench south of the Aleutian Islands is remarkably straight, and one may easily predict that the ranges hereafter to be formed in the North Pacific Ocean will be remarkably parallel like those now seen in Virginia and Pennsylvania. Under the circumstances can any one doubt that the sea was once very deep near where the Blue Ridge stands to-day?

Excluding from consideration the crystalline belt on the east, Claypole estimated the shortening of the Appalachians in Pennsylvania at 46 miles. In the same way McConnell estimated that of the Laramide range in British America at 25 miles, and Leconte that of the Coast Range in California at from 9 to 12 miles. Corresponding estimates have been made for many other mountain ranges; but, for reasons already given in dealing with the origin of the Swiss Alps, § 28, these estimates are too large. The crust was broken apart at both top and bottom when the ranges were in the sea, and the folds heretofore assumed to be complete were never really so. Consequently no slack in the earth's crust is required to explain these folds; it was never loose from the globe and never moved horizontally, except when forced by earthquake movements proceeding from the underlying trenches in the sea bottom.

The undermining and folding of the crust has given the Appalachian Mountains in many places the aspect of a series of immense billows, running parallel, as if swept in by a vast disturbance of the sea. But not even seismic sea waves of the most imposing magnitude could approach the size of these gigantic folds, the origin of which heretofore has been so mysterious. The finding of a simple and natural explanation of *these great billows of the land* will be scarcely less interesting than the discovery of the cause of seismic sea waves. Both depend on earthquakes, though in very different ways. The land billows are cumulative products of an infinite series of seismic disturbances along the margin of the sea; the seismic waves are small in comparison, and result from a single disturbance of the sea bottom, made in process of shaping the vast billows of the land, which in all generations have appealed to the imagination of the painter, poet, and student of nature.

§ 31. *Analogy Between the Uplift of the Islands of Japan by the Movement from the Tuscarora Deep and of the Plateau of Tibet from the Indian Ocean.*—The uplift of the Islands of Japan now going on by the expulsions of lava from beneath the Tuscarora Deep is proved by the terrible earthquakes and seismic sea waves afflicting that region, as well as by the historical fact that the east coast of Japan is known to be rising from the sea. Perhaps in general the movement is slow and insensible, but occasionally earthquakes have produced large disturbances of the level. The nature of earthquake movement in expelling lava from under the sea is too well known to leave any doubt as to what is going on in Japan. And the theory is confirmed by the fact that if Nipon and Yezo were dug off and thrown into the Tuscarora Deep they would about fill up that profound abyss and leave the sea of average depth.

Now there is a certain analogy between the uplift of these Japanese Islands, which are considerable areas, by the Pacific, and of the Plateau of Tibet by the Indian and Pacific oceans combined. Undoubtedly the valleys of the Indus, Ganges and Brahmaputra are the relics of ancient sea troughs which largely produced the Himalayas and the great plateau of Tibet. How much these troughs have been modified in later geological times we cannot estimate; but even now enough remains to tell the true story of Himalayan development. This is also indicated by the preservation of the earthquake belt south of the Himalayas. The meaning of these valleys and earthquake belts admits of no possible doubt. Just as the whole island of Nipon is being raised by movements from the Tuscarora Deep, so the whole of the Plateau of Tibet was once raised by an Indian Deep, of which these valleys are the remains.

In the same way the Valley of the Po is the remains of the sea valley which was most influential in uplifting the Swiss Alps. But in the case of the Alps, Geikie has shown that there was also a sea on the north, which has now quite disappeared, though traces of its former existence still remain.

§ 32. *The Origin of Volcanoes and the Conditions of their Maximum Development.*—It appears from the line of proof developed in this theory that volcanoes may break forth in any region near the sea where there are severe earthquake disturbances, by which the crust of the globe is sufficiently cracked to afford a vent for the steam imprisoned beneath. Now such vents are greatly facilitated in a chain such as the Aleutian Islands, in which the crumpling is extreme, and the expulsion of lava from beneath the sea rapid and violent. The crumpling breaks the crust along many lines, and as the earthquakes due to the expulsion of lava are both frequent and terrible, the chance of steam breaking through to the surface is much greater than in regions less wrinkled and less afflicted by earthquakes. The crust in the Andes was once folded by the sea in the same way as that in the Aleutian islands, and from this circumstance arises the violence of the volcanic outbreaks noticed all along the west coast of South America. From the great similarity of the volcanic phenomena in the Andes and in the Aleutian Islands, and its enormous prominence in both ranges, it seems obvious that we have here the conditions for its maximum development.

Charles Darwin believed that volcanoes usually break out in regions of elevation. No doubt this is true, for mountain ranges are the most conspicuous of rising areas. And according to this theory the tendency to rupture the crust is a maximum, when the ranges are being both folded and raised from the sea. Thus while some volcanoes may break out in less fractured regions of the earth's crust, the greatest volcanic activity develops where mountains are being formed in the sea, as in the Aleutian Islands. This view also enables us to understand why many volcanoes in the Andes are now extinct, though they were formerly active for immense periods of time, as we know from the thick deposits of volcanic debris and the immense height of the cones built up of lava, ashes and cinders.

## IV. Comparison of the New Physical Theory of Mountain Formation Depending on the Leakage of the Oceans with the Theory of Secular Cooling and Contraction Heretofore Held by Men of Science.

§ 33. *General Remarks on the Method of Comparison Adopted.*—The new physical theory of mountain formation depending on the leakage of the oceans outlined in the three memoirs recently published by the American Philosophical Society and somewhat more fully developed in the present paper might seem incomplete if we failed to compare the new theory with the theory of secular cooling and contraction of the globe heretofore held by men of science generally. On several grounds an examination of the older theory can hardly fail to be instructive. And if this comparison of the older theory with that now adopted shall be the means of harmonizing in any considerable degree the divergent views heretofore prevailing, and of showing *that there is no important geological phenomenon which the new theory does not explain in a more simple and direct manner than the old theory,* such a comparison will no doubt seem quite justifiable. For it is highly desirable to establish the adequacy of the new theory to explain the *geological* as well as the *physical* phenomena noticed at the surface of the earth.

In making this comparison it is necessary to bear in mind that the geological data on many points are still very incomplete, and therefore we should expect agreement with the body of phenomena rather than with the details, about which much uncertainty still exists. Owing to the incompleteness of our knowledge of the mode of origin of the great mountain chains of the globe, the best plan of procedure seems to be: First, to give an exposition of the views of previous writers in regard to the individual great mountain systems; second, to add a résumé of the views of certain great geologists on mountain formation in general. Obviously such condensation of the views of others should wherever possible be given in their own words.

As this subject is extensive and widely scattered in a variety of publications, we must content ourselves with selecting those citations which seem of most interest, without in any way claiming to exhaust the subject. Indeed it may well be that some discussions of value will be entirely overlooked, but, as the theories have been but very little changed for many years, it is hoped that the following citations will be found adequate to give an intelligent grasp of the views heretofore accepted by the leading authorities. If there be those who doubt the propriety of including lengthy quotations from well-known authors, I must plead in extension of the course here adopted, that this memoir is intended for others besides geologists, and that all who are interested in the physics of the earth, whether they be mathematicians, astronomers, physicists, seismologists, geologists, or even chemists and biologists, are entitled to have a clear summary of the principal theories heretofore accepted in regard to the development of our globe. In dealing with a subject of such universal interest to all men of science, any reasonable condensation of the previous theories may be considered admissible, and one may have no hesitation in invoking the aid of many authors. If the establishment of a great law of nature may be thus facilitated, surely no one will doubt that the space utilized was devoted to a most useful purpose. The extreme specialization characteristic of the science of our day makes such summaries both useful and necessary for the intelligent study of great problems; and if more effort were made in this direction it might contribute materially to the progress of scientific research.

### (A) Accounts of Particular Mountain Systems, and Their Supposed Mode of Development.

§ 34. *The Andes.*—We shall begin with the Andes of South America, because this is one of the largest, simplest and most typical of mountain systems; and if a theory will not explain the Cordilleras, we may despair of its explaining the more complicated mountains of the globe. The reader should carefully bear in mind not only what the author in question says from his own point of view, but also how the facts he mentions accord with the new theory developed in this paper.

In the *Encyclopedia Britannica,* ninth edition, under the article "Andes," we find the following lucid exposition of Andean development. It is not signed, but is supposed to have passed under the review of Sir Archibald Geikie.

> "The formation of the Andes is due to several causes operating at distinct intervals of time. They consist mainly of stratified material which has been more or less altered. This material was deposited at the bottom of a sea, so that at some former time the highest portions were submerged, probably in consequence to a certain extent, of subsidence of the sea bottom. Since the latest deposits there has been upheaval and denudation. The range, then, has resulted from the accumulation of sediment on a subsiding area; from the subsequent upheaval of such deposits, which have been increased in height by the ejection of volcanic products; and from the operation of denuding agents.
>
> "As far as our present knowledge goes, it appears to be probable that the Andes mark an area on which sedimentary deposits have been accumulated to a greater thickness than on any other portion of South America. It is further demonstrable that these deposits belong to several geological periods, the elevation having occurred at different periods, while their axes extend in different directions. Hence it is a complex range of mountains formed by the combination of several distinct systems of ridges. The width of the

range varies from about 60 to 300 or more miles, but, as compared with other mountains, the Andes are for the most part narrow relatively to their height. Where their special features are most characteristically developed, they consist of a massive embankment-like foundation, rising with a rapid slope from the low country on either side, and having its margins surmounted by lofty ridges of ragged or dome-like summits. These Cordilleras, as they are usually termed, flank longitudinal valleys, or plain-like depressions which form the highest levels of the central portion of the gigantic embankment, and which vary in width from twenty to sixty miles. At intervals the longitudinal depression is broken up, either by ridges connecting the Cordilleras, or by lofty plateau-like uplands. In several cases these transverse ridges and belts of high ground form the main watershed of the country. They are rarely cut across by the river systems, whereas both the marginal Cordilleras are intersected at numerous points, and more especially by the rivers draining the eastern slope of the country. In no case do these eastern rivers originate to the west of the western Cordilleras. A few of the central valleys, or plain-like depressions, have no connection either with the western or eastern river system. Roughly speaking the height of the central plains or valleys is from 6000 to 11,000 feet above the sea; of the passes and knots, from 10,000 to 15,000 feet; and of the highest peaks, from 18,000 to 23,290 feet—the last being the altitude of Aconcagua in Chili, which is generally considered to be the highest peak in America. Judging from these estimates, we may regard the bulk of the Andes as somewhere about that of a mass 4400 miles long, 100 miles wide, and 13,000 feet high, which is equivalent to 5,349,801,600,000,000 cubic feet. On this basis we find that the Mississippi would carry down an equivalent mass of matter in 785,000 years. The rate of denudation in certain river basins varies from one foot in 700 years to one foot in 12,000 years. Assuming that similar rates would apply to the Andes, they would be denuded away in from 9 to 156 million years. In all probability, much less than 9 million would suffice. On the other hand the Andes would be swept away in 135,000 years, supposing the denuding powers of the globe were concentrated on them alone. From the above data, and assuming the average specific gravity of the matter forming the Andes to be 2.5, the weight of the portion above the sea may be estimated at 368,951,834,482,750 tons, giving an average of about 1,000 tons on each square foot at the level of the sea. Under Aconcagua the pressure would be about 1,780 tons per foot at the same level, provided, of course, it were not, as it no doubt is, more or less modified by lateral pressure. These figures afford some, though at best a vague, conception of the mighty grandeur of this range of mountains, and of the scope there is for the exertion of enormous pressure. How vast then, must be those forces which have counteracted such pressures, and upheaved the ocean-spread sediments of the continents, until the Andes, that

'giant of the Western Star,
Looks from his throne of clouds
O'er half the world!'

But, however vast the Andes may seem to us, it should be remembered that they form but an insignificant portion of the globe itself. Aconcagua is about 1/2,000 of the earth's diameter, which is relatively not more than a pimple 1/30 of an inch high on the skin of a tall man." (Ency. Brit., Vol. II, pp. 15–16.)

The account here given of how the Andes were formed seems exceedingly instructive. In the sea troughs formerly existing between the ocean and the eastern range, which was the first thrown up, we have a complete explanation of the extraordinary depth of sedimentation; for in such trenches adjacent to a new range the rate of sedimentation would be a maximum. The subsequent uplifting of the western side of the sea troughs, with the vast lateral folding and compression necessarily accompanying this movement, accounts for the plateaus, valleys and general structure of the Andes, as well as for the violent volcanic outbreaks, which are said to greatly predominate in the range nearest the sea, from which the expulsion of lava giving rise to this mighty Cordillera proceeded. The vastness and height of the Andes and the terrific forces operating to erect this gigantic wall along the shore of the continent is a true measure of the secular leakage of the Pacific Ocean, and of the automatic relief it finds by folding the earth's crust along the border, in the countless successive expulsions of lava from beneath the bed of the sea. It is needless to point out how perfectly the new theory explains the persistence of the earthquake belt along the western shore of South America, and of the seismic sea waves by which that region is so often afflicted. It is obvious that the forces which uplifted the mountain also carried up the plateaus enclosed between the various ranges.

§ 35. *The Himalayas.*—The following luminous account of the Himalayas by the late Lieutenant General Sir Richard Strachey, *Encyclopedia Britannica,* article "Himalayas," is of extreme interest. General Strachey resided in India for many years, and made a life long study of the Geology and Geography of Central Asia. He was the principal authority of his time on this little explored continent and died February 12, 1908, at the age of 91 years.

"Scientific investigation has clearly shown that, so far as the main characteristics of the mountains are concerned, the natural boundaries of the Himalayan system must be carried much farther than had at first been recognized. Considerable obscurity still involves the eastern portion of these mountains, and there is great want of precise knowledge as to their connection with the ranges of western China, from which are thrown off the great rivers of China, Siam, and Burmah. On the west, however, it has been completely established that a continuous chain extends beyond the Indus along the north of the Oxus, and ends in that quarter about 68° E. long. In like manner it is found that no separation can be established, except a purely arbitrary one, between the Himalaya as commonly defined and the greatly elevated and rugged table-land of Tibet; nor between this last and the mountain ranges which form its northern border along the low-lying desert regions of central Asia.

"It thus appears that the Himalaya, with its prolongation west of the Indus, constitutes in reality the broad mountainous slope which descends from the southern border of the great Tibetan table-land to the lower levels of Hindustan and the plains of the Caspian; and that a somewhat similar mountain face, descending from the northern edge of the tableland, leads to another great plain on the north, extending far to the eastward, to the northern borders of China. Towards its northwest extremity this great system is connected with other mountains—on the south, with those of Afghanistan, of which the Hindu-Kush is the crest, occupying a breadth of about 250 miles between Peshawur and Kunduz; and on the north, with the mountains that flank the Jaxartes or Sir on the north, and the Thian-shan or Celestial Mountains. The eastern margin of Tibet descends to western China, and the south-eastern termination of the Himalaya is fused into the ranges which run north and south between the 95th and 100th meridians, and separate the rivers of Burmah, Siam, and western China.

"Nor can any of the numerous mountain ranges which constitute this great elevated region be properly regarded as having special, definite, or separate existence apart from the general mass of which they are the component parts; and Tibet cannot be rightly described, as it has been, as lying in the interval between the two so-called chains of the Himalaya and the Kouenlun or Kara Koram. It is in truth the summit of a great protuberance above the general level of the earth's surface, of which these alleged chains are nothing more than the south and north borders, while the other ranges which traverse it are but corrugations of the mass more or less strongly marked and locally developed.

"The average level of the Tibetan tableland may be taken at about 15,000 feet above the sea. The loftiest points known on the earth's surface are to be found along its southern or Himalayan boundary; one of them falls very little short of 30,000 feet in elevation, and peaks of 20,000 feet bound the entire chain. The plains of India which skirt the Himalayan face of the tableland, for a length of rather more than 1,500 miles, along the northern border of British India, nowhere rise so much as 1,000 feet above the sea, the average being much less. The low lands on the north, about Kashgar and Yarkend, have an elevation of from 3,000 to 4,000 feet, and no part of the Central Asiatic desert seems to fall below 2,000 feet, the lake of Lob-nor being somewhat above the level. The greatest dimension of the Tibetan mountain area from east to west may be about 2,000 miles, while its average breadth somewhat exceeds 500 miles; about 100 miles on either side constitute the sloping faces, the central tableland having a width of about 200 miles on the west and probably 500 miles at its eastern border."

General Strachey thus shows that the Himalayan mountains and Tibetan Plateaus are directly and intimately connected as merely different parts of one great continuous movement of the earth's crust.

After describing many features of the Himalayas, General Strachey continues:

"The general conclusion that may be drawn from the facts of structure thus briefly indicated is that the elevation of the Himalaya to its present great height is of comparatively recent occurrence. An area of land must have existed where the main line of snowy peaks now stands, which has not been submerged since the Palæozoic period, and which then had its northern boundary somewhere along what has been termed the Indian watershed. Evidence of a similar ancient sea on the south also exists, but in less definite shape; and whether it was united with the northern sea or not is still a matter of conjecture, though the distinctive character of the fossils rather indicates that there was no direct union. The possible connection of this ancient Himalayan land area with the pre-Tertiary land of the peninsula of India is also only a matter for speculation.

"There is further reason to infer that the existence of the great line of peaks is rather due to some previous line of elevation on the ancient land, which has continued to retain its relative superiority while the whole areas have been raised, rather than to any special line of energy of upheaval of recent date; and that the fundamental features of its former configuration of surface in mountain and valley have been preserved throughout. There is evidence for the conclusion that the chief rivers of the pre-Tertiary land issued from the mountains where the present main streams are found, and this embryo Himalaya may have been of such moderate height as to have permitted the passage across it of the Siwalik mammals, the remains of which appear both on the border of the Indian plain and in Tibet. It is after the middle Tertiary epoch that the principal elevation of these mountains must have taken place, and about the same time also took place the movements which raised the tablelands of Afghanistan and Persia, and gave southern Asia its existing outlines.

"The best answer that can be given to an inquiry as to how changes of level could have arisen, such as those which are observed in the Himalaya, is that they should be regarded as due rather to secondary actions consequent on the general contraction of the cooling terrestrial sphere than to direct elevating forces, for which no known origin can be assigned. The contraction of the cooling but now solid crust of the earth must have set up great horizontal strains, partly of tension and partly of compression which would necessarily have been followed by rupture or crushing along lines of least resistance, and the movements on such lines are marked by the great mountain ranges that traverse the surface. A dislocation of the solid crust of the earth once having taken place, it would probably continue to be a line of least resistance ever after, and a succession of movements during past geological periods may thus be reasonably expected along such lines. Somewhat in proportion as the disturbing forces are intense, and the thickness of the crust on which they act is great, will be the tendency of the lines of rupture to be continuous for a considerable distance; and as the disturbed area is extended in its dimensions, the probability will increase of a repetition of a series of similar dislocations on lines approximately parallel to, or at right angles to, one another and to the line on which the greatest compression and consequent tension take place. In a disturbed area, one transverse dimension of which is sensibly greater than the rest, the longitudinal ruptures will predominate in the interior and the transverse towards the borders. Almost all mountains give indications of having been shaped by forces thus related, and to the action of such forces may the main characteristics of the structure of the Himalaya, and the arrangement of its ridges and valleys be attributed. Whatever may be the power of rivers in general as instruments of erosion, and whatever effect the Himalayan rivers have had in removing the fragments of the rocks over and among which they took their courses, it is hardly possible to doubt that their main directions were determined by the anterior lines of dislocation which opened up hollows down which they could flow, and which must invariably have been accompanied by a destructive and crushing action on the rocks along them, which has enabled the waters the more readily to sweep away the obstacles in their path. The parallelism of many of the great Tibetan and Himalayan rivers for hundreds of miles together, and such mountains, seems wholly inexplicable in any other manner." (Ency. Brit., p. 828.)

This account is quite clear and satisfactory, except that part of it which deals with the cooling and contraction of the globe. Here General Strachey has made the best of a very inadequate hypothesis.

Just as the Andes were formed by expulsions of lava from under the Pacific, so also here the Himalayas were formed by a corresponding movement due mainly to the Indian Ocean, which has also raised high mountains along the eastern border of Africa. We cannot yet give all the details of the Himalayan development, but in general it is evident that it was similar to that of the Andes. The uplift of the great plateau of Tibet corresponds to that of Titicaca. And the parallel ranges of the Himalayas originated by the usual process of the folding up of successive sea trenches. On the outside of these mountains there still remain trough-like depressions where the Indus, Ganges and Brahmaputra now flow. The undermining produced in raising the Himalayan embankment still shows in the valleys to the south, though the sea has receded; and the great earthquake belt south of the Himalayas still discloses to us the nature of the forces which produced this mighty uplift.

The following critical passages by General Strachey are also of decided interest:

> "The great peaks are, with few exceptions, composed of schistose rock, though granite veins may be seen in the mountain faces to very great elevations; one of these exceptions is the great peak of Kamet in Kumaon, which rises to about 25,000 feet in what appears to be a mass of grey granite.
>
> "Passing to the north of the line of great peaks the metamorphosed schists are suddenly replaced by slates and limestones, which are in many places highly fossiliferous, exhibiting what appears to constitute in the aggregate a fairly continuous series from the Lower Silurian to the Cretaceous formations, though the complete sequence has not been observed in any one locality. The western region of the Himalaya alone has been sufficiently explored to admit of any positive statements, but the indications gathered from such imperfect accounts and other data as exist relative to the eastern parts of the mountains leave little doubt that the change observed in the west on approaching and entering Tibet holds good on the east also, and that the general physical features of the whole tract are much alike, though doubtless with many differences in detail.
>
> "The fossiliferous strata of western Tibet are continued, though perhaps with some breaks, to the Tertiary period. In certain localities nummulitic rocks, probably Eocene, have been observed, and from the great alluvial deposit which forms the plain of Gugé, already noticed, the remains of mammals, apparently of Siwalik age, have also been obtained. Among these were bones of the elephant and rhinoceros, the existence of which, in the present condition of these regions, would be wholly impossible; so that there is no room to doubt that these deposits have been raised from a comparatively low level to their existing great elevation of upwards of 15,000 feet, since they were laid out. As in the case of the plain of India, we here, too, have no complete proof of the origin of these great nearly horizontal deposits, but it seems clear, from the materials of which they are formed, that they must have been laid out by the water, either by the sea or some great inland lake. They are largely composed of boulder deposits, and large boulders are strewed over the surface imbedded in the ground in a manner that seems only explicable as the result of the action of a considerable body of water.
>
> "Several lines of granitic and eruptive rock occur in western Tibet, of which all that need here be said is that they appear all to be older than the Tertiary alluvium, but some of them are possibly contemporaneous with the nummulitic and older formations." (Ency. Brit. p. 828.)

In an earlier passage, after comparing some of the smaller Himalayan ranges to the Swiss Alps, General Strachey adds:

"To obliterate these two ranges from the Himalaya would make no very sensible inroad on it, though they surpass in bulk the whole of the Swiss Alps; and it is no exaggeration to say that, along the entire range of the Himalaya, valleys are to be found among the higher mountains into which the whole Alps might be cast without producing any result that would be discernible at a distance of ten or fifteen miles. And it is important to bear in mind these relations of magnitude, for the terms at our disposal in the description of the mountains are so limited that it is necessary to employ the words chain, range, ridge, spur, etc., rather with reference to relative than to absolute importance, so that the scale of our nomenclature changes with the extent and altitude of the mountains of which we speak." (Ency. Brit., p. 827.)

§ 36. *The Alps.*—In the *Enclycopedia Britannica,* article "Alps," by John Ball, we find the following brief outline of the salient features:

"Accurate knowledge of the Alps is so recent that few attempts have been made to establish a general division of the entire region, and it cannot be said that any one arrangement has obtained such general recognition as not to be open to future modification; but there is a pretty general agreement as to the main features of that here proposed, to which a few general remarks must be premised.

"Whatever may have been the original cause of the disturbances of the earth's crust to which great mountain chains owe their existence, it is generally, though not universally, true that the higher masses (formed of crystalline rock and geologically more ancient) are found towards the central part, and that these are flanked by lower ranges, composed of more recent rocks, which surround the central groups very much as an outer line of entrenchment may be seen to surround a fort. In most cases it is not possible to descend continuously in a nearly direct line from the crest of a great mountain chain to the plains on either side, for there are usually intermediate valleys, running more or less parallel to the central range, which separate this from outer secondary ranges. These in turn, are often accompanied by external ranges, intermediate between them and the plains, and related to them as they are to the central ranges. The type of arrangement here described is more or less traceable throughout the greater part of the Alps, but is most distinctly exhibited in the eastern portion lying between the Adige and the frontier of Hungary. We have a central range, composed mainly of crystaline rock; a northern range, formed of secondary rocks, separated from the first by the great valleys of the Inn, the Salza, and the Enns; a southern range, somewhat similar to the last in geological structure, divided from the central one by the Rienx, or east branch of the Adige, and the Drave. Flanking the whole, as an external entrenchment on the north side, are the outer ranges of the Bavarian Alps, of the Salzkammergut, and of Upper Austria, to which corresponds on the south side the Monti Lessini, near Verona, the mountains of Recoaro, those of the Sette Comuni, and the considerable masses crowned by the summits of the Grappa, the Col. Vicentino, the Monte Cavallo, the Monte Matajur, and Monte Nanos. Where, as in the case above mentioned, the secondary ranges of the Alps rise to a greater altitude, and are completely separated from the neighbouring portions of the central chain, it is impossible not to distinguish them as distinct groups; but the outermost ranges, which rarely rise above the forest zone, are in all cases regarded as appendages of the adjoining groups. These outer ranges are called in German Voralpen, and in Italian Prealpi." (Ency. Brit., p. 623.)

Again on page 620, this author remarks:

"In every mountain system geographers are disposed to regard the watershed, or boundary dividing the waters flowing towards the opposite sides of the range, as marking the main chain; and this usage is often justified by the fact that the highest peaks lie on, or very near, the boundary so defined. In applying this term in the case of the Alps, there are, however, difficulties arising from their great extent and the number of their branches and ramifications. Many of the loftiest groups lie altogether on one side of that which we call the main chain, and at the eastern extremity, where all drainage is ultimately borne to the Black Sea, we must be partly guided by geological considerations in deciding which of several ranges deserves to be considered pre-eminent." (Vol. I., p. 620.)

Sir Archibald Geikie's discussion of the origin of the Alps, in the article "Geology," *Encyclopedia Britannica* (pp. 373-374), bears on the problem now before us:

"The Alps, on the contrary, present an instructive example of the kind of scenery that arises where a mass of high ground has resulted from the intense corrugation and upheaval of a complicated series of stratified and crystalline rocks, subsequently for a vast period carved by rain, frost, springs and glaciers. We see how, on the outer flanks of those mountains among the ridges of the Jura, the strata begin to undulate in long wave-like ridges, and how, as we enter the main chain, the undulations assume a more gigantic tumultuous character, until, along the central heights, the mountains lift themselves towards the sky like the storm-swept crests of vast earth billows. The whole aspect of the ground suggests intense commotion. Where the strata appear along the cliffs or slopes they may often be seen twisted and crumpled on the most gigantic scale. Out of this complicated mass of material the sub-aerial forces have been ceaselessly at work since its first elevation. They have cut valleys, sometimes along the original depressions, sometimes down the slopes. They have eroded lake-basins, dug out corries or cirques, notched and furrowed the ridges, splintered the crests, and have left no part of the original surface unmodified. But they have not effaced all traces of the convulsions by which the Alps were upheaved."

In his account of the Miocene ("Text-book of Geology," p. 1261, edition of 1903), Geikie says:

> "The Gulf of Gascony then swept inland over the wide plains of the Garonne, perhaps even connecting the Atlantic with the Mediterranean by a strait running along the northern flank of the Pyrenees. The sea washed the northern base of the now uplifted Alps, sending, as in Oligocene time, a long arm into the valley of the Rhine as far as the site of Mainz, which then properly stood at the upper end, the valley draining southward instead of northward. The gradual conversion of salt into brackish and fresh water at the head of this inlet took place in Miocene time. From the Miocene firth to the Rhine, a sea-strait ran eastwards, between the base of the Alps and the line of the Danube, filling up the broad basin of Vienna, sending thence an arm northwards through Moravia, and spreading far and wide among the islands of southeastern Europe, over the regions where now the Black Sea and Caspian basins remain as the last relics of this Tertiary extension of the ocean across southern Europe. The Mediterranean also still presented a far larger area than it now possesses, for it covered much of the present lowlands and foot-hills along its northern border, and some of its important islands had not yet appeared or had not acquired their present dimensions."

On pages 1371-2 of Geikie's "Geology," we find the following interesting passages:

> "*Alpine Type of Mountain Structure.*—It is along a great mountain chain like the Alps that the most colossal crumplings of the terrestrial crust are to be seen. In approaching such a chain, one or more minor ridges may be observed running on the whole parallel with it, as the heights of the Jura flank the north side of the Alps, and the sub-Himalayan hills follow the southern base of the Himalayas. On the outer side of these ridges, the strata may be flat or gently inclined. At first they undulate in broad gentle folds; but traced towards the mountains these folds become sharper and closer, their shorter sides fronting the plains, their longer slopes dipping in the opposite direction. This inward dip is often traceable along the flanks of the main chain of mountains, younger rocks seeming to underlie others of much older date. Along the north front of the Alps, for instance, the red molasse is overlain by Eocene and older formations. The inversions and disruptions increase in magnitude till they reach such colossal dimensions as those of the Glärnisch, where pre-Cambrian schists, and Triassic, Jurassic, and Cretaceous rocks have been driven for miles over the Eocene and Oligocene flysch (pp. 677, 693). In such vast crumplings and thrusts it may happen that portions of older strata are caught in the folds of later formations, and some care may be required to discriminate the enclosure from the rocks of which it appears to form an integral and original part. Some of the recorded examples of fossils of an older zone occurring by themselves in a much younger group of plicated rocks may be thus accounted for.

"The inward dip and consequent inversion traceable towards the center of a mountain chain lead up to the fan-shaped structure (p. 678) where the oldest rocks of a series occupy the center and overlie younger masses, which plunge steeply under them. Classical examples of this structure occur in the Alps (Mont Blanc, Fig. 258, St. Gothard), where crystalline rocks such as granite, gneiss, and schists, the oldest masses of the chain, have been ridged up into the central and highest peaks. Along these tracts, denudation has been of course enormous, for the appearance of the granitic rocks at the surface has been brought out, not necessarily by actual extrusion into the air, but more probably by prolonged erosion, which in these higher regions, where many forms of sub-aerial waste reach their most vigorous phase, has removed the vast overreaching cover of younger rocks under which the crystalline nucleus doubtless lay buried."

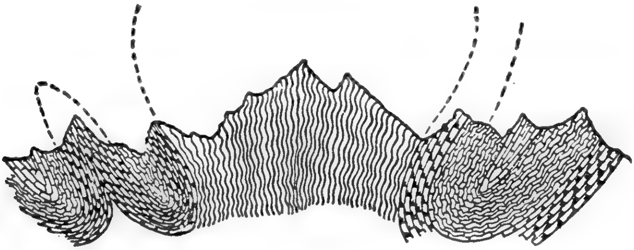


Fig. 13. Fan-shaped Structure, Central Alps.

Again on page 1372, we read:

"A mountain chain may be the result of one movement, but probably in most cases is due to a long succession of such movements. Formed on a line of weakness in the crust, it has again and again given relief from the strain of compression by undergoing fresh crumpling and upheaval. Successive stages of uplift are usually not difficult to trace. The chief guide is supplied by unconformability. . . .

"In most great mountain chains, however, the rocks have been so intensely crumpled, dislocated, and inverted, that much labor may be required before their true relations can be determined.

"The Alps offer an instructive example of a great mountain system formed by repeated movements during a long succession of geological periods. The central portions of the chain consist of gneiss, schists, granite, and other crystalline rocks, partly referable to the pre-Cambrian series, but some of which (Schistes lustrés, Bündnerschiefer) include metamorphosed Palæozoic, Secondary, and in some places, perhaps, even older Tertiary deposits (pp. 802, 1099). It would appear that the first outlines of the Alps were traced out even in pre-Cambrian times, and that after submergence, and the deposit of Palæozoic formations along their flanks, if not over most of their site, they were reelevated into land. From the relations of the

Mesozoic rocks to each other, we may infer that several renewed uplifts, after successive denudations, took place before the beginning of Tertiary times, but without any general and extensive plication. A large part of the range was certainly submerged during the Eocene period under the waters of the wide sea which spread across the center of the Old World, and in which the nummulitic limestone and flysch were deposited. But after that period the grand upheaval took place to which the present magnitude of the mountains is chiefly due. The older Tertiary rocks, previously horizontal under the sea, were raised up into mountain-ridges more than 11,000 feet above the sea-level, and together with the older formations of the chain, underwent colossal plication and displacement. Enormous slices of the oldest rocks were torn away from the foundations of the chain and driven horizontally for miles until they came to rest upon some of the newest formations. The thick Mesozoic groups were folded over each other like piles of carpets, and involved in the lateral thrusts so as now to be seen resting upon the Tertiary flysch. So intense was the compression and shearing to which the rocks were subjected that lenticles of the Carboniferous series have been folded in among Jurassic strata, and the whole have been so welded together that they can hardly be distinguished where they meet, and what were originally clays and sands have been converted into hard crystalline rocks. It is strange to reflect that the enduring materials out of which so many mountains, cliffs, and pinnacles of the Alps have been formed are of no higher geological antiquity than the London Clay and other soft Eocene deposits of the south of England and the north of France and Belgium. At a later stage of Tertiary time, renewed disturbance led to the destruction of the lakes in which the molasse had accumulated, and their thick sediments were thrust up into large broken mountain masses, such as the Rigi, Rossberg, and other prominent heights along the northern flanks of the Alps. Since that last post-Eocene movement, no great orogenic paroxysm seems to have affected the Alpine region. But the chain has been left in a state of unstable equilibrium. From time to time normal faults have taken place whereby portions of the uplifted rocks have sunk down for hundreds of feet, and some of these dislocations have cut across the much older and more gigantic displacements of the thrust-planes (Fig. 282). At the same time continuous denudation has greatly transformed the surfaces of the ground, so that now cakes of gneiss are left as mountainous outliers upon a crushed and convoluted platform of Tertiary strata. Nor, in spite of the settling down of these broken masses, has final stability been attained. The frequent earthquakes of the Alpine region bear witness to the strain of the rocks underneath, and the relief from it obtained by occasional rents propagated through the crust along the length of the chain."

In view of the explanation of the folding of the Alps given in § 28, we need not comment on these views. They confirm the theory outlined in this paper, that the plications of all such chains must be sought in the actions of the sea, and mainly while the range is under water, and not at all in the secular cooling of the globe.

## V. Comparison of the Old and New Theory of Mountain Formation Continued.

### (B) Views of Eminent Geologists on Mountain Formation in General.

§ 37. *Elie de Beaumont's Theory of the Secular Cooling and Collapse of the Globe.*—This venerable theory is thus condensed by Lyell:

> "The origin of these chains depends not on partial volcanic action or a reiteration of ordinary earthquakes, but on the secular refrigeration of the entire planet. For the whole globe, with the exception of a thin envelope, much thinner in proportion than the shell to an egg, is a fused mass, kept fluid by heat, but constantly cooling and contracting in dimensions. The external crust does not gradually collapse and accommodate itself century after century to the shrunken nucleus, subsiding as often as there is a slight failure of support, but it is sustained throughout whole geological periods, so as to become partially separated from the nucleus until at last it gives way suddenly, cracking and falling in along determinate lines of fracture. During such a crisis the rocks are subjected to great lateral pressure, the unyielding ones are crushed, and the pliant strata bent, and are forced to pack themselves more closely into a smaller space, having no longer the same room to spread themselves out horizontally. At the same time, a large portion of the mass is squeezed upwards, because it is in the upward direction only that the excess in size of the envelope, as compared to the nucleus can find relief. This excess produces one or more of those folds or wrinkles in the earth's crust which we call mountain-chains."

De Beaumont's theory is given more from its antiquity than from its present day importance, and yet in some form it still holds its place in all our treaties on geology. Indeed the latest works include discussions of the strength of domes, as if the nucleus of the globe were shrinking away from the crust, and the latter thus subjected to crushing from its own weight.

§ 38. *Views of Lyell.*—This great geologist always rejected Elie de Beaumont's theories of mountain formation, and gave the most cogent reasons for his course. He adopted the theory that the land is occasionally depressed and elevated, by internal forces, but did not definitely decide what forces produced these progressive or oscillatory movements of the earth's crust. One of Lyell's greatest disciples was Charles Darwin, whose views we shall now very briefly recall.

§ 39. *Views of Charles Darwin.*—The views of Darwin are very briefly and lucidly set forth by Professor Suess ("Face of the Earth," Vol. I, p. 104), as follows:

> "The earthquake of February 20, 1835 (at Conception, Chili), gave rise to one of the most important works on the elevation of mountains, indeed I may say to the the only attempt, based on direct observation of nature, to establish more exactly the older theories concerning the force which is supposed to have raised up mountain chains. The author of this work is Charles Darwin. Since that time no second attempt, or at least no attempt of equal importance, has been made in this direction. To day, more than half a century later, it is possible to hold other opinions on these questions and yet to recognize the boldness of the generalization which even then revealed the master.
>
> "Darwin saw the awakening activity of the volcanoes during and after the earthquake; he believed he saw elevation, although not uniform elevation of the solid ground; in addition he saw the terraces along the coast. But he also knew that similar terraces occur on the east coast of South America, where there are no volcanoes and no earthquakes. The earthquakes must therefore have appeared to his eyes as the local expression of a universal force. The secular contraction of the earth, a theory already eagerly advocated by several investigators, Darwin justly held to be entirely unsuited to explain those intermittent elevations which the terraces betrayed, and thus he reached the conclusion:
>
> "'*That the form of the fluid surface of the nucleus of the earth is subject to some change, the cause of which is entirely unknown and the effect of which is slow, intermittent but irresistible.*'"

§ 40. *Views of Professor James D. Dana.*—The views of this eminent geologist have been carefully discussed in the paper on "The New Theory of Earthquakes and Mountain Formation as Illustrated by Processes Now at Work in the Depths of the Sea," § 13. The reader is referred to that discussion. Here it must suffice to say that, although Dana recognized that there was a fundamental relationship between the depth and extent of an ocean and the height of the mountains which surround it, he was unable to define this relationship except in very general terms, and could not assign any definite cause for the law which he pointed out. He considered the oceanic basins as subsiding, while the continents were being elevated.

Though Dana's views were somewhat modified by later study and investigation, he always maintained that "the principal mountain chains are portions of the earth's crust which have been pushed up and often crumpled or plicated by lateral pressure resulting from the earth's contraction." In order to explain this supposed mode of action he held that the oceanic areas have been "the regions of greatest contraction and subsidence, and that their sides have been pushed like the ends of an arch, against the borders of the continents."

Even with these arbitrary assumptions it is not at all clear how the settlement of the Pacific Ocean could elevate our great plateau west of the Rocky Mountains, which is nearly a thousand miles wide. If the subsidence of the ocean bed had pushed up the margin of North America, the crumpling and elevation of the land could not well extend one third of the way across the continent. We need not, however, be greatly surprised at this difficulty, for at best Dana's theory is vague, and he evidently could not understand just how the elevation had come about. Yet so fully was Dana convinced of the dependence of the mountains on the oceans adjacent to them that he reduced it to calculation by the rule-of-three. He says:

> "The relation of the oceans to the mountain borders is so exact that the rule-of-three form of statement cannot be far from the truth. *As the size of the Appalachians to the size of the Atlantic, so is the size of the Rocky chain to the size of the Pacific.* Also, *as the height of the Rocky chain to the extent of the North Pacific, so are the height and boldness of the Andes to the extent of the South Pacific.*" ("Manual of Geology," 1863, p. 25.)

This was indeed a remarkably near approach to the great law of nature, that the mountains along the coasts are formed by the expulsion of lava from under the sea, and are, therefore, everywhere proportional to extent and depth of the adjacent oceans.

§ 41. *Views of James Hall.*—In 1857 this distinguished American geologist announced in a presidential address to the American Association at Montreal, that the enormous depth of the sedimentation along the Appalachian chain was due to the prolonged accumulation of sediments along a sinking, off-shore line of sea bottom. He reached this view from the careful study of the

Appalachian and other American mountain regions. To explain such deposits he supposed that marine currents had formerly traversed these regions and by gradually depositing sediments of great weight had also sunk the crust till at length a great thickness was attained. When the rocks thus formed had become solidified and crystallized the borders of the continent were afterwards upraised somehow. He did not indicate how the uplift had come about, nor did he think that the mountain regions had been raised separately. Denudation had then commenced, and finally given the mountains the forms they have today.

Keferstein, Sir John Herschel, Dr. T. Sterry Hunt and others, along with Hall, or even before him, in some cases, had developed the theory of aqueo-igneous fusion, which was supposed to produce a plastic zone between the consolidated crust and the solid nucleus. This theory supposed that the isogeotherms rise in regions of heavy sedimentation. Hall held that this would

> "cause the bottom strata to establish lines of weakness or of least resistance in the earth's crust, and thus determine the contraction which results from the cooling of the globe to exhibit itself in those regions, and along those lines where the ocean's bed is subsiding beneath the accumulated sediments."

Many of the views afterwards more fully developed by Leconte are here faintly traced by Hall, and for that reason these early views of mountain formation are worthy of attention.

§ 42. *Views of Leconte.*—This veteran geologist gave great attention to mountain formation throughout a long career, and his residence on the Pacific Coast gave him exceptional facilities for studying the ranges of our western states, and especially of California, which includes the most remarkable developments in North America. The views at which Leconte arrived, as set forth in his "Elements of Geology," edition of 1896, are as follows:

> "*Mountain Origin.*
>
> "Leaving aside for the present all disputed points, it is now universally admitted that mountains are not usually pushed up by a vertical force from beneath, as once supposed, but are formed wholly by *lateral pressure.* The earth's crust along certain lines is *crushed together* by lateral or horizontal pressure and rises into a mountain-range along the line of yielding, and to a height proportionate to the amount of mashing. But the yielding is not by rising into a hollow arch, nor into such an arch filled beneath with liquid

(for in neither case would the arch support itself), but by mashing together and in thickening and crumpling of the strata and an upswelling of the whole mass along the line of greatest yielding. That this is the immediate or *proximate* cause of the origin or elevation of mountains is plainly shown by their structure. As to the *ultimate cause—i. e.,* the cause of the enormous lateral pressure—this lies still in the field of discussion. We shall discuss it briefly in its proper place" (pp. 261–2).

Again, on page 264, we find this account:

"*Proof of Elevation by Lateral Pressure alone: 1. Folding.*—It is evident that foldings such as those represented in all the above figures, and which occur in nearly all mountains, cannot be produced except by lateral pressure, and are therefore proof of such pressure. But, moreover, it can be shown that, when we take into consideration the immense thickness of mountain strata and the degree of folding, lateral pressure is *sufficient* to account for the whole elevation, without calling in the aid of any upward pushing from beneath. For example, the Coast range of California (Fig. 228) is composed of at least five anticlines and corresponding synclines. If its folded strata were spread out horizontally in the position of the original sediments, they would undoubtedly cover double the space. Now, supposing the strata here are only 10,000 feet thick—a very moderate estimate—in mashing to one half the extent, they would be thickened to 20,000 feet, which would be a clear elevation of 10,000 feet if they were not subsequently eroded. According to Renevier, a section of the Alps reveals seven anticlines and corresponding synclines, and some of them are complete overfolds (Fig. 230). We are safe in saying that Alpine strata have been mashed horizontally into one half their original extent. Supposing these were originally 30,000 feet thick (they were really much thicker), this would make a clear elevation of 30,000 feet. Of course, most of this has been cut away by erosion. In the Appalachian range, according to Claypole, the foldings are so extreme that in one place 95 miles of original extent have been mashed into 16 miles, or six into one, and yet the Appalachian strata are estimated as 40,000 feet thick. Cases of still greater doubling of strata upon themselves occur. In

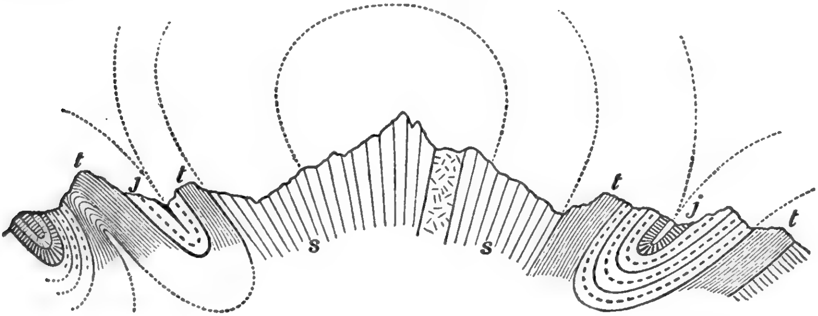


FIG. 14. Section of a Portion of the Alps.

the Highlands of Scotland the strata by lateral thrust were broken and slidden one over another for ten miles. In the Canadian Rocky Mountains there is an overthrust of seven miles, by which the Cambrian is made to override the Cretaceous, and 50 miles of strata are mashed into 25 miles (McConnell). In the Appalachians of Georgia the *Rome fault* is an overthrust which brings the Cambrian in contact with the Carboniferous and the fault under different names may be traced northward for 275 miles; and in the Cartersville thrust-fault there is an overriding of 11 miles (Hayes). The manner in which this is done is illustrated on a previous page (Fig. 209). Evidently, then, the whole height of the mountains mentioned above is due to lateral crushing alone."

If Professor Leconte had been familiar with the folding produced in the sea trenches he could have completed the theory of mountain formation developed in this paper. As geologists have for centuries recognized the fossils found in mountains as having been deposited in the sea, it is remarkable that the suggestion seems never to have occurred to them that the folding was done in the sea before the land was lifted above the water, and by earthquake processes due to the sea itself. Leconte, however, came very near this view, as the following will show (p. 267 et seq.):

"*Mountains are made out of lines of thick sediments.*—But the question occurs, What determines *the place* of a mountain-range? The answer is, A mountain-range while in preparation—before it became a range—was a line of very thick sediments. This is a very important point in the theory of mountain origin, and therefore must be proved. The strata of all mountains, where it is possible to measure them, are found to be of enormous thickness. The strata involved in the folded structure of the Appalachian, according to Hall, are 40,000 feet thick, the strata exposed in the structure of the Wahsatch, according to King, are more than 50,000 feet thick; the Cretaceous strata of the Coast Range, near the Bay of San Francisco, according to Whitney, are 20,000 feet thick; and if we add to this 10,000 feet for the Eocene and Miocene strata, the whole thickness is probably not less than 30,000 feet, while the Cretaceous alone in Northern California, according to Diller, is 30,000 feet. The Alpine geologists estimate the thickness of the strata involved in the intricate structure of the Alps as 50,000 feet. The strata of Uintah, according to Powell, are 32,000 feet thick.

"Now, it must not be imagined that these numbers merely represent the *general* thickness of the stratified crust; only that in these places the strata are turned up and their edges exposed by erosion, and thus their thickness revealed. On the contrary, it may be shown that the same strata are much thinner elsewhere. The same strata which along the Appalachian range are 40,000 feet thick, when traced westward thin out to 4,000 feet at the Mississippi River. The same strata which along the line of the Wahsatch are 30,000 feet thick, when traced eastward thin out to 2,000 feet in the region of the plains. It is evident, therefore, that mountain-ranges are lines of *exceptionally* thick strata.

"*Mountain-ranges were once Marginal Sea-Bottoms.*—Where, then, do sediments now accumulate in greatest thickness? Evidently on marginal sea-bottoms, off the coasts of continents. The greater part of the washings of continents are deposited within 30 miles of shore, and the whole usually within 100 miles. From this line of thickest and coarsest deposit the sediments grow thinner and finer as we go seaward. But evidently such enormous thicknesses as 40,000 feet cannot accumulate in the same place *without pari passu subsidence* such as we know takes place now whenever exceptionally abundant sedimentation is going on (p. 145). Therefore, *mountain-ranges before they were yet born*—while still in preparation as embryos in the womb of the ocean—*were lines of thick off-shore deposits gradually subsiding,* and thus ever renewing the conditions of continuous deposits.

"As this is a very important point, it is necessary to stop here awhile in order to show that such was actually the fact in the case of all the principal ranges of the American Continent—*i. e.,* that for a long time before they were actually formed, the places which they now occupy were marginal sea-bottoms receiving abundant sediments from an adjacent continent. We shall be compelled to anticipate some things that belong to Part III, but we hope to make statements so general that there will be no difficulty in understanding them.

"1. *Appalachian.*—The history of this range is briefly as follows: At the beginning of the Palæozoic era there was a great V-shaped land-mass, occupying the region now covered by Labrador and Canada, then turning northwestward from Lake Superior and extending perhaps to polar regions about the mouth of the Mackenzie River. This is shown on map, Fig. 269, on page 303. There is another great land-mass occupying the present place of the eastern slope of the Blue Ridge and extending eastward probably far beyond the present limits of the continent—as shown in the same figure by dotted line in the Atlantic Ocean. The western coast-line of this land-mass was the present place of the Blue Ridge. Westward of this line extended a great ocean—'the interior Palæozoic Sea.' The Appalachian range west of the Blue Ridge was then the *marginal bottom of that sea.* During the whole of the Cambrian, Silurian, and Devonian, this shoreline remained nearly in the same place, although there was probably a slow transference westward. Meanwhile, throughout this immense period of time, the washings from the land-mass eastward accumulated along the shore-line, until 30,000 feet of thickness was attained. At the end of the Devonian some considerable changes of physical geography of this region took place, which we will explain when we come to treat of the history of this period. Suffice it to say now that during the Carboniferous the region of the Appalachian was sometimes above the sea as a coal-swamp, and sometimes below, but all the time receiving sediment until 9,000 or 10,000 feet more of thickness was added, and the aggregate thickness became

40,000 feet. Of course, it is impossible that such thickness could accumulate on the same spot without *pari passu* subsidence of the sea-floor. In fact, we have abundant evidences of comparatively shallow water at every step of the process—evidence sometimes in the character of the fossils, sometimes in the form of shore-marks of all kinds, sometimes in the form of seams of coal, showing even swamp-land conditions. Again, of course, the sediments were thickest and coarsest near the shore-line, and thinned out and became finer towards the open sea, *i. e.,* westward. Finally, after 40,000 feet of sediments had accumulated along this line the earth-crust in this region gave way to lateral pressure, and the sediments were mashed together and folded and swollen up into the Appalachian range. Subsequent erosion has sculptured it into the forms of scenic beauty which we find there to-day.

"2. *Sierra.*—This was apparently the ***first-born*** of the Cordilleran family. Its history is as follows: During the whole Palæozoic and earlier part of the Mesozoic, there was in the Basin region a land-mass, whose form and dimensions we yet imperfectly know, but whose Pacific shore-line was *east of the Sierra.* The Sierra region was therefore at that time the marginal bottom of the Pacific Ocean. Probably the position of this shore line changed considerably at the end of the Palæozoic. The extent of this change we will discuss hereafter. Suffice it to say now that, during the whole of this time, the Sierra region received sediments from this land-mass until an enormous thickness (how much we do not know, because the foldings are too complex to allow of estimate) was accumulated. At last at the end of the Jurassic, the sea floor gave way to the increasing lateral pressure along the line of thickest sediments, and these latter were crushed together with complex foldings and swollen up into the Sierra. An almost inconceivable subsequent erosion has sculptured it into the forms of beauty and grandeur which characterize its magnificent scenery.

"3. *Coast Range.*—The birth of the Sierra transferred the Pacific shore-line westward, and the waves now washed against the western foot of that range, or possibly even father westward in the region of the Sacramento and San Joaquin plains. At this time, therefore, the region of the Coast Range was the marginal bottom of the Pacific Ocean. During the whole Cretaceous, Eocene, and Miocene, this region received abundant sediments from the now greatly enlarged continental mass to the eastward; until finally, at the end of the Miocene, when 30,000 feet of sediments had accumulated along this line, the sea-floor yielded to the lateral pressure, and the Coast Range was born; and the coast-line transferred to near its present position.

"4. *Wahsatch.*—The physical geography of the region to the east of the Wahsatch (Plateau region) during Jura-Trias time is little known. But during the Cretaceous the region of the Wahsatch was the western marginal bottom of the great interior Cretaceous Sea (see map, Fig. 760, p. 486), receiving abundant sediments from the great land-mass of the Basin and Sierra region. This greatly increased the enormous thickness of sediments already accumulated along this line in earlier times. At the end of the Cretaceous the sediments yielded, and the Wahsatch was born. It is necessary, however, to say that both the Sierra and Wahsatch underwent very great changes of form produced by a different process and at a much earlier period. We shall speak of this later.

"5. *Alps.*—Mr. Judd has recently shown that the region of the Alps, during the whole Mesozoic and Early Tertiary, was a marginal sea bottom, receiving sediments until a thickness was attained not less than that of the Appalachian strata. At the end of the Eocene these enormously thick sediments were crushed together with complicated foldings and swollen upward to form these mountains and afterward sculptured to their present forms.

"The same may be said of the Himalayas and nearly all other mountains. We may, therefore, confidently generalize, and say that the place now occupied by mountain-ranges have been previous to their formation, places of great sedimentation, and therefore usually marginal *ocean bottoms.* In some cases, however, the deposits in interior seas or mediterraneans have yielded in a similar way, giving rise to more irregular ranges or groups of mountains." . . .

"*Why thick Sediments should be Lines of Yielding.*—Admitting, then, that mountains are formed by the squeezing together of lines of very thick sediments, the question still occurs, *Why does the yielding take place along these lines in preference to any others?* This is a capital point in the theory of mountain formation. The answer is as follows: We have already seen (p. 231) that accumulation of sediments causes the isogeotherm to rise and the interior heat of the earth to invade the lower portion of the sediments with their included waters. Now this invasion of heat in its turn causes hydrothermal softening or even fusion, not only of the sediments, but also of the sea-floor on which they rest. Thus a line of thick sediments becomes a line of softening and therefore a line of weakness, and a line of yielding to the lateral pressure, and therefore a line of mashing together and folding and upswelling—in other words a mountain-range. As soon as the yielding commences we have an additional source of heat in the crushing itself. In addition to this, upheaval by lateral crush by the tendency to arch the strata would produce relief of gravitative pressure, and therefore fusion (p. 103). It follows from this that there is or was beneath every mountain a line of fused or semi-fused matter. This we will call the *sub-mountain liquid.* This by cooling and solidification becomes a *metamorphic or granitic core,* which by erosion forms the metamorphic or granitic axis and crest of many great mountains" . . . (pp. 271–2).

"*Cause of Lateral Pressure.*—We have thus proved that the immediate cause of the origin and the growth of mountains is lateral pressure acting on thick sediments, crushing them together and swelling them up along the line of great thickness. But still the question remains, What is the *ultimate* cause, *i. e.,* the *cause of the lateral pressure?* This, as we have already said, lies still in the domain of doubt and discussion, but the view which seems most probable may be briefly stated as follows:

"In the secular cooling of the earth there would be not only unequal radial contraction, giving rise, as shown on page 175, to continents and ocean-basins, but also to unequal contraction of the *exterior* as compared with the *interior.* At first, and for a long time, the exterior would cool fastest; but there would inevitably, sooner or later, come a time when the exterior, receiving heat from abroad (sun and space), as well as from within, would assume an almost constant temperature, while the interior would still continue to cool, and contract. Thus, therefore, after a while the interior nucleus would contract faster than the exterior shell. It would do so, partly because it would cool faster, and partly because the coefficient of contraction of a hot body is greater than that of a cooler body. Now, as soon as this condition was reached, the exterior shell, following down the shrinking nucleus, would be thrust upon itself by a lateral or horizontal pressure which would be simply irresistible. If the earth's crust were a hundred times more rigid than it is (thirty times as rigid as steel, 500 to 1,000 times as rigid as granite—Woodward, *Science,* Vol. XIV, p. 167, 1889), it must yield. Mountain-ranges are the lines along which the yielding takes place, and this yielding takes place along the lines of thick sediments because these are lines of weakness.

"There are several serious objections which may be brought against this view: 1. Calculations seem to show that the amount of crumpling and folding actually found in the mountains is many times greater than could be produced by the contraction of the earth by *cooling.* But it may be answered (1) that the calculations take no account of the greater coefficient of contraction at high temperatures, and therefore at great depths, (2) and that there may be *other causes* of contraction besides cooling. For example, loss of constituent gases and vapors from the interior of the earth, through volcanic vents and fissures, has been suggested by O. Fisher (p. 102).

"2. Again, it has been shown by Dutton that it is impossible that the effects of differential contraction should be concentrated along certain lines, so as to give rise to mountain-ranges without a shearing of the crust upon the interior portions, which is inadmissible if the earth be solid. Instead, therefore, of conspicuous mountain-ranges, the effects of differential contraction would be distributed all over the surface, and be wholly imperceptible. But in answer to this it may be said that there is no difficulty in the way of shearing, and therefore of such concentration of effects along certain lines, if *there be a sub-crust liquid* or semi-liquid layer, either universal or else underlying large areas of surface.

"Still other objections have been raised, but these are so recent that they have not yet been sufficiently sifted by discussion to deserve mention here.[1] The origin of mountains by lateral pressure is a fact beyond dispute. This is the most important fact for the geologist. How the lateral pressure is produced is a pure physical question which must be left to the physicists to settle among themselves" (pp. 274–5).

Leconte treats also of Monoclinal mountains, as found in the Great Basin, which he explains by normal faulting, or vertical movement of crust blocks, and finally adds:

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[1] For a completer discussion of this subject, see "Theories of Mountain Origin," *Jour. Geol.,* Vol. I., p. 542, 1893.

"Thus, then, there are two types of mountains strongly contrasted, mountains of the one type are formed by lateral *pressure and crushing,* of the other type by lateral *tension and stretching.* The one gives rise mainly to reverse faults, the other always to normal faults. Mountains of the one type are formed by upswelling of thick sediments, those of the other type by irregular readjustment of crust-blocks. Mountains of the one type are *born of the sea,* those of the other type are born *on the land.* We find examples of the one type in nearly all the greatest mountains everywhere, but especially in the Appalachian, the Alps and the Coast Range. The best examples, perhaps the only examples, of the other type are the Basin ranges. Some mountains, as the Sierra, the Wahsatch, and certainly *some* of the Basin ranges, belong to both types. In their origin, they have formed in the first way, but afterward have been modified by the second way. Thus the first is the fundamental method, and the second only a modifying process" (p. 277).

These views of Leconte call for no special comment, beyond the remark that normal faulting itself is wholly unexplained. If secular cooling were the cause, such faults ought to occur east of the Rocky Mountains as well as west of them. The important difference is that the Pacific Ocean was on the west pushing up the land, and a continental basin on the east, either dry or covered by shallow water and therefore doing little or no pushing at all. In any case the great plateaus of the west were certainly uplifted by the Pacific, through the expulsion of lava under the land. In the Andes of South America the plateaus are higher indeed, but also narrower than those in North America, because in our continent the relief resulting from the leakage of the ocean took a broader and less elevated form. It is impossible for any one to doubt the identity of the forces which raised the Andes and their plateaus, the Himalayas and their plateaus, and the Rocky Mountains and the mountains and plateaus of the Great Basin. The principle of continuity shows clearly that the cause was everywhere one and the same. Several American geologists have suggested vertical uplifts in the Great Basin, from the way in which the crust blocks are displaced; but heretofore no known cause for such movements could be assigned, because it was held that secular cooling is the chief if not the only cause operating in the development of the globe.

§ 43. *Views of Rev. O. Fisher.*—The Rev. O. Fisher was the first to show by long and patient research the total inadequacy of secular cooling to account for the observed height of mountains.

He showed that the mountains are hundreds of times higher than the cooling of the earth will explain. On this point his labors mark a distinct advance in geological science; for next in importance to establishing true theories is the overthrow of erroneous ones, which clears the ground for a fresh start. But notwithstanding the unanswerable character of Fisher's argument, the old theories have been retained by geologists as the best they could devise. Fisher's criticisms of geological theories are carefully thought out, and worthy of attention. He has always denied the entire solidity of the earth, holding that the movements noticed in mountains proved the existence of a mobile substratum beneath a crust some twenty miles thick. Here again he was certainly right, and it is difficult to see how such an obvious proposition could be denied.

We need not dwell on Fisher's views of mountain formation, because they imply convection currents within the earth, and these latter are certainly inadmissible, except just beneath the crust in earthquake movements, as developed in the theory set forth in this paper.

§ 44. *Views of Major C. E. Dutton.*—Like the Rev. O. Fisher, Major Dutton was one of the earliest authorities to question the adequacy of secular cooling to account for the wrinklings noticed in the earth's crust. Using the results of Fourier's solution for the variation of temperature, as developed in the work of Lord Kelvin, Dutton found that

> "the greatest possible contraction due to secular cooling is insufficient in amount to account for the phenomena attributed to it by the contraction hypothesis. By far the larger portion of this contraction must have taken place before the commencement of the Palæozoic age. By far the larger portion of the residue must have occurred before the beginning of the Tertiary, and yet the whole of this contraction would not be sufficient to account for the disturbances which have occurred since the close of the Cretaceous."

Major Dutton concludes that "the determination of plications to particular localities presents difficulties in the way of the contractional hypothesis which have been underrated." He held that the localization of the plications could result only from a large amount of horizontal slipping of the crust over the nucleus, and the friction involved in this movement even over a liquid nucleus would be so great as to render the assumption a physical absurdity.

If wrinkling resulted from uniform cooling and consequently uniform shrinkage, the effect would be analogous to that of a withered apple, with small wrinkles all over it, instead of a surface presenting in one region a continuous system of folds extending from Cape Horn to Alaska, and in another, a zone a thousand miles wide, from the Appalachian to the Rocky Mountains, with scarcely any evidence of disturbance whatever.

In these considerations Major Dutton has forcibly expressed the difficulty of supposing that a mountain range is formed by the cooling of the earth contracting equally along all its radii. Such a supposed mode of formation of our ranges, folded and crumpled as they are, is clearly impossible; and Major Dutton shares with the Rev. O. Fisher the credit of having been the first to recognize the total inadequacy of the contraction theory.

It is remarkable that after this antiquated theory had been thus clearly disproved, it should have continued in use. No one seems to have been able to frame a theory based on any cause except secular cooling, till the present writer developed the theory based on the leakage of the oceans and the formation of mountains by the expulsion of lava under the land, which perfectly explains all the phenomena.

§ 45. *Views of Geikie.*—In the article "Geology," *Encyclopedia Britannica,* p. 375, we find the following statement of the contraction theory:

> "There still remains the problem to account for the original wrinkling of the surface of the globe, whereby the present great ridges and hollows were produced.
>
> "It is now generally agreed that these inequalities have been produced by unequal contraction of the earth's mass, the interior contracting more than the outer crust, which must therefore have accommodated itself to this diminution of diameter by undergoing corrugation. But there seems to have been some original distribution of materials in the globe that initiated the depressions on the areas which they have retained. It has been already pointed out (ante, p. 223) that the matter underlying the oceans is more dense than that beneath the continents, and that, partly at least, to this cause must the present position of the oceans be attributed. The early and persistent subsidences of these areas, with the consequent increase of density, seems to have determined the main contours of the earth's surface. . . .
>
> "The effects of this lateral pressure may show themselves either in broad dome-like elevations, or in narrower and loftier ridges of mountains.

The structure of the crust is so complex, and the resistance offered by it to the pressure is consequently so varied, that abundant cause is furnished for almost any diversity in the forms and distribution of the wrinkles into which it is thrown. It is evident, however, that the folds have tended to follow a linear direction. In North America, from early geological times, they have kept on the whole on the lines of meridians. In the Old World, on the contrary, they have chosen diverse trends, but the last great crumplings—those of the Alps, Caucasus, and the great mountain ranges of central Asia—have risen along parallels of latitude.

"Mountain chains must therefore be regarded as evidence of the shrinkage of the earth's mass. They may be the result of one movement, or of a long succession of such movements. Formed on lines of weakness in the crust, they have again and again given relief from the strain of compression by undergoing fresh crumpling and upheaval."

Geikie's views may be considered the accepted views of geologists generally, and it will be seen that they rest on the theory of contraction due to secular cooling.

On the constitution of the globe Geikie quotes ("Geology," p. 73) from the paper of Arrhenius, "Zur Physik des Vulcanismus" (1900), the following theory of the illustrious Swedish physicist:

"If the rocks at the earth's surface have a density half that of the globe as a whole, and if the density continues to hold good for the magma that arises from the melting of these rocks, we must conceive the existence of a much denser substance in the earth's interior. On various grounds, such as the preponderance of iron in nature, both in meteorites and in the sun, and the phenomena of terrestrial magnetism, it may be inferred that this substance is metallic iron. In consequence of its greater density this iron will naturally be deeper than the rock magma, and on account of the high temperature must exist in a gaseous condition. Somewhere about a half of the planet therefore should consequently consist of iron, and of other metals mingled with it in smaller proportions. The semi-diameter of this gaseous iron-sphere will thus include about 80 per cent. of the earth's semi-diameter. Then will come about 15 per cent. of the gaseous rock magma, next to it the liquid rock-magma for a thickness of about 4 per cent. of the terrestrial semi-diameter, and lastly the solid crust, for which not more than 1 per cent. may be claimed" (pp. 404–5).

Referring to the light thrown on the constitution of the interior by the observation of waves propagated by earthquakes, Geikie also adopts the theory of Arrhenius, which is as follows:

"The density of much the largest part (reckoned linearly) of this interior, amounting, as above stated, to about 80 per cent. of the radius, must be nearly three times higher than that of quartz. Since now the mean velocity of transmission of earthquake waves in the interior of the earth has been ascertained to amount to 11.3 kilometers per second, the compressibility of that region must be 31 times less than that of quartz, that is, eight times less than that of solid steel, according to Voigt. This is a figure of precisely that order of magnitude which was to be expected. We may well believe that at depths of more than 1,000 kilometers the compressibility of gaseous iron sinks down to some ten times less than that of steel.

"The interior of the earth, therefore, with the exception of a solid crust about 40 kilometers thick, consists of a molten magma 100 or 200 kilometers in depth which shades continuously inward into a gaseous center. The liquids and gases in the interior possess a viscosity and incompressibility such as permit them to be regarded as solid bodies. From these, however, they are distinguished in the first place by the fact that differentiations are possible to a considerable degree, the effects of which may long endure. In the second place, long continued pressures, when acting on a large enough scale, may produce great deformations. Further, the liquids must possess the property of great expansion on a diminution of the high pressure, thereby readily becoming fluid. The process must thus differ but little from a normal melting with increase of volume, and especially of fluidity, as well as with absorption of heat. And yet the condition of aggregation is not thereby altered."

Geikie remarks that the theory of Arrhenius accords well with geological requirements:

"With reference to the crust of the earth, it meets the constantly repeated objections of the geologists to whom the existence of a comparatively thin crust has always seemed an essential condition for the production of that crumpled and fractured structure which the rocks of the land so universally present. If the solid crust of the earth is allowed to be about 25 miles thick, we must conceive that in the lower four fifths of its mass the rocks are in a condition of latent plasticity. They lie much beyond the crushing strength which they exhibit at the surafec. They are not crushed into powder as they would be under a similar strain above ground, but they are ready to yield to the deformations that may arise consequent upon adjustments of the gigantic pressure to which they are subjected. Hence the solid crust down as far as its structure has been disclosed abounds in proofs that it has undergone colossal plication and fracture, and that higher portions of it many square miles in extent have been thrust bodily over each other for many miles."

The last view here expressed by Geikie as to how the crust becomes thrust over itself for many miles is not, we think, well founded, because it is shown in this paper that all this folding and overlapping of the crust arises in the trenches dug out in the sea bottom by earthquakes. This crumpling and overthrusting of the crust certainly would not arise except for earthquakes produced by the leakage of the oceans, to which mountain formation is due. Of course the plasticity of this layer beneath the crust contributes to the final result, but the leakage of the oceans, with the resulting earthquakes, supplies the deforming force.

§ 46. *Views of Professor Suess.*—In the "Face of the Earth" (Vol. I, p. 107) we find the following brief exposition of Professor Suess' views:

> "*The dislocations visible in the rocky crust of the earth are the result of movements which are produced by a decrease in the volume of our planet.* The tensions resulting from this process show a tendency to resolve themselves into *tangential* and *radial* components, and thus into horizontal (*i. e.,* thrusting and folding), and into vertical (*i. e.,* sinking) movements. Dislocations may therefore be divided into two main groups, of which one is produced by the more or less horizontal, the other by the more or less vertical relative displacement of larger or smaller portions of the earth's crust.
>
> "There are large areas in which the first, and others in which the second group predominates, and there are also regions in which both groups appear together, and in which an intimate connection may be recognized between them, the resolution of the movements in space having in these cases been less complete. This essential difference in the movements of the lithosphere may be clearly perceived from a comparative study of the structure of the Old World; nor has it escaped the notice of American geologists.
>
> "'The geological provinces of the Great Basin,' remarks Clarence King, has suffered two different types of dynamic action: one in which the chief factor was evidently tangential compression, which resulted in contraction and plication, presumably in post-Jurassic time; the other of strictly vertical action, presumably within the Tertiary, in which there are few evidences or traces of tangential compression.'
>
> "Our colleagues on the other side of the ocean have even gone a great deal further. After comparison of the folded Appalachian mountains with the depressed Basin Ranges, Gilbert had in 1875 already suggested the possibility that in the Appalachians the causes of movement were superficial, in the Basin Ranges deep-seated. We shall have an opportunity, when discussing the relation of the Alps to their northern foreland, of determining to what extent this supposition finds confirmation in Europe. We may however state at once that as a rule it is only the dislocations of the second group which are accompanied by volcanic eruptions."

§ 47. *Views of Arrhenius.*—It is well known that this distinguished Swedish physicist holds that the earth's interior is essentially gaseous (cf. § 45, above), but under the great pressure operating in the globe made to behave very nearly as a solid.[1] In his

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[1] See Postscript, page 274.

paper "Zur Physik des Vulcanismus," published in 1900, Arrhenius points out that in fluids at high temperature, where no increase in volume takes place, the internal friction of the molecules rises with the temperature, so that the viscosity increases and the fluidity diminishes; that a similar effect is observable in both gases and liquids; that although gases have the highest and solids the lowest compressibility, nevertheless when a gas near its critical temperature passes into a liquid, through a trifling physical change, there is practically no change in the compressibility. The higher the pressure the smaller is the compressibility, and a gas above the critical temperature may be made to acquire the properties of a solid by pressure alone. Such a mass has great density, small compressibility, and large viscosity, so that it has the properties of a solid, though really an imprisoned gas.

At a depth of 40 kilometers Arrhenius says the temperature is about 1200° C., and the pressure about 10,840 atmospheres; and as these conditions would render nearly all ordinary minerals fluid, he concludes that below that depth the matter is molten, in the form of a magma—that is, a viscous and nearly incompressible liquid made to act nearly as a solid by pressure.

At greater depths the temperature is above the critical temperature of every known substance, as the pressure rapidly increases and the liquid magma becomes a gaseous magma with larger and larger viscosity, and smaller and smaller compressibility—in other words, an elastic solid with rigidity increasing with the depth.

## VI. Abandonment of the Old Theories of the Physics of the Earth.

§ 48. *The Total Inadequacy of the Old Theories to Account for the Fault Movements near the Sea, which Raise Vertical Blocks and Walls of Granite*[1] *Thousands of Feet above the Water.*—The vast

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[1] Andesite is the name used to designate the kind of granitic rock found in the Andes. Charles Darwin showed that all granitic rocks are closely related. In his "Text-book of Geology," edition of 1903, book II, Part II, § 7, pp. 230–260, Sir Archibald Geikie gives tables of the chemical compositions of all these rocks, which show very clearly their close relationship. When we use the term *granite* therefore we mean *granitic rock* in the wide sense.

vertical walls and blocks of granite so often lifted thousands of feet above the sea, with deep water all around their bases, frequently encountered in different parts of the world, cannot be explained except by the present theory. Thus along the west coast of Chili and Patagonia, from Cape Horn to Valparaiso, in the Straits of Magellan, as well as in the ranges of the Andes further from the coast, in the Sierras of California, and elsewhere these vertical uplifts are common. It is obvious that they cannot possibly be explained by the old theories depending on the shrinkage of the globe. But if lava is expelled from beneath the sea, owing to the secular leakage of the ocean bottom, and the crust is fractured and rent into blocks by the earthquake forces, some of these blocks would naturally be pushed upward, leaving vertical walls of granite thousands of feet high. Occasionally the blocks would be forced apart, leaving the sea pass between, as so often seen in Chili, Patagonia and Tierra Del Fuego. The Straits of Magellan no doubt arose in this way. As already remarked in § 27, Darwin describes similar breaks in the Andes further north, through which the sea once flowed, but they are now raised above the water. No doubt the time will come when Tierra Del Fuego will be joined solid to Patagonia, by uplifts which will cause the sea to withdraw from the Straits of Magellan and it will become dry land, like those ancient passages further north mentioned by Darwin.

There are many other parts of the world where similar phenomena may be seen. The origin of the fiords in Norway has long been a matter of debate. It seems to be conceded that these inlets are made by mountains running into the sea, and more or less modified above water by ice and glaciers. They are supposed to be quite old, and certainly date back of the glacial epochs.

It may no doubt be safely assumed that these Norwegian mountains originated, like other mountains, by the uplift of faults, owing to the expulsion of lava from beneath the sea.[1] Hence the precipitious walls along the sea coast, with deep water between. The blocks

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[1] Having read the earlier papers of this series with great interest, Professor Schiaparelli has kindly called my attention to the trough in the sea along the Norwegian coast. This confirmation of the theory by the illustrious astronomer of Milan is exceedingly interesting.

of the earth's crust were lifted vertically by the pushing of lava beneath them. It is in this way that all such walls of granite and other towering rock are to be explained, and the fact that the sea still encroaches on them shows how the movements came about. Probably there has been little vertical movement for a long time along the coast of Norway, and subsidence as well as elevation may have taken place, both here and elsewhere. Subsidence is common along most sea coasts, but it does not prevail in the long run, as is proved by Professor Suess's work, showing a universal lowering of the strand line throughout the world.

§ 49. *The Theory of Arches and Domes Inapplicable to the Crust of the Earth, because the Globe is not Shrinking but actually Expanding.*—In Chamberlin and Salisbury's "Geology," Vol. I, p. 583, we find the statement that

> "The principle of the dome is brought into play whenever an interior shell shrinks away, or tends to shrink away, from an outer one which does not shrink. In this case there is a free outer surface and a more or less unsupported under surface towards which motion is possible. The dome may, therefore, yield by crushing or by contortion."

Owing to the important part the domed form of the crust has played in theories of deformation, these authors give quantitive results calculated by Hoskins, showing that such a dome of continental dimensions, if unsupported from below, *would sustain only 1/525th of its own weight.*

In his consideration of the "Mathematical Theories of the Earth" (*Proc. Am. Assoc. for Adv. Sci.,* 1889, p. 49), Professor R. S. Woodward reached the analogous conclusion that "If the crust of the earth were self-supporting, its crushing strength would have to be about thirty times that of the best cast steel, or five hundred to one thousand times that of granite."

In view of these results it is remarkable that any one should have viewed the earth's crust as a wholly or partially self-supporting dome; for it could not be supported even over a very small area. And moreover secular cooling is wholly inadequate to cause a separation of the interior layers from the crust. All that has been published on this point, therefore, is inapplicable to the earth, because it rests on a false hypothesis. The supposed conditions have no reality.

The earth is not shrinking and the crust does not tend to separate itself from the underlayers, except where the lava has been expelled from beneath it by earthquakes. The collapse of the crust when thus undermined, however, shows that it will not support its own weight even for a short distance. Over such small areas the crust may be taken as part of a plane, or sometimes as concave, where subsidence is already at work, and hence the theory of the arch or dome is scarcely applicable; yet the observed collapse and sinking, even where the area is no larger than in ocean troughs, confirms the above conclusions regarding the total inability of the crust to support itself.

Could therefore anything be more absurd than to discuss the stresses in the crust due to the progress of secular cooling? Stresses arise only where mountain making is in progress, and therefore chiefly near the oceans, but never appear far inland; and are wholly due to the pressure arising from steam-saturated rock and the expulsion of lava from beneath the oceans, or to movements traceable to surface water slowly sinking into the earth. The theory of arches and domes therefore confirms the present theory, but this result is indirect; and such lines of thought did not enable geologists and physicists to reach correct conceptions regarding the physics of the earth's crust.

§ 50. *On the Doctrine that Earthquake Movements depend on Slight Inequalities of Loading, and on the Abandoned Theory that the Earth is a Failing Structure.*—As the crust of the earth is made up of solid rock and soil arising from the disintegration of rock of various kinds, and as this material is elastic and yields under pressure, it naturally occurred to physicists that inequalities of surface loading deposited on adjacent areas would impose upon the underlying crust unequal stresses, and perhaps give rise to relative movements. Thus many physicists, in default of a better theory, have supposed that surface loads, depending on erosion and sedimentation, tides and varying barometric pressure, would be adequate to produce stresses that would cause readjustment of the surface strata and perhaps movements of faults in earthquakes.

It is undeniable that these varying loads do produce some small effects, and very slight changes of level may often arise in this way. We owe the establishment of these effects of loading chiefly to the researches of Professor Sir G. H. Darwin, whose labors have so greatly advanced our knowledge of the physics of the earth. They have an extremely high importance in the theory of bodies approximating elastic solids. The undisturbed crust of the globe fulfills these conditions quite perfectly.

But to suppose that any of these small surface effects could give rise to world-shaking earthquakes which would shake down cities, raise sea coasts, and uplift mountains and islands in the sea, is too severe a test of credulity to be entertained. The class *of minute movements,* due to surface yielding under varying loads depending on sediments, tides and meteorological causes, and the class of *great movements,* due to the expulsion of lava from under the bed of the sea, are quite distinct. One class of these phenomena is microseismic, the other magaseismic. Previous investigators have generally confounded the two classes of phenomena, and hence they have been unable to recognize the true cause of earthquakes and mountain formation. For that reason it was necessary to restrict our investigation to the great disturbances, in the first search for the cause of the great movements of the earth's crust.

We repeat that both classes of phenomena are important in a complete theory of the physics of the earth; but the small yieldings of microscopic dimensions must be kept distinct from the great movements which have shaped the surface of the globe. Many of the small effects depend on the greater movements of the earth, while few of the great movements are influenced by surface forces—indeed none at all, except where accumulation of subterranean stresses has already rendered the conditions highly unstable. In this latter case small surface forces may occasionally accelerate the outbreak of an earthquake, just as a spark discharges a loaded gun, or a shock explodes a charge of dynamite.

On a par with the theory that slight inequalities of surface loading produce earthquakes is another equally untenable view that the earth is a failing structure. Such a doctrine might have been entertained a quarter of a century ago, when the theory of secular cooling was generally accepted, but to-day such a view is antiquated and utterly indefensible. *Owing to the demonstrated de-*

*pendence of mountain making upon the sea the earth emphatically is not a failing structure.* So far from failing by collapse, our planet seems to be expanding from 10 to 100 faster than it contracts from loss of heat. Thus have arisen all the highest mountains and plateaus of the globe. These great uplifts invariably face the deepest oceans, from which the expulsion of lava has mainly proceeded. Such antiquated doctrines as that the earth is a failing structure are now absolutely without excuse, and practically abandoned, and the sooner they disappear from scientific literature the better for sound knowledge of the physics of the earth.

§ 51. *Changes of the Force of Gravity in Regions Affected by the Movement of Lava Beneath the Crust.*—In view of the demonstrated movement of lava streams beneath the crust of the globe, it follows that such bodily displacement of matter but a short distance below the surface may modify sensibly the observed intensity of gravity. A region which is being undermined will have the intensity of gravity decreased, and a region which is being filled up will have the attraction increased. And not only will the *intensity* vary, but also the *direction* of the vertical, according to the movements which occur beneath the crust. And these effects may be large enough to become sensible to very refined observation.

It is in this way that the anomalies of gravity in the neighborhood of mountains have arisen in the process of mountain formation. And in regions where the expulsion of lava is still in progress, both the direction and intensity of gravity are subject to change by earthquakes. Thus in the region of the Aleutian Islands, the east coast of Japan, and many other places, such as the west coast of South America, the direction and intensity of gravity is certainly subject to change by seismic disturbances.

As the crust of the globe often suffers horizontal and vertical movement during the greatest earthquakes, the *altitude* and *azimuth* of places are also subject to change; and exact geodetic triangulation remains valid only for the interval between great earthquakes. Even then there may be a very slow and gradual settlement owing to plastic yielding of the crust and especially of the substratum beneath. Thus after earthquakes such as occur in Peru and Chili, Japan and Alaska, gravity and geodetic determinations need repetition, as was done in California after the great earthquake of April 18, 1906. And as the disturbance may alter the direction and intensity of local gravity, this possibility must be taken account of in the repetition of the observations. In order to be entirely rigorous the equations connecting the triangulation should include undetermined multipliers to take account of possible variations in the local attraction at each point. If with this general condition imposed, the triangulation before and after the earthquake comes out rigorously the same, within the limits of errors of observation, it may be supposed that the surface effects of the disturbance are insensible; otherwise the difference must be attributed to disturbances due to the earthquake.

With the refinement now possible in geodesy, it is not to be doubted that these effects will occasionally prove to be sensible to observation. The great earthquake in Assam-Bengal gave rise to horizontal movements of the order of 20 or 30 feet, which may affect the latitude by 0″.2 or 0″.3, and are thus within the limits of astronomical measurement. But apparent changes in latitude may result from change in the direction of gravity as well as from actual displacements of the crust, and both possibilities need to be taken into account.

§ 52. *The Necessity of Further Study of the Contours and Movements of the Sea Bottom.*—In view of the results brought out in this paper and those which have preceded it, but especially that on "The New Theory of Earthquakes and Mountain Formation as Illustrated by Processes now at Work in the Depths of the Sea," it is scarcely necessary to point out the extreme importance of further study of the contours and movements of the sea bottom. Our present maps of the ocean depths are very incomplete, although they afford a good general idea of the sea basins. But one can scarcely doubt that more exact surveys would bring to light additional mountain ranges and plateaus in regions heretofore but slightly explored; moreover certain places in the sea bottom would be found to be covered with a great variety of peaks or submerged islands which do not reach the surface.

Where the water is deep the exact survey of the bottom presents considerable difficulty. As movements arising from earthquakes are extremely small in comparison with the depth of the sea, it would perhaps be very difficult to detect resulting changes of the sea bottom, except in cases where sinking takes place, and the drop is large. In some cases of actual measurement in the laying of cables the sinking has been found to be hundreds of fathoms, which would be very easily recognized if the exact place of former soundings could be found. But as the changes of level in the sea bottom are fully as capricious as on land, we see that regions where mountain formation is in progress would present extreme complexity; and unless the place were very accurately known, one could not be sure that two soundings were over the same spot. This difficulty would be less near known islands than in the open sea, but it would be considerable in all places where the ship is at the mercy of the winds and currents.

Under the circumstances it is clear that great natural difficulty would arise in the exact Hydrographic survey of the deep sea, and an economic difficulty would be added, on the ground that such surveys are not required in practical navigation. Yet the laying and repair of cables would necessitate fairly accurate knowledge of the depths, and we may hope, in spite of the growth of the wireless telegraph, that our ocean surveys are still in the infancy of what they will be in another half century.

Where trenches are being dug out by earthquakes there will be the double incentive to ascertain the stage of the process and the rapidity and location of the changes. These considerations may contribute to our knowledge of particular regions; and, after all, the changes in the larger regions of the ocean bottom are small.

When the regions in which trenches are forming are once clearly recognized, attention will naturally be centered upon them, to the neglect of less disturbed areas. The most interesting regions, from a seismological point of view, are those in which islands are being uplifted and the sea bottom sinking, as near the Aleutian, Kurile and Japanese islands, the Antandes, and along the west coast of South America. But it may also be hoped that the changes in depth near individual islands, such as Guam and Martinique, will not be overlooked. Here the subsidence of the bottom often takes the form of a hole rather than of a trench. Yet in time the movements may give rise to neighboring islands. All of these considerations show the value of accurate knowledge of the sea bottom at this epoch.

§ 53. *Greatness of the Forces which Uplift and fold the Earth's Crust.*—The tremendous power of earthquake and volcanic forces has been proverbial from the earliest ages of history, and finds expression also in the universal terror thus excited among all living beings. This extreme terror is only too well justified by the vast extent of the ruin too often wrought in different parts of the world. But probably only those who have witnessed a great earthquake can adequately appreciate the awful character of the commotion, and the gigantic forces which must underly it. This is shown also by the many published attempts to belittle the significance of earthquake disasters.

Some writers of eminent mathematical learning, but apparently lacking in grasp of the larger physical phenomena, have ascribed earthquakes to inequalities of loading, changes of barometric pressure, etc., and have with strange and almost marvelous credulity believed that the settlements of the earth thus arising would shake down cities and devastate whole countries. How these learned authorities imagined that small subsidences under the steady action of these infinitesimal forces could bring about such long continued shaking and proportionately great havoc is difficult to understand. If the forces are so small, and act so slowly, is it conceivable that the yielding could be anything else than gradual and insensible? Such minute settlements evidently would be like those now experienced in dry inland regions free from real earthquakes.

The titanic nature of the forces which have uplifted islands, mountains, plateaus and continents, can scarcely be realized; yet even the ancients grasped it to some extent when they described the whole region between Naples and Sicily as underlaid by a giant, whose movements disturbed the intervening sea bottom. In his account of the Chilean earthquake of 1835, Charles Darwin showed that the entire region from the island of San Fernandez to the Andes, about 450 miles across, had been moved together by underlying forces. "There was undoubtedly a connection between the volcanic forces acting under this island, and under the continent, as was shown during the earthquake of 1835," says the great naturalist.

As such views have been carefully set forth by the greatest of original investigators, from Aristotle to Darwin, it is remarkable to witness the puny efforts which have been made to belittle these forces. A gentleman holding a university position, in a public address at Boston, recently likened the shock of an earthquake to the jar experienced by an insect attached to a reed which was bent till it snapped. According to this authority the earthquakes are due to the snapping of the rock of the earth's crust in the bending produced by secular cooling. Is it necessary to point out the misleading character of the comparison made, and this lecturer's utter inability to grasp the phenomena of nature?

An equally common fallacy is to ascribe these tremendous disturbances to inequalities of surface loading, due to geological and meterological causes. Such views seem the more surprising, because formerly they have proceeded from physicists of eminent learning. But at least partial excuse may be found in the universal acceptance of the theory of secular cooling heretofore, and in the proved rigidity of the globe, which naturally led to the supposition that the crust was adjusting itself to the shrinking sphere.

Before the development of the theory of ocean leakage no adequate theory presented itself to investigators, who had unfortunately not discriminated between the great and small earthquakes. With a false premise and such an indiscriminate mixture of phenomena, real progress was difficult, if not impossible.

§ 54. *Darwin's Remarks on the Forces which Uplift Continents.*—In the extract quoted from Professor Suess, § 39, allusion has already been made to Charles Darwin's attempt to explain the origin of mountains by the direct observation of nature. His paper "On the Connection of Certain Volcanic Phenomena in South America and the Formation of Mountain Chains and Volcanoes as the Effect of the Same Power by which Continents are Elevated" (*Transactions of the Geological Society*, Vol. V, 1838, pp. 601–631) led Darwin to the conclusion:

> *"That the form of the fluid surface of the nucleus of the earth is subject to some change, the cause of which is entirely unknown and the effect of which is slow, intermittent, but irresistible."*

Again, in the "Voyage of the Naturalist," Chapter XIV, he adds:

> *"The forces which slowly and by little starts uplift continents, and those which at successive periods pour forth volcanic matter from open orifices, are identical."*

It is unnecessary to dwell on the irresistible power which the great naturalist correctly abscribed to volcanic and earthquake forces. It is of more interest to notice that he declared them to be identical with those which uplift continents. The same result is reached in the present paper, about three quarters of a century later, and the proof of the proposition now seems overwhelming.

If Darwin had known the cause of seismic sea waves, and had seen how trenches are dug out in the sea bottom by the expulsion of lava from beneath the sea under the land, can anyone doubt that he would have discovered and proved the leakage of the oceans, and developed the correct theory of mountain formation?

§ 55. *On the Oscillatory Movements of the Crust Shown in the Coal Measures.*—In view of the results established in this paper we need not dwell on the coal measures, and other evidences of the oscillation of the earth's crust. It suffices to say that these oscillations actually took place, as geologists have long believed. The coal fields in Pennsylvania were formed by vegetation growing rapidly and with great luxuriance over areas near the sea level which were again and again elevated and as often depressed by earthquakes. When the land was under the sea the vegetation died out, and mud and shale were deposited; when the area was again upraised another layer of vegetation was produced, and sometimes it was deposited by floods, currents, and drifting where it had not grown. This was during the Carboniferous Age, and while all the land was near the level of the ocean.

The details of such inquiries must be left to geologists and paleontologists, who study the flora and fauna of past ages. Our aim in these papers has been to give a firm basis for legitimate study and speculation, without which the phenomena of nature remain unintelligible. The progress of the sciences of the earth requires two conditions: first, true physical causes; and second, the intelligent and consistent application of these causes to the explanation of the phenomena, both of the animate and inanimate world. The physicist must content himself with showing the mechanical causes at work and their mode of operation, while the geologist and paleontologist may deal with the evidences of life under these known conditions.

§ 56. *The Equilibrium of the Earth between the Land and Water Hemispheres Explained by the Intumescence of the Land Arising from the Expulsion of Porous Lava from under the Bed of the Sea.* —The remarkable equilibrium preserved by the earth between the land and water hemispheres has long been a matter of speculation among philosophers. Sir John Herschel justly remarked that the high altitude of the continents in the land hemisphere would be most easily accounted for by an intumescence of the land. Pratt has since treated the question in a convincing manner, and shown that the solid parts of the earth's crust beneath the water hemisphere, with pole in New Zealand, must be denser than in the corresponding parts on the opposite side, otherwise the water would flow away towards the land hemisphere and tend to submerge it more completely. (Cf. "Figure of the Earth," 3d edition, pp. 159–160.) Hence he concludes that

> "There must therefore be some excess of matter in the solid parts of the earth between the Pacific ocean, and the earth's center which retains the water in its place."

When Pratt wrote this forty years ago there was no suspicion of an intumescent layer beneath the land due to the expulsion of porous lava from beneath the bed of the sea, and accordingly he added that

> "This effect may be produced in an infinite variety of ways; and therefore, without data, it is useless to speculate regarding the arrangement of matter which actually exists in the solid parts below."

Now, however, it is proved that the plateaus and continents have been uplifted by intumescent matter expelled from under the sea; and consequently we have data for speculating on how the observed effect is produced.

It is clear that all the great plateaus of the globe and even the continents themselves are underlaid by material lighter than the average of the earth's crust. Naturally the effects are greatest where the plateaus are highest, as in Himalayas and Tibet, where the deficiency in the attraction of these elevated masses long ago attracted attention. In his "Account of the Operations of the Great Trigonometric Survey of India," Calcutta, 1879, General J. T. Walker says:

> "There appears to be no escape form the conclusion that there is a more or less marked negative variation of gravity over the whole of the Indian continent, and that the magnitude of this variation is somehow connected with the height.
>
> "Pratt's calculations had reference only to the visible mountain and oceanic masses and their attractive influences—the former positive, the latter negative—in a horizontal direction; he had no data for investigating the density of the crust of the earth below either the mountains on the one hand, or the bed of ocean on the other. The pendulum observations furnished the first direct measures of the vertical forces of gravity in different localities which were obtained, and these measures revealed two broad facts regarding the disposition of the invisible matter below; first, that the force of gravity diminishes as the mountains are approached, and is very much less on the summit of the highly elevated Himalayan table-lands than can be accounted for otherwise than by a deficiency of matter below; secondly, that it increases as the ocean is approached, and is greater on islands than can be accounted for otherwise than by an excess of matter below. Assuming gravity to be normal (in amount) on coast lines, the mean observed increase at the islands stations was such as to cause a seconds' pendulum to gain three seconds daily, and the mean observed decrease in the interior of the continent would have caused the pendulum to lose 2½ seconds daily at stations averaging 1,200 feet above the sea level, 5 seconds at 3,800 feet, and about 22 seconds at 15,400 feet—the highest elevation reached— in excess of the normal loss of rate due to the height above the sea."

The facts here mentioned by General Walker are recognized in geodesy as applying in different degrees to all the elevated table-lands and mountainous regions of the globe. The physical cause of this deficiency in attraction is now established beyond all doubt, and the intumescence of the land, first suggested by Sir John Herschel, is shown to have arisen from the expulsion of lava from beneath the sea. Thus arises the physical condition which secures the equilibrium of the earth between the land and water hemispheres. This must be regarded as not the least remarkable among several interesting results on the physics of the earth deduced from the principle of the secular leakage of the oceans. Earthquakes, volcanoes, mountain formation, the uplift of islands, plat-

Fig. 15. Map Showing the World Ridge. (From Frye's Complete Geography, by permission of Ginn & Co., Publishers.) It will be noticed that the high mountains and great plateaus everywhere face the outside, which is towards the water hemisphere. This map therefore bears impressive testimony to the truth of the New Theory, and the World Ridge stands as an everlasting witness to the secular action of the oceans in uplifting the land hemisphere of the globe.

eaus, and continents, seismic sea waves, trenches and holes in the bottom of the sea, the feeble attraction of mountains, and plateaus, the equilibrium of the globe between the land and water hemispheres, are all closely related and dependent upon a single physical cause.

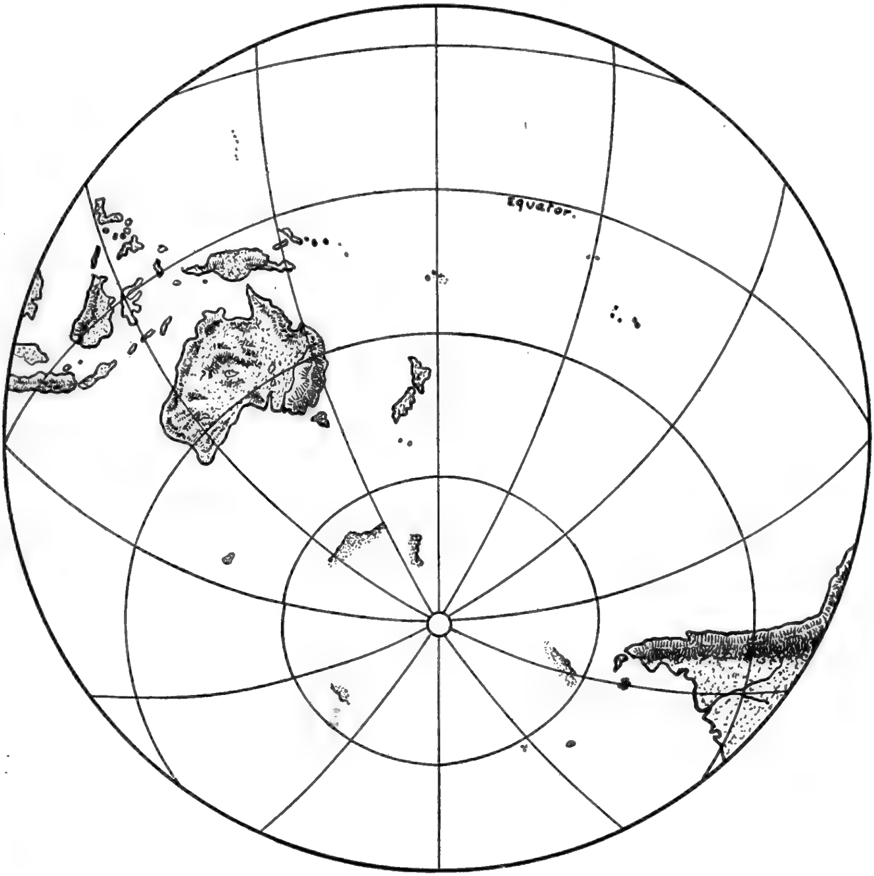

FIG. 16. Water Hemisphere, which has the World Ridge around it, drawn by W. R. Smith, of Mare Island.

In view of the order and harmony thus established among these varied phenomena, who will not concur in the view of the great Newton that "Nature is pleased with simplicity and affects not the pomp of superfluous causes"?

## CONCLUSIONS.

Some of the chief conclusions reached in this and the preceding papers on the physics of the earth may be briefly summarized as follows:

1. The theory of the secular leakage of the oceans explains satisfactorily six great classes of phenomena, not heretofore closely associated, namely: (1) Earthquakes, (2) volcanoes, (3) mountain formation, (4) the formation of islands, plateaus and continents, (5) seismic sea waves, (6) the feeble attraction of mountains and plateaus long noticed in geodesy.

2. And the theory not only explains the leading facts of each class of phenomena separately, but also in relation to all the other classes of phenomena; and this harmonious mutual relationship of all the phenomena proves the theory to rest on a true physical cause.

3. A *vera causa,* once established, should not only explain all the phenomena, and all the relations, but also exclude the consideration of other possible causes, by necessary and sufficient conditions. This alone ensures the entire validity of the reasoning, and the present theory meets this severe test perfectly.

4. We have traced the details of the processes involved in mountain formation, and have exhibited illustrations of its working by processes now observed in the depths of the sea. All stages of mountain formation are thus brought out, and they are all shown to be consistent with this simple theory, which explains the principal phenomena of the earth's crust.

5. This theory explains the distribution of mountains about the continents, their great height which the contraction theory cannot account for; the formation of parallel ridges by the uplift of the side of the trough nearest the sea, when the bottom has so far subsided that the folding up of the nearer side becomes the path of least resistance in the expulsion of molten rocks from under the sea.

6. Several successive troughs are often thus dug out, with ridges forced up between them; and when the whole is raised above the water we have a series of parallel ranges, such as the Allegheny, Tuscarora and Blue Ridge Mountains in Pennsylvania and Vir-

ginia. Heretofore these vast billows of the earth's crust have been utterly bewildering to the naturalist.

7. When several such trenches have been dug out, and the expulsion of lava is from both sides, as happens when the sea is thus distributed, the ridges may finally be forced up and so crowded together from both sides that overturned dips and inverted strata are produced, as in the Swiss Alps. No previous theory has been adequate to account for this amazing phenomenon, the explanation of which is thus seen to be exceedingly simple. This test may be justly considered the *experimentum crucis* of the theories of mountain formation.

8. The Andes in South America are nothing but a vast wall or embankment erected by the Pacific Ocean, through the expulsion of lava, along its border. Hence the persistence of the earthquake belt and seismic sea waves along this coast.

9. This embankment includes not only the peaks and chains of mountains, large and small, in the Eastern and Western Cordillera, but also the intervening plateaus, such as those of Quito, Caxamarca, Cuzco, and Titicaca.

10. The molten rock expelled from under the sea is lighter than average material of the layer below the earth's crust, and when the included vapor of steam is allowed to expand, as in volcanoes, pumice is formed, and often blow out in vast quantities. Pumice of various degrees of density underlies the mountain chains, and some of it is blown out of those mountains which become volcanoes.

11. The way in which these plateaus are interwoven with the Andes mountains shows that the whole embankment is due to the continued action of one common cause. And since the mountains were uplifted by the expulsion of lava from under the sea, as proved by the uplifting of the land in earthquakes and the sinking of the sea bottom, indicated by the accompanying seismic sea waves, it follows that the plateaus also are underlaid by matter lighter than the average, which has been expelled from under the ocean.

12. The total quantity of matter thus expelled from beneath the ocean is very large, but it is the result of an infinite number of earthquakes and seismic sea waves during past geological ages. This circumstance affords us an idea of the immense age of the

Andes Mountains, which are the youngest of the great mountain systems of the globe.

13. The terrible fracturing of the crust in the sharp folding involved in the formation of the Andes enabled a vast number of volcanoes to break out, and about one hundred and five have been active within historical times.

14. The formation and activity of the volcanoes in the Aleutian and Japanese Islands is similar to those in the Andes, and represent conditions suitable to the maximum development of volcanic activity. These are sharp folds of the crust near a deep sea from which the expulsion of lava is rapid and violent.

15. The connection of earthquakes with volcanoes and of both phenomena with the sea is clearly established by the geographical distribution and by the vapor of steam emitted by volcanoes. The nature of the underlying material is shown by the ashes, cinders, pumice and lava forced out by the accumulating subterranean steam pressure.

16. Earthquakes, however, are the more general, volcanoes the more special phenomena. The mountains are formed by the sea, but only a few of the peaks break out into volcanoes. No volcano long remains active very far from the ocean or other large body of water, because as the lava hardens in the throat of the volcano the supply of steam is inadequate to maintain activity.

17. If we consider the innumerable islands in the sea, it is evident that they too have been uplifted by earthquakes. Sometimes the sea bottom near them has been undermined in the process of uplifting, and afterwards sunk down, making an adjacent hole in the bottom, and producing seismic sea waves of the first class, as in mountain formation where trenches are being dug out near the continents.

18. Seismic sea waves of the second class are produced by the uplift of the sea bottom, into ridges, or submarine plateaus and islands. In such cases the water rises suddenly without previously withdrawing from the shore.

19. But seismic sea waves of the first class due to the sinking of the sea bottom, after it is undermined by the expulsion of lava, are the most important and most celebrated. The waves at Helike,

373 B. C.; Callao, 1746; Lisbon, 1755; Arica, 1868; Iquique, 1877; Japan, 1896, were all of this class.

20. We may pass directly from the Andes to the Himalayas, and from the high plateaus of South America to those of Asia. Just as the plateaus from Quito to Titicaca were formed by the expulsion of matter from under the Pacific, so also those of Tibet and Iran are due mainly to the expulsion of lava from beneath the Indian and Pacific Oceans.

21. In the case of the plateau of Tibet the resulting uplift is partly due to the combined action of the Pacific, which thus folded the ranges to the East. With two oceans so large and deep as the Indian and Pacific coöperating in this uplift, it is no wonder that the maximum effect was produced and that Tibet became the highest plateau in the world.

22. The Himalayas are higher and further from the sea than the Andes, but the earthquake belt at the base still persists in both cases, and the configuration in regard to the sea shows that the causes at work to produce these mighty uplifts were absolutely similar. And if the mountains are due to the same cause, the plateaus are also.

23. The total height of Tibet is only about one sixth or seventh of the thickness of the earth's crust, and hence the uplift, great as it is, is not such as would necessarily produce great volcanic outbreaks at the surface.

24. Great lava flows, however, occurred in India, and some volcanic phenomenon are known in the Himalayas, but our knowledge of these mountains is not yet adequate to enable one to estimate just how much volcanic activity developed there.

25. Great lava flows are due to the rupture of the crust, by the opening of a fault near the sea, not to volcanic outbreaks. These flows are seen in Utah, Oregon and India, on a scale commensurate with the forces which have uplifted the mountains and plateaus.

26. One may pass directly from the mountains and plateaus of South America to those of Asia, and then to those on the Pacific slope of North America, by the most gradual stages.

27. In this transition the processes are so similar and the differences so small, that it is impossible to deny that the mountains

and plateaus west of the Rocky Mountains were all formed through the uplift of the land by the Pacific Ocean.

28. The North American Plateau is larger, but correspondingly lower than those in Asia, so that the volume of material involved in the two uplifts is comparable. Thus all the great plateaus of the globe are due to the action of the sea, in the course of immeasurable ages. The slowness of the process conveys the best conception of the vast interval of time since the consolidation of the globe.

29. Charles Darwin long ago held that "the forces which slowly and by little starts uplift continents and those which at successive periods pour forth volcanic matter from open orifices are identical." He showed that the southern end of South America has recently risen from the sea, and Professor Suess has shown that the universal lowering of the strand line throughout the principal countries gives a similar indication for all the lands of the globe.

30. If one end of a continent can be raised by earthquake forces depending on the sea, then obviously a whole continent can be raised by these forces; and similar uplifts can occur for all the continents in both hemispheres. The vast vertical walls of granite so often found rising from the sea in South America and elsewhere have clearly been uplifted by earthquakes.

31. We therefore reach the conclusion that the forces which have raised the mountains, islands and plateaus, have also raised the continents and established the equilibrium of the globe between the land and water hemispheres. This force is nothing else than common steam, operating through the expansion of molten rock beneath the crust and arises principally from the secular leakage of the ocean bottoms.

32. The main effect of earthquakes is the production of more land. The continents are being lifted out of the sea, in spite of erosion, as we see by the withdrawal of the oceans to a greater and greater distance from old mountain chains, such as the Rocky Mountains and Appalachians in America and the Alps in Europe.

33. But for this uplift of the land by the leakage of the oceans none of the higher forms of life could have developed upon the earth. The climate and drainage of all continents have been largely

determined by these forces, which have produced the mountains and river systems of the world.

34. We cannot prove by experiments on rock twenty miles thick that it will leak under the pressure of the ocean, but we can observe the surface movements in earthquakes such as occur in Alaska, where lava is being expelled from under the ocean and pushed under the land.

35. This movement is everywhere in the same direction, whether in Alaska, Japan, the Antandes, South America, or elsewhere—namely from the ocean towards the land. The reason of this is that much steam is formed under the oceans, but scarcely any under the land, and hence it pushes up the crust along the edge of the continents and finally almost walls them in with mountains, as was long ago pointed out by Dana.

36. The old theory of secular cooling and contraction of the globe is false and misleading, and all who have carefully examined it agree that it is totally inadequate to account for terrestrial phenomena. In fact so far from contracting it seems certain that the earth is actually undergoing a slow secular expansion.

37. The Rev. O. Fisher and Major Dutton were among the earliest to reject this theory as incapable of explaining mountain ranges. But it is remarkable that after the contraction theory was proved to be unsatisfactory, it continued to be used in all works on geology and kindred sciences, and indeed still is accepted by those who adhere to the antiquated doctrine that the earth is a failing structure. Such views had some justification a quarter of a century ago; today they are absolutely without excuse.

38. There are the best grounds for accepting the doctrine of Isostacy, as approximately true for the earth at all times; consequently there are no sensible stress-differences, or tendencies to flow, except in the layers just beneath the crust. At greater depths the matter of the earth is made solid by pressure, being at the centre about three times more rigid than nickel steel. Hence deep down the earth is now and always has been quiescent. The only layer of the earth which is plastic and perhaps viscous is that just beneath the crust; this layer flows under the tremendous forces at work in earthquake movements. It is the movement of this molten rock be-

neath the crust, chiefly when it is expelled from under the sea, which shakes down cities and devastates whole countries.

39. This expulsion of lava under the land can mean nothing else than the secular leakage of the oceans, because the mountains along the coast which are rent by the shaking of the earth till they break into volcanoes, emit chiefly vapor of steam. Moreover the unsymmetrical shape of the mountain folds, showing the gentler slope towards the shore, indicates that the folds of the crust were pushed from the direction of the sea. This was produced by the expulsion of lava under the crust arising from the secular leakage of the ocean bottom.

40. By the study of seismic and other phenomena now observed in the great laboratory of nature we may penetrate the deepest secrets hidden beneath the earth's crust, to which no mortal eye can ever bear direct witness. And these researches may greatly increase the safety of whole communities, and especially of cities and of commerce, throughout the world, by enabling us to guard against the dangers of earthquakes and seismic sea waves. This appropriate use of the laboratory of Nature is one of the ultimate objects of natural philosophy.

Blue Ridge on Loutre,
Montgomery City, Missouri,
February 19, 1908.

## POSTSCRIPT.

In a paper read before the Royal Society in 1902, Professor J. H. Jeans, formerly of Cambridge, now of Princeton University, has the following theory of earthquakes:

> "It seems to be almost certain that the present elastic constants of the earth are such that a state of symmetrical symmetry would be one of stable equilibrium. On the other hand, if we look backward through the history of our planet, we probably come to a time when the rigidity was so much that the stable configuration of equilibriums would be unsymmetrical. At this time the earth would be pear-shaped and the transition to the present approximately spherical form would take place through a series of ruptures. It is suggested that the earth, in spite of this series of ruptures, still retains traces of a pear-shaped configuration. Such a configuration should possess a single axis of symmetry, and this, it is suggested, is an axis which meets the earth's surface somewhere in the neighbourhood of England (or possibly some hundreds of miles to the southwest of England). Starting from

England we find that England is at the centre of a hemisphere which is practically all land; this would be the blunt end of our pear. Bounding the hemisphere we have a great circle, of which England is the pole, and it is over this circle that earthquakes and volcanoes are of most frequent occurrence. Now, if we suppose our pear contracting to a spherical shape, we notice that it would probably be in the neighbourhood of its equator that the changes in curvature and the relative displacements would be greatest, and hence we would expect to find earthquakes and volcanoes in greatest number near this circle. Passing still further from England, we come to a great region of deep seas, the Pacific, South Atlantic, and Indian Oceans; these may mark the place where the 'waist' of the pear occurred. Lastly we come almost to the antipodes of England, to the Australian continent. This may mark the remains of the stalk-end of the pear." (*Nature,* Vol. LXVII., p. 190.)

After what has been shown in this series of papers, it is unnecessary to dwell upon this hypothesis of Professor Jeans, which has the merit of originality; but we may remark that if it gave a true view of the physics of the earth, there should be a belt around the globe of at least the width of the terrestrial radius, over which the earthquakes are about equally distributed, whereas in fact they are felt principally along the margins of the Pacific Ocean. The observed earthquake belt on land is so narrow that it is clearly impossible to ascribe the effects to this supposed adjustment of the earth's figure. And of course it fails totally to account for the sinking of the sea bottom and the uplift of the coast, which is typical of mountain formation.

# THE ABSORPTION SPECTRA OF NEODYMIUM CHLORIDE AND PRASEODYMIUM CHLORIDE IN WATER, METHYL ALCOHOL, ETHYL ALCOHOL AND MIXTURES OF THESE SOLVENTS.

(With six plates.)

## Twenty-first Communication.

By HARRY C. JONES and JOHN A. ANDERSON.

(*Read April 25, 1908.*)

(This is a preliminary report on part of an investigation carried out with the aid of a Grant from the Carnegie Institution of Washington.)

The absorption spectra of salts of cobalt, nickel, copper, iron, chromium, neodymium, praseodymium and erbium have been studied in the present investigation. Of these the salts of neodymium and praseodymium are perhaps the most interesting and important. This is due to the large number of absorption bands shown by these substances, and, further, to the very unusually sharp character of these bands.

The method employed in making the spectrograms consists in allowing light from a spark, or from a Nernst filament, to pass through the solution in question, fall upon a grating and then upon the photographic plate.

For visual work a small direct vision grating pocket spectroscope was found very convenient and useful. For photographing the spectra the vertical grating spectroscope used by Jones and Uhler[1] was employed.

In making the photographs the Seed L-ortho film was used for the region from λ 2000 to about λ 6000.

For photographing the red end of the spectrum a Wratten and Wainwright panchromatic glass plate was used.

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[1] Carnegie Publication No. 60.

The Nernst filament was found to be the most satisfactory source of light from the extreme red to the beginning of the ultra-violet. It is sufficiently brilliant to require an exposure of only a minute, but practically ceases at about λ 3200. For wave-lengths shorter than this some spark spectrum must be used.

The cadmium-zinc spark used by Jones and Uhler was fairly satisfactory, especially in the extreme ultra-violet, but has the drawback that there are present a limited number of very intense lines, on a rather faint continuous background. We tried to obtain a spark spectrum having a very large number of lines, but with no lines of very great intensity. We found that tungsten, molybdenum and uranium all satisfied these requirements.

The terminals finally used were prepared by dipping pieces of carbon in a concentrated solution of ammonium molybdate, and then heating in a bunsen burner. They were then dipped into a solution of uranium nitrate and similarly heated.

The coil used to produce the spark was a large Röntgen X-ray coil.

## Making a Spectrogram.

In making a spectrogram consisting of seven photographic strips, the following mode of procedure was adopted: Seven separate solutions were made up of the desired strengths. The cell[2] to be used was filled to the required depth with the most concentrated solution of the series, and the quartz plates determining the depth of the solution adjusted to parallelism. The exposure to the Nernst lamp was then made, being usually one minute long. An opaque screen covering up the visible spectrum as far down as λ 4000 was then interposed between the grating and the photographic film, and the exposure to the light of the spark in the ultra-violet made. The duration of this exposure was usually about two minutes. The photographic film was then moved into the proper position for the next exposure. The above series of operations was then repeated for each of the succeeding strips.

After the film had been exposed for each solution and the spark spectrum impressed, it was necessary to make a similar series of

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[2] See Carnegie Publication No. 60.

exposures on a panchromatic plate for the red end of the spectrum, using the same set of solutions.

The scale accompanying the spectrograms was made by photographing an ordinary paper scale. Several photographs were taken, the distance between the paper scale and the lens of the camera being varied slightly from exposure to exposure. The resulting negative which fitted the majority of spectrograms best was selected and used throughout.

## NEODYMIUM CHLORIDE IN WATER—BEER'S LAW.

(See plate 1.)

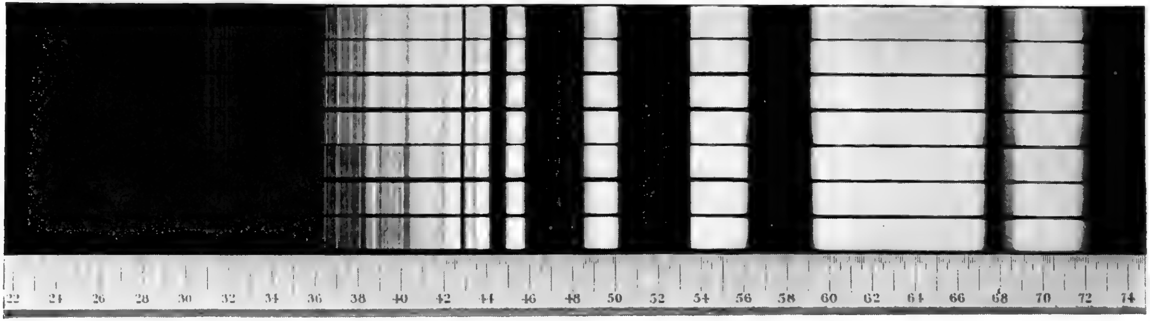
The concentrations of the solutions of neodymium chloride were so chosen and the depths of cell so selected that the total amount of coloring matter in the path of the beam of light was kept constant. From Beer's Law the absorption shown by the several solutions, under these conditions, should be the same. The concentrations of the solutions used in making the negative for *a*, plate 1, beginning with the one whose spectrum is adjacent to the numbered scale, were 3.40, 3.02, 2.72, 2.38, 2.17, 1.90 and 1.70; the corresponding depths of cell being 12, 13.5, 15, 17, 19, 21.5 and 24 mm. For *b*, plate 1, the concentrations were 3.40, 2.55, 1.70, 1.13, 0.80, 0.57 and 0.43; the corresponding depths of absorbing layer being 3, 4, 6, 9, 13, 18 and 24 mm.

The most concentrated solutions appeared brownish yellow in their bottles, from which the color changed on dilution to a yellowish pink, the color being extremely faint in the most dilute solutions.

The exposures to the light of the Nernst lamp and spark were, respectively, 1 minute and 2 minutes; the slit having a width of 0.01 cm. The exposures and slit width were not varied in the work recorded in the present chapter, the object being to make the spectrograms as nearly comparable as possible.

Both *a* and *b* of plate 1 show the presence of some general absorption in the ultra-violet, which decreases quite rapidly with dilution. The absorption bands also narrow somewhat with decrease in concentration, especially from 3.4 normal to about 1.7 normal. For concentrations less than about 1.5 normal Beer's Law seems to hold very accurately indeed, with the exception of the

PLATE I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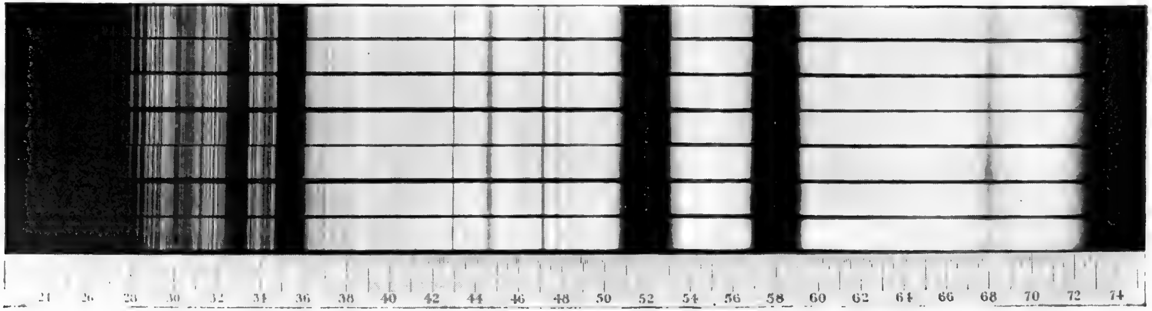
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shading towards the red accompanying the band near λ 5800, which seems to decrease somewhat with dilution for concentrations of one normal or less.

In the following table the measurements of the positions of the bands were made on the seventh strips of *a*, plate 1, and, therefore, refer to a concentration of 1.7 normal with a depth of layer of 24 mm. The remarks referring to changes with dilution apply to a change in concentration from 3.4 to 1.7 normal, the depths of layer being so varied that the product of concentration and depth remains constant.

| λ | Character. | Remarks. |
|---|---|---|
| 2810 | Faint transmission begins. | |
| 2890–2910 | Band with well defined sharp edges. | |
| 2970–2995 | A double band, strongest component to violet. | The observed narrowing with dilution perhaps due largely to general U. V. absorption. |
| 3220–3330 | Strong band of complete absorption, sharp edges. | Narrows slightly with dilution. |
| 3380–3400 | Rather faint band, most intense towards red. | |
| 3435–3595 | Complete absorption, edges sharp. | |
| 4180 | Hazy, not very intense. | Narrows some with dilution. |
| 4275 | Very intense and sharp. | Narrows considerably at first. |
| 4290 | Narrow and faint. | Between this and λ 4275 is fairly strong absorption in the most concentrated solution. This absorption has disappeared in the spectrum measured. |
| 4330 | Hazy. | |
| 4410–4465 | Edges rather hazy. | This band is coincident with band due to praseodymium, and is to be ascribed to this element which has not been completely separated from the neodymium. It does not change with dilution. |
| 4580–4650 | Band with hazy edges not completely separated from λ 4665–λ 4710. | Narrows slightly with dilution. |
| 4665–4710 | More sharply defined on red than on violet side. | Partly due to praseodymium. Does not change with dilution. |

| λ | Character. | Remarks. |
|---|---|---|
| 4740–4770 | Fairly sharp edges. | Not affected by dilution. |
| 4820 | Hazy on violet side. | Due at least partly to praseodymium. |
| 5000–5330 | Red limit sharp, violet a little hazy. | Violet shading a little greater in concentrated solutions. |
| 5660–5930 | Violet limit sharp. Red edge hazy. | Shading on red side decreases with dilution. |
| 6235 | First and strongest band in orange group. | Not affected by dilution. |
| 6260 | Narrow and rather faint. | Not affected by dilution. |
| 6270–6310 | Faint band. | Not affected by dilution. |
| 6360–6390 | Faint band. | Not affected by dilution. |
| 6730 | Faint, in shading of principal red band. | Not affected by dilution. |
| 6770–6840 | Principal red band. Edges hazy. | Not affected by dilution. |
| 6890 | Band with hazy edges. | Not affected by dilution. |
| 7250 | End of transmission. | Not affected by dilution. |

The most marked change produced by dilution from 3.4 to 1.7 normal, excepting that in the red shading of the λ 5660–5930 band, is that taking place on the red side of the narrow absorption line at λ 4275. In the spectrum of the most concentrated solution the red edge of this line falls at λ 4280, from which place a uniform absorption extends to λ 4295. In the third spectrum, counting from the numbered scale, the shading has almost completely disappeared, leaving a very narrow line at approximately λ 4290. The width of this line is only 2 or 3 A. U. and it persists with unchanged intensity throughout the remaining strips of the spectrogram. Its intensity is, however, not sufficient to make it show in the reproduction, and not even great enough to make it visible on the negative for *b*, plate 1.

The limits of transmission for the yellow band, as shown by the spectrum of the most concentrated solution, are λ 5660 and λ 5950; hence the narrowing of its red side amounts to 20 A. U.

*b*, plate 1, starts at the same concentration as *a*, but the effective depth of absorbing layer is only one-fourth of that used in *a*. Hence this spectrogram represents the spectrum of a solution of neodymium chloride 24 mm. deep and having a concentration of 0.43 normal. The absorption bands are all much narrower, and several of them are shown in the process of breaking up into simpler bands. The bands in the ultra-violet have disappeared excepting the one at λ 3435–λ 3595, which is still intense, and a trace of the one at λ 3220–λ 3330. Transmission in this region now extends faintly to λ 2460. No new absorption bands beyond λ 2800 can be seen.

The λ 3435–λ 3595 band now has the limits λ 3450–λ 3580, and shows a weak transmission at λ 3485, which increases somewhat with dilution, thus dividing the band into two.

The band at λ 4180 is weak throughout *b*, plate 1.

The band having its middle at λ 4445, perhaps due entirely to praseodymium, in *a*, plate 1, has about the same intensity as it shows in a solution of praseodymium chloride having a concentration of 0.85 and a depth of absorbing layer equal to 3 mm. This indicates that the percentage of praseodymium in the neodymium salts used was about 6 per cent. The band at λ 4825 partly due to praseodymium may also be seen throughout the entire series under consideration. The wave-length of the praseodymium band being λ 4815, while that of the band showing in all the neodymium spectra has the position λ 4825, showing that neodymium has a band nearly coincident with that given by praseodymium, but lying a little closer to the red end of the spectrum. The remaining praseodymium band has the position λ 4685, this nearly coinciding with the rather narrow, strong neodymium band whose position is λ 4695.

The band which under *a*, plate 1, was recorded as having the limits λ 4580–λ 4650, shows in *b* as a hazy band with its center at 4615, together with a narrow faint line at λ 4645.

The band which in the table is recorded as λ 4740–λ 4770 has in *b*, plate 1, become a slightly hazy band having its middle at λ 4760. Its intensity is intermediate between that of the bands at λ 4695 and λ 4825.

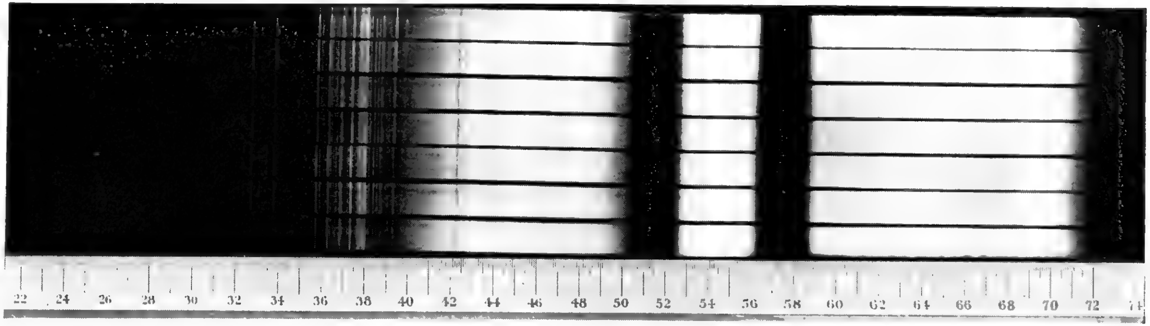
The band which in *a*, plate 1, has the limits λ 5000–λ 5330, breaks up into a rather complicated series of bands on dilution, some idea of which may perhaps be gained from the following: *b*, plate 1, shows some absorption throughout the region given, but with a deep, narrow band at λ 5090, and faint transmission at λ 5100 and in the region λ 5150–λ 5180. Absorption is complete from λ 5105 to λ 5150, and from λ 5180 to λ 5270. There is again incomplete absorption from λ 5270 to λ 5330, with indication of a band at λ 5315.

The limits of the yellow band in *b,* plate 1, are λ 5700–λ 5880, in the strip corresponding to the most concentrated solution. The band narrows by 30 Angström units on this spectrogram, the narrowing being due to a decrease in the shading towards the red, with decrease in concentration.

The most intense bands of neodymium chloride, and hence the ones which would be most conspicuous in a very dilute solution are the following: λ 3465, λ 3540, λ 4275, λ 5205, λ 5225, λ 5745, λ 5765 and λ 7325.

The wave-lengths of all the bands are collected in the following table, together with a brief description of the appearance of each band. It is to be understood that this table is not meant to represent what could be seen or photographed in any one solution of neodymium chloride in water. It merely records the positions of all the bands that can be seen in a layer from 3 to 12 mm. deep, when the concentration is varied from 0 to 3.4 normal.

| λ | Description. |
|---|---|
| 2900 | About 20 A. U. wide. |
| 2985 | About 25 A. U. wide. |
| 3225 | Narrow and sharp. |
| 3390 | Narrow, faint. |
| 3465 | Very intense, narrow. |
| 3505 | Rather wide. |
| 3540 | Very intense, narrow. |
| 3560 | Faint, narrow. |
| 4180 | Faint, hazy. |
| 4275 | Very intense and sharp. |
| 4290 | Very narrow, faint. |
| 4330 | Hazy edges. |
| 4615 | Rather wide and hazy. |
| 4645 | Very narrow, faint. |
| 4695 | Narrow, intense. |
| 4760 | Hazy edges, fairly narrow. |
| 4825 | Narrow and fairly intense. |
| 5090 | Narrow, intense. |
| 5125 | Rather wide and hazy. |
| 5205 | Very intense, narrow. |
| 5222 | Very intense, narrow. |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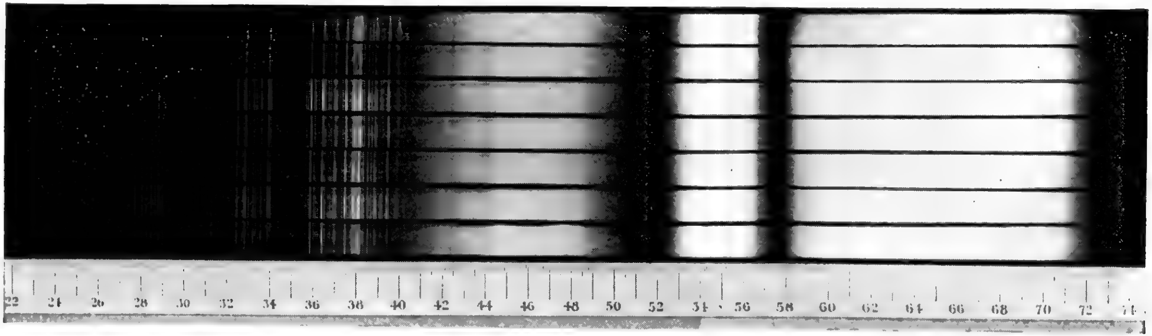
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|---|---|
| 5255 | Narrow, intense. |
| 5315 | Hazy edges, faint. |
| 5725 | Narrow, intense. |
| 5745 | Very intense. |
| 5765 | Very intense. |
| 5795 | Intense, moderately narrow. |
| 5830 | Very faint and hazy. |
| 6235 | Fairly narrow. |
| 6260 | Very narrow, faint. |
| 6270–6310 | Faint, hazy edges. |
| 6360–6390 | Faint, hazy edges. |
| 6730 | Faint band. |
| 6800 | Moderately intense, hazy edges. |
| 6890 | Hazy edges. |
| 7325 | Very intense and narrow. |
| 7350 | Narrow. |
| 7390 | Rather wide band. |

### Neodymium Chloride in Methyl Alcohol—Beer's Law.

(See plate 2.)

The concentrations of the solutions used in making the negative for *a,* beginning with the one whose spectrum is adjacent to the numbered scale were 0.50, 0.40, 0.315, 0.25, 0.20, 0.16 and 0.125; the corresponding depths of absorbing layer being 6, 7.5, 9.5, 12, 15, 19 and 24 mm. The concentrations for *b* were in the same order 0.20, 0.16, 0.13, 0.10, 0.08, 0.06 and 0.05, the depths of cell being the same as used in *a.*

There is some absorption in the extreme ultra-violet, which is to be ascribed to the solvent, however, and not to the neodymium chloride.

No trace of absorption due to the dissolved substance is visible until we reach the group of bands near $\lambda$ 3500. These are three bands having their centers at $\lambda$ 3475, $\lambda$ 3505, and $\lambda$ 3560. Of these the one at $\lambda$ 3560 is the widest and also the most intense; the one at $\lambda$ 3475 being somewhat fainter than that at $\lambda$ 3505. The bands are all much wider and hazier than those occurring near the same place in the aqueous solution. No change with dilution, indicating a deviation from Beer's Law, can be detected in these or any of the other bands in the alcoholic solutions of the chloride.

In the violet and blue regions we find the following band at λ 4290, about 10 A. U. wide and only moderately intense. At λ 4325 a band somewhat wider and fainter. At λ 4460, a rather wide hazy band with a faint hazy companion towards the violet. This is the band which is perhaps due to praseodymium. The much greater concentration of the alcoholic solutions of praseodymium chloride studied in this work, makes it impossible to verify this by seeing whether the praseodymium band in dilute solution really has this general character.

There are bands at λ 4700, λ 4780 and λ 4825, all of about the same intensity; the one at λ 4770 being, however, much narrower than the other two, of which λ 4825 is somewhat the wider. Both λ 4700 and λ 4780 have faint companions to the violet.

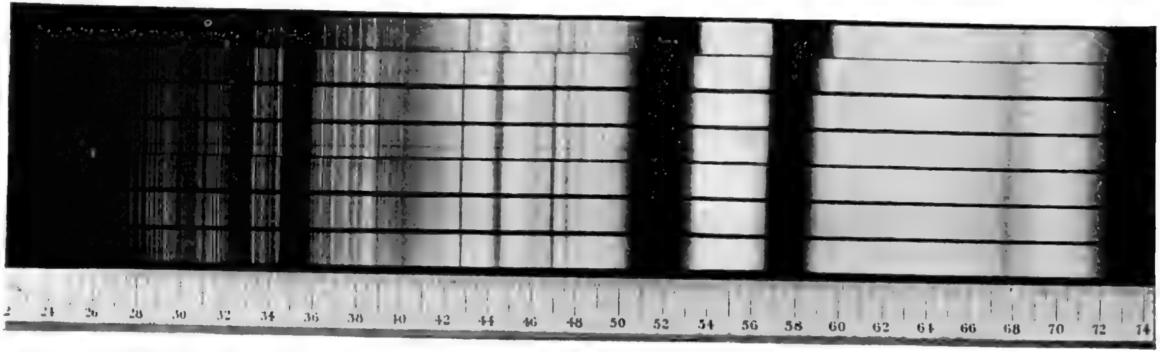
The group in the green is made up of six bands as follows: λ 5125 hazy and rather wide, moderately intense; λ 5180, also hazy but much fainter; λ 5220 moderately intense and narrow; λ 5245 intense and with faint companion towards the red; λ 5290 narrow and moderately intense. Shading as far as λ 5330 with indications of faint band at λ 5315.

The yellow group is made up of seven bands having the following characteristics: λ 5725 moderately intense with hazy edges; λ 5765 narrower, but not quite as intense as λ 5725; λ 5800 fairly narrow, strong; λ 5835 very intense; λ 5860 hazy and moderately intense; not clearly separated from λ 5835 shading to λ 5970, with two faint bands superposed on it, one at λ 5895 and the other at λ 5925.

No trace of bands is to be seen in the orange, but in the red there is a fairly narrow but faint band at λ 6860. The spectrum ends at λ 7355 in a deep, rather narrow band. It is evident that the spectrum of neodymium chloride when dissolved in methyl alcohol is quite different from its spectrum in aqueous solution.

## NEODYMIUM CHLORIDE IN MIXTURES OF METHYL ALCOHOL AND WATER. (See plates 3 and 4.)

Since, as we have just seen, the absorption spectrum of neodymium chloride in aqueous solution is so different from that of the alcoholic solutions, it was thought to be of some interest to see how the change from one to the other would take place if one of the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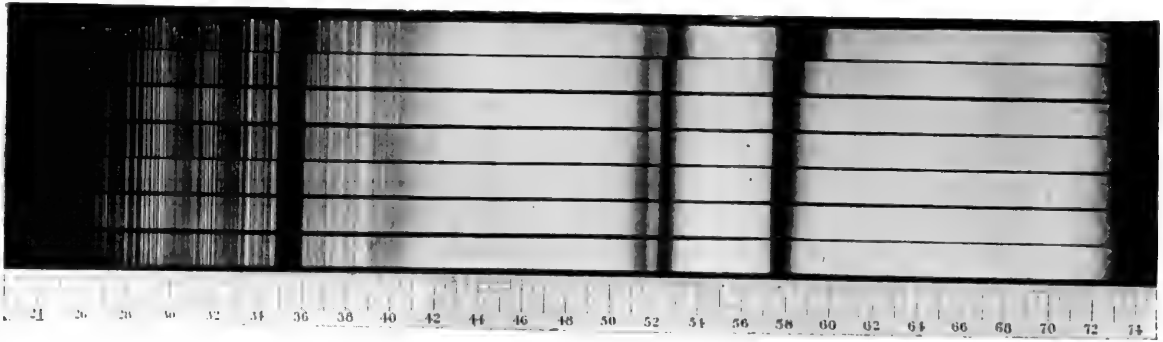
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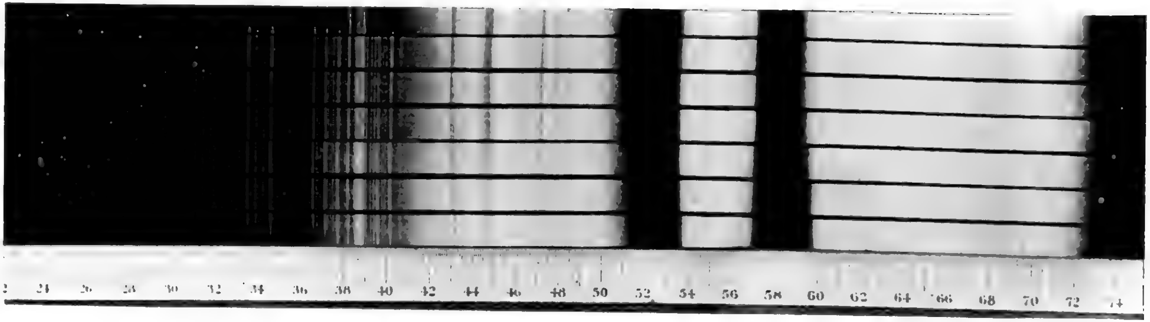
PLATE IV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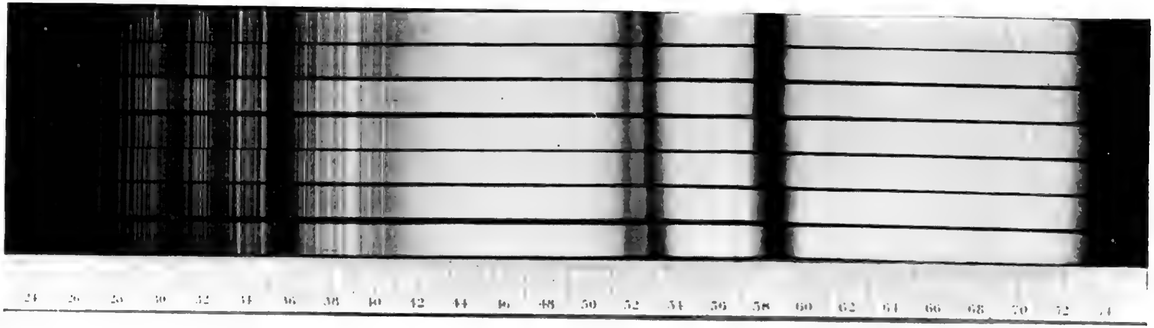
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solvents was made to displace the other gradually. A series of solutions was accordingly made up, the concentration of the dissolved salt being constant and equal to 0.5 normal, but the character of the solvent varying as follows: The percentages of water in the seven solutions were 0, 16⅔, 33⅓, 50, 66⅔, 83⅓ and 100; the corresponding percentages of methyl alcohol were 100, 83⅓, 66⅔, 50, 33⅓, 16⅔ and 0. Two spectrograms were made, namely *a*, plate 3, where the depth of the cell was 1.5 cm. and *b* where the cell had a depth of only 5 mm. *a* was made in order to show clearly the change taking place in the narrower and fainter bands, while *b* was intended to show the change of structure of the more intense bands such as the green and yellow ones. The strip which is adjacent to the numbered scale belongs to the solution in pure water, while the one nearest the narrow comparison spark spectrum belongs to the solution in pure methyl alcohol.

Plate 3 shows that beginning with the strip nearest the scale, the first six spectra are very nearly identical. From the sixth to the seventh there is an abrupt change which at first sight consists in a shift of all the bands towards the red, but which on closer examination is seen to consist in a disappearance of one spectrum and the appearance of the other. Since the first strip is the spectrum of the solution in pure water, it follows, since the sixth is nearly identical with the first, that as large a percentage of alcohol in the solvent as 83 per cent. does not change the absorption spectrum materially; the chief change taking place when the percentage of alcohol is varied from 83 per cent. to 100 per cent.

It is to be noted that the apparent shift of the bands towards the red is in reality not quite as great as it appears at first sight from plate 3, owing to the fact that the film accidently shifted slightly towards the red between the sixth and seventh exposures. The amount of this mechanical shift is easily seen, however, by comparing the spark lines in the ultra-violet. A measurement of the shift shows it to be approximately 3 Angström units, and the same for both *a* and *b*, while the "apparent" shift of the absorption line at λ 4275 in aqueous solution is actually 15 Angström units, its position in the alcoholic solution being λ 4290.

The slight changes taking place with some of the bands throughout the spectrograms of plate 3 are perhaps sufficiently clear in the reproductions. However, as a good deal of the detail shown by the negatives is lost even in the most perfect processes of reproduction, we give here a description of the changes taking place in two of the bands as seen on the original negative. We select the bands at λ 4275, and λ 4760 from the negative for *a*, plate 3.

In the aqueous solution the λ 4275 band is very intense and narrow, its whole width being less than 5 Angström units. The edges are only very slightly shaded. In the alcoholic solution the position of the center of the corresponding band is λ 4290. It has a width of from 12 to 13 Angström units, and is not nearly as intense as in the aqueous solution.

Throughout the first six strips the λ 4275 band maintains its position and intensity almost unchanged. Its position does not change in the least, but its intensity in the sixth strip is a trifle less than in the others. In the seventh strip there is not the faintest trace left of it. In the third strip, corresponding to the solution whose alcohol content was 33⅓ per cent., there appears at λ 4285 an extremely faint and narrow line. In the fourth strip it is somewhat wider and more intense, but its center is still at λ 4285. In the fifth strip it is beginning to be fairly conspicuous, and in the sixth it is a band of moderate intensity having its center at about λ 4287. This band is undoubtedly the same one which in the pure alcoholic solution has its center at λ 4290 or very near there; the exact wavelength being perhaps nearer to λ 4292. We see then that even when the mixed solvent contains only about one-half alcohol this band exists independent of and distinct from the band characteristic of the aqueous solution; that it is at first only a very narrow and faint line which widens towards the red as the percentage of alcohol is increased.

The band whose center is at λ 4760 has the following appearance in the aqueous solution: Faint absorption begins at λ 4748 and rises rapidly to a maximum between λ 4755 and λ 4760, then decreases slowly to nothing at λ 4775. The band is accordingly a trifle asymmetrical, the slope towards the violet being considerably steeper than that towards the red. The corresponding band in the alcoholic solution is double and answers the following description: Very faint absorption begins at λ 4753 and rises to a faint maximum at about λ 4757, becoming again zero at λ 4760. It begins again at λ 4772, rises rapidly to a strong maximum at λ 4780 and falls to zero at λ 4790. The component whose center is at λ 4757 is very faint compared with the main band.

In the first and second strips we have nothing but the band corresponding to the aqueous solution. In the third strip the red side of the band has increased slightly in intensity, making it appear much more nearly symmetrical. This change increases in the fourth and fifth strips, the band at the same time widening considerably. In the sixth strip its appearance is as follows: Absorption begins at λ 4748 and rises to a maximum just to the violet side of λ 4760, then decreases slightly towards λ 4770, after which it increases somewhat to λ 4778, then falls off to zero at λ 4787.

It is very evident from a study of the change in this band that the two bands characteristic of the aqueous and alcoholic solutions coexist, and that the band appearing in our photographic strips is the sum of the two taken in different proportions. The proportion of the alcohol band being, however, very much smaller than the proportion of alcohol in the corresponding solution. A similar description might be given for any one of the other bands, but this is not necessary as the changes are of exactly the same nature as those we have already indicated. In every case where the alcoholic solution has a strong band, which differs somewhat in position from any band in the aqueous solution, we begin to see traces of this band when the proportion of alcohol in the mixture reaches 50 per cent., but the band remains comparatively faint even when the proportion is as high as 83⅓ per cent.

In order to study the change which takes place between the sixth and seventh strips of the spectrograms of plate 3, more carefully, a series of alcohol solutions were prepared containing the following percentages of water, 0, 2⅔, 5⅓, 8, 10⅔, 13⅓ and 16. The concentration of the neodymium chloride was constant and equal to 0.5 normal. Two spectrograms were made, one with a depth of absorbing layer of 1.5 cm., in order to show the fainter bands, and the other with the depth of the cell only 5 mm. in order to show as much as possible of the structure of the larger bands. The first spectrogram is reproduced as *a*, the second as *b*, plate 4. The strips corresponding to the pure alcohol solutions are adjacent to the numbered scale, the spectrum of the solution containing 16 per cent. water being next to the comparison spark spectrum.

Although we found in considering plate 3 that some slight change in the spectrum takes place where the percentage of alcohol is changed from 0 to 83 per cent., yet this change is so small and the bands due to the aqueous solution are so strong that we may regard the spectrum of a solution containing 16 per cent. of water as practically that of the aqueous solution. Accordingly, the spectrograms on plate 4 may be taken to show very nearly the whole change which takes place when the solvent of neodymium chloride is gradually changed from pure water to pure methyl alcohol.

In *a* the ultra-violet band is rather too intense to allow its structure to be seen. Accordingly, we see the whole band remains sensibly unchanged as the water is varied from 16 per cent. to 8 per cent., and then shifts towards the red with increasing rapidity as the water is reduced to zero; the whole apparent shift amounting to about twenty Angström units. On the negative the intense band at λ 3465 may, however, be clearly seen, and its intensity decreases very slowly from the first to the third strips, counting from the narrow comparison spark spectrum. In the fourth strip its intensity is about half of what it was in the first strip, and from this it decreases rapidly, vanishing entirely in the strip nearest the scale. In *b* the structure of this band is seen very distinctly, and we find that the bands characteristic of the aqueous solution gradually decrease in intensity, especially from the third to the sixth strips, while the wider bands characteristic of the alcoholic solutions increase in intensity, the two sets existing together. The change in the band at λ 4275 is the one that shows the best, because here the two bands belonging to the aqueous and alcoholic solutions, respectively, are both intense and narrow and clearly separated from each other. The alcoholic band is clearly visible in the first strip, and it increases continuously in intensity as the amount of water is decreased, but more rapidly from the fourth to the seventh strips than from the first to the fourth. Its position also shifts somewhat towards the red from the first to the fourth strips, the wave lengths of its center for the two strips being, respectively, λ 4287 and λ 4292. Accompanying this shift is a change in its character which may be gathered from the following statements: In the first strip it has the appearance of an unsymmetrical band, the maximum intensity being nearer the violet; in the third strip it extends from λ 4280 to λ 4295 and has about the same intensity throughout; in the fourth strip the intensity of its violet edge has decreased, while that of the red edge has increased considerably, giving it the appearance of an unsymmetrical band with the maximum intensity towards the red. In the fifth strip the violet shading from λ 4280 to about λ 4284 has disappeared, leaving a band very nearly symmetrical about λ 4290. It appears, therefore, that we are really dealing with two unresolved bands, one having its center at about λ 4285, and the other at λ 4292.

The band at λ 4275, due to the aqueous solution, decreases in intensity throughout, but more rapidly from the third to the sixth strips than at first. Its position remains the same throughout. As near as the eye can judge, this band has had its intensity reduced to about half-value when the fourth strip is reached, corresponding to 8 per cent. of water in the solution. The alcohol band at λ 4292 also has about 50 per cent. of its final intensity in the same solution.

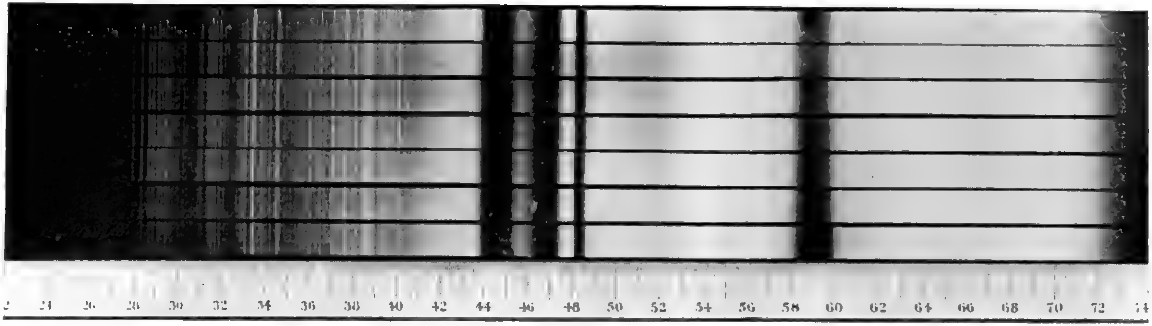
The band at λ 4760 shows the same kind of a change that we described in some detail above, only the change is much more gradual and easy to follow here. It also shows about equal intensity for the two sets of bands when the amount of water is 8 per cent. of the whole.

The green and yellow bands are not sufficiently resolved in *a* to allow the change in the individual bands to be followed, and hence these apparently show only a gradual shift towards the red with decrease in the amount of water. In *b,* however, they are sufficiently resolved to enable us to follow the change in each individual band, which, although a little difficult, on account of their large number and the incompleteness of their separation in some cases, may still be done. The change is in every respect the same as we have found for the other bands; namely, those due to the aqueous solution diminish in intensity and reach about half value in the 8 per cent. aqueous solution, while those belonging to the alcoholic solution increase in intensity, as the amount of water is decreased.

The band in the red near λ 6800 shows the change very well indeed, the "water" band having the position λ 6800, while that pertaining to the alcoholic solution is situated at λ 6860, and hence the two are well separated. Here the point of equal intensity appears to be reached in the solution containing 10⅔ per cent. of water, but this is due to the fact that the alcoholic band has a considerably greater intensity than that due to the aqueous solution, conditions as to concentration and depth of layer being the same. Taking this into account it is seen that this band obeys substantially the same rule as the others.

The change in the band at λ 7325 is more difficult to follow, on account of the small intensity of the photographic action on the less refragible side of this position. The band belonging to the aqueous solution may be seen very clearly even in the strip corresponding to the 2⅔ per cent. water solution, but is of course entirely absent in the alcoholic solution. Its intensity in the 2⅔ per cent. solution, however, seems a little greater than we should expect from the behavior of the other bands, but this is perhaps due to the rather weak photographic action in this part of the spectrum, combined with the great intrinsic intensity of the band. The alcoholic solution transmits light as far as λ 7355 where its spectrum ends abruptly in a band.

Throughout this description we have laid great stress on the fact that on plate 4 the two sets of bands coexist; the bands due to the aqueous solution decreasing, while those belonging to the alcoholic solution increase in intensity with decrease in the percentage of water. We have also called attention to the fact that the two sets of bands have about one-half their full intensity in a solution containing about 8 per cent. of water. This was for a 0.5 normal solution.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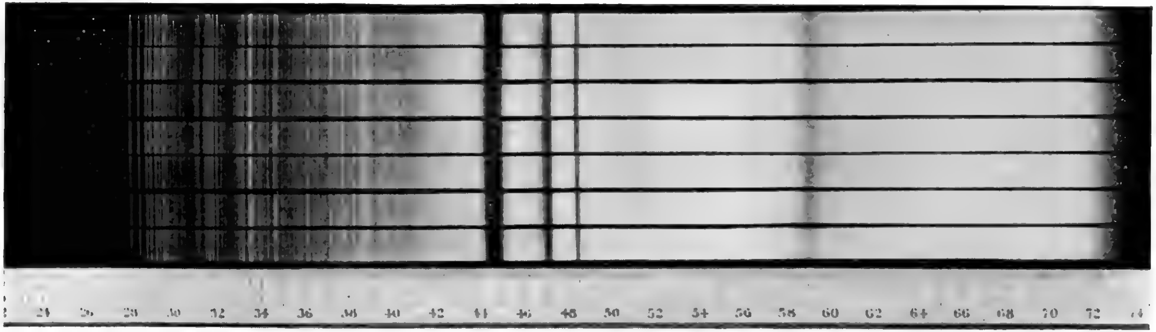
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### PRASEODYMIUM CHLORIDE IN WATER—BEER'S LAW.

(See plate 5.)

The concentrations of the solutions used in making the negative for *a*, beginning with the one whose spectrum is adjacent to the numbered scale were 2.56, 1.92, 1.25, 0.85, 0.60, 0.42 and 0.32. For *b* the concentrations were 0.85, 0.63, 0.42, 0.28, 0.20, 0.14 and 0.11; the depths of absorbing layer being, respectively, 3, 4, 6, 9, 13, 18 and 24 mm.

The solutions of praseodymium chloride are all green or yellowish green, only the intensity of the color changing with change in the concentration.

For these solutions Beer's Law holds very exactly, excepting for the extreme ultra-violet absorption in *a*, and the yellow bands in the two or three most concentrated solutions of *a*.

The limits of transmission in the ultra-violet for the most concentrated and most dilute solutions of *a* are, respectively, λ 2720 and λ 2650. The edge is fairly sharp, indicating the presence of a rather intense band. This is also indicated by *b*, where the spectrum ends abruptly at λ 2630, the limit being the same for all the solutions.

The absorption bands shown in *a* are as follows: λ 4380 to λ 4480, strong band with red edge somewhat shaded; λ 4640 to λ 4710, sharp on red side, quite diffuse towards the violet; λ 4800 to λ 4830, sharply defined on both sides; λ 5860 to λ 5950, both edges diffuse; λ 5985, fairly narrow band with diffuse edges. The region between this band and the principal yellow one shows very strong absorption.

*b* shows the following: λ 4410 to λ 4465, both edges a little diffuse; λ 4685, fairly narrow band, still more diffuse towards the violet, although somewhat shaded also towards the red; λ 4815, narrow band with edges slightly shaded; λ 5900, wide hazy band; absorption not complete even at its middle; λ 5985, rather faint, hazy band.

The greenish tinge of the solutions would suggest that there is considerable general absorption in the red, because the absorption in the yellow is not sufficient to impart any marked color to the solution, and the bands in the violet and blue could only give it a yellow tint. The negative for *a* does, in fact, show pretty strong general absorption from λ 7100 to the end of the red, but no doubt a spectrophotometric study of the solutions would show general absorption much farther down into the red. The negative for *b* shows no sign of this absorption for very obvious reasons.

## Praseodymium Chloride in Mixtures of the Alcohols and Water.

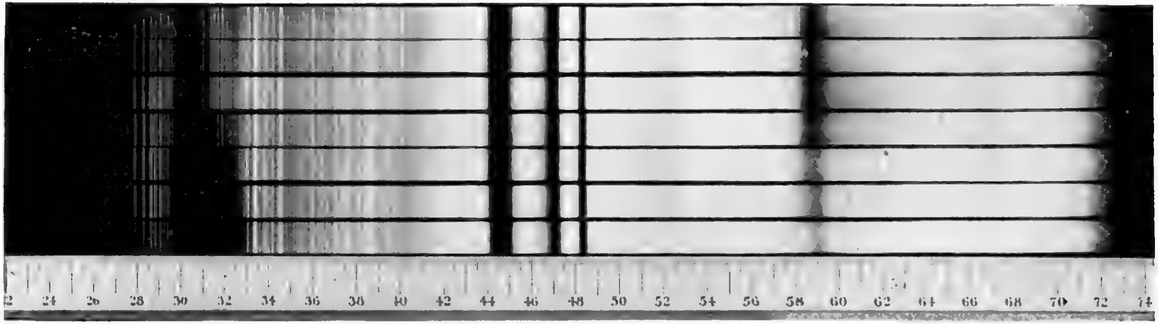
(See plate 6.)

The concentrations of the praseodymium chloride was constant throughout and equal to 0.5 normal. The percentages of water in the solutions, beginning with the one whose spectrum is adjacent to the numbered scale, were 0, 2⅓, 5⅔, 8, 10⅔, 13⅓ and 16. The depth of absorbing layer was 1.0 cm.

Methyl alcohol was the chief solvent in the solutions pertaining to *a*, while ethyl alcohol was used in the solutions used in making the negative for *b*. The two spectrograms are identical, except for a little greater general absorption in the ultra-violet with the ethyl alcohol.

The most striking feature of the spectrograms is the appearance of the intense absorption band near λ 3000 as the percentage of water is gradually decreased. Only a faint trace of this band is visible with 16 per cent. of water in the solution, and the band is comparatively weak even with only 8 per cent. of water. From this point it increases very rapidly in width and intensity with decrease in the amount of water, until in the pure alcohol solutions its limits (transmission) are λ 2970 and λ 3230, being by far the most intense band in the whole spectrum.

The bands in the violet and blue apparently shift somewhat towards the red, this being, however, due to the fact that the alcohol bands are a little nearer the red end of the spctrum, and that when the percentage of water changes from 16 to 0, the two sets of bands coexist, but are far from being separated. The change is exactly the same in character as the one described in detail in discussing the λ 4760 band in mixtures of alcohol and water for neodymium chloride. The positions of the bands in the solution, containing 16 per cent. of water, are as follows: λ 4390 to λ 4470,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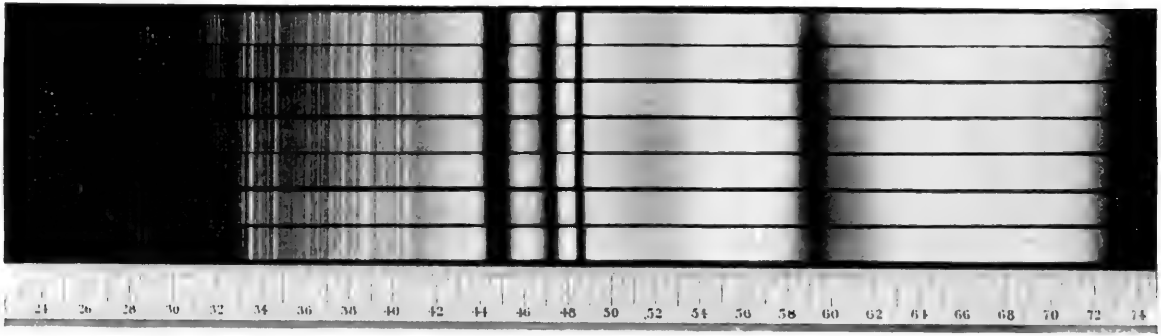
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λ 4660 to λ 4700, λ 4800 to λ 4825. In the solution in pure alcohol they are λ 4410 to λ 4480, λ 4690 to λ 4715, λ 4810 to λ 4840. Hence it appears that the two most refragible bands have a slightly greater width in the aqueous solution, while the λ 4815 band is more intense in the alcoholic solutions.

The bands in the yellow show very well, indeed; the fact that here as in the spectrum of neodymium chloride we have the coexistence of two sets of bands when the water content of a one-half normal solution is in the neighborhood of 8 per cent. The band in the yellow has already been described under Beer's Law, but as the concentration and depth of layer is different here, the following will serve to indicate what the spectrum of the 16 per cent. aqueous solution shows.

Absorption begins at λ 5850 and rises to a maximum at about λ 5900, then decreases to a minimum at λ 5950, from which it again rises to a maximum at about λ 5980, falling off to zero at λ 6000. The solution in pure alcohol shows the following: Weak absorption begins at λ 5800, and continues without material change up to λ 5880, where it falls almost to nothing. At λ 5900 it begins to increase and reaches a strong maximum at λ 5955, falling off gradually to zero at λ 6000. The intermediate solutions show the gradual disappearance of the bands characteristic of the aqueous solution, and the increase in intensity of those belonging to the alcoholic solution as the percentage of water is gradually decreased. The maximum change takes place from the fifth to the third strips, counting from the numbered scale, indicating here as with neodymium chloride that the two sets have about half their normal intensity when the water content of the solution is about 8 per cent., or when the solution contains about ten molecules of water per molecule of the dissolved substance.

## Discussion of the Results.

The results established by these plates may be briefly summarized as follows:

1. The absorption spectra of a salt in different solvents are, in general, different.

2. When a salt is dissolved in mixtures of two solvents the

relative percentages of which are varied, there is not a gradual change of one spectrum into the other, but the spectrum given in the mixture is a superposition of the two spectra, the two sets of bands existing together. If the salt is one whose spectrum changes considerably with its state of dissociation, we have in addition to the above phenomena the changes due to the varying dissociation of the dissolved salt produced by the varying composition of the mixture.

A study of all the plates (eighty in number) obtained in this work shows that deviations from Beer's Law is the rule rather than the exception; only a limited number obey Beer's Law even approximately. Beer's Law could only hold in cases where the relative concentrations of the different kinds of absorbers in solution do not change with the dilution, or where the different kinds of absorbers have the same kind of absorption. The first condition is perhaps never realized, while the second is undoubtedly closely approached with such salts as neodymium chloride and praseodymium chloride.

The rule is that the different absorbers have different absorbing powers, and the problem of absorption spectra is to determine which kind of absorbers in solution are responsible for the different bands.

The theory of Ostwald, which would refer absorption in solution mainly to the ions present, has been found to be entirely insufficient to account for the facts established in this investigation.

The other theories which aim to account for the deviations are of two kinds, viz.:

1. Those that assume that the increased absorption in concentrated solutions is due to the formation of aggregates of the molecules of the dissolved substance, or of the molecules and the ions into which they break down in dissociation.

2. Those that assume that the deviation is due to the *formation of solvates,* that is, combinations of the parts of the dissolved substance with the molecules of the solvent.

Now, it has been shown by Hartley and other workers, who have studied the change in the absorption with change in temperature, that the bands which widen with increase in concentration (conditions for Beer's Law assumed to obtain) also widen with rise in temperature; that is, a rise in temperature produces very much the same effect as increase in concentration. This seems to us pretty conclusive evidence against the theories which are based on the formation of aggregates, for it is well known that the change in the aggregates produced by rise in temperature is *not the same* as that produced by increase in concentration, but *exactly the opposite.*

The theories which assume the formation of solvates are not open to this objection, because it is well known that the change in the solvates produced by rise in temperature is in general the *same* as that produced by increase in concentration. As a solution becomes more concentrated the solvates become simpler and simpler, that is, fewer molecules of the solvent are combined with each part of the dissolved substance. Rise in temperature also breaks down complex solvates into simpler ones. Of course, it does not follow that the solvates of a solution of concentration $c_1$ at temperature $t_1$ are *exactly* the same as those in a solution of concentration $c_2$ at a temperature $t_2$; since under the changed conditions it may happen that the particular solvates, which were most stable when the conditions were $c_1$ and $t_1$, may be less stable than solvates of nearly the same composition at $c_2$, $t_2$.

For this reason and also because our work on neodymium and praseodymium salts in mixed solvents *seems almost conclusive evidence in favor of the existence of solvates, we have used the solvate theory as a working hypothesis throughout this work.* That it is not far from being correct is shown by the fact that all the phenomena observed in the great number, about 1,200, of solutions studied, are accounted for without anything but the simplest assumptions in regard to the behavior of the solvates in question.

The most interesting and important results were obtained from the study of the salts of neodymium and praseodymium, especially those of the former. These substances have not only very many absorption bands, but they are remarkably narrow and sharp, and, hence, peculiarly suitable for spectrographic study. The chief experimental results were the following:

1. The absorption spectrum of aqueous solutions of the chloride and bromide of neodymium changes very little with change in con-

centration, and the two are nearly identical, throughout, excepting for the fact that the absorbing power of the bromide appears to be somewhat greater than that of the chloride.

2. Solutions of the salts in non-aqueous solvents give spectra which are not only different for different salts, but the spectrum of any one salt is different in the different solvents. An apparent exception is the spectrum of neodymium or praseodymium chloride in methyl and ethyl alcohols, which are almost exactly alike.

3. When a salt like neodymium chloride is dissolved in mixtures of water and one of the non-aqueous solvents, and the relative amounts of the two solvents in the mixture is varied, no marked change in the spectrum is observed when the amount of water is changed from 100 per cent. to about 15 or 20 per cent. As the amount of water is still further reduced we find that the solution gives a spectrum which consists of a superposition of the spectra belonging to the aqueous and the non-aqueous solutions; the former decreasing in intensity while the latter increases as the amount of water is decreased. The composition of the mixed solvents, which will show the two spectra with about one-half their normal intensity, depends upon the concentration of the salt in solution; and a constant ratio between the number of molecules of water and those of the dissolved salt were indicated by the experiments, this ratio having the value 10.

Praseodymium chloride, dissolved in mixtures of water and methyl or ethyl alcohol, shows in general the same kind of change in the spectrum as neodymium chloride; but in addition there appears in the alcoholic solutions an entirely new band having no analogue in the aqueous solution. In the former this new band in the ultraviolet is by far the most intense in the entire spectrum. It disappears entirely on addition of water, having about half its normal intensity for a half normal solution when the water content of the solvent is about 8 per cent.

These facts seem to us inexplicable on any other hypothesis than the one we have made, namely, that when a salt of one of these elements is dissolved in any solvent, both *the molecules of the salt and the ions formed from these become solvated, that is, they combine with a certain number of molecules of the solvent.* While in the case of some salts the spectra point to the existence of solvates of varying complexity, in the case of salts of neodymium and praseodymium they indicate rather the existence of one definite hydrate. A more extended study, including the changes in the spectra produced by changes in temperature, may, however, somewhat modify this conclusion.

Granting the existence of solvates all of the facts observed in connection with the absorption spectra of neodymium and praseodymium salts can be readily explained.

Physical Chemical Laboratory,
Johns Hopkins University,
June, 1908.

# PRELIMINARY REPORT UPON A CRYSTALLOGRAPHIC STUDY OF THE HEMOGLOBINS: A CONTRIBUTION TO THE SPECIFICITY OF CORRESPONDING VITAL SUBSTANCES IN DIFFERENT VERTEBRATES.

By EDWARD T. REICHERT and AMOS P. BROWN.

(*Read April 24, 1908.*)

The primary object of this research was to determine whether or not corresponding proteins are identical in different species. Hemoglobin was selected as a favorable substance to begin such a study upon because of its being readily obtained in a state of comparative purity, and, in many cases, readily isolated in crystals. When a sufficient supply of blood was available, it was nearly always possible, by the use of suitable methods, to produce well formed crystals that could be satisfactorily examined and studied by the method adopted. The crystallographic method was chosen because, by its means, differences in substances may be observed that would elude the ordinary methods of analysis employed by the chemist. Moreover, it is comparatively rapid and therefore well adapted to the study of a substance so liable to alteration as hemoglobin. In the method employed it was not even necessary to remove the crystals from the mother liquor for examination. In studying the crystals and measuring the crystallographic constants the petrographic microscope was used, but in the case of these crystals of hemoglobin we have this advantage over the petrographer in his examination of rock sections, in that these crystals are not imbedded in an opaque or semi-opaque matrix, but are in a transparent medium and are usually isolated from each other. Moreover, hundreds and often thousands of crystals are open to observation in a single slide, and these present almost all possible orientations, allowing the optical characters to be determined with much greater accuracy than is usually the case with minerals in rock sections. Measurements within the limit of error of the instrument could frequently be obtained, and, as various orientations were available, the results of the angular measurements often furnished complete data for the calculation of the axial ratios. The crystals examined were usually complete and often geometrically perfect, so that the symmetry and crystal habit could be determined as readily as in the case of ordinary mineral substances occurring in isolated crystals.

A chemical substance, possessing a rational composition, tends to arrange its parts in an orderly manner so that a definite structure is assumed, which results in a definite external form. This is so universally true that the crystalline condition is the normal one for matter of definite composition. Differences of crystalline form hence indicate differences of substance; and, by the crystallographic method of investigation, obscure differences, such as those between isomerides, may readily be detected.

Photographic records of the crystals were secured and upwards of 2,500 negatives have been made. The hemoglobins of more than one hundred species have been examined and data secured in regard to their crystals. From a study of these records certain facts stand out very prominently.

1. *The Constancy of Generic Characters in the Crystals.*—The crystals of the species of any genus belong to a crystallographic group. When their characters are tabulated, they at once recall the crystallographic groups of minerals. The crystals of the genus *Felis* form an isomorphous group; as strictly isomorphous, in fact, as the group of the rhombohedral carbonates among minerals. The genus *Canis* is even more strictly isomorphous, but the crystals of hemoglobin from the two genera are perfectly distinct, the one from the other.

As an example of the individuality of these generic characters the following may be cited: A sample of blood, marked as that of a certain species of baboon was received from one of our Zoölogical Gardens. Upon making preparations and examining the crystals, it was at once evident that they did not correspond to any species of baboon thus far examined, nor did they show the characters of the genus *Papio*. They were identified by their crystallographic characters as belonging to the cats (genus *Felis*) but not to any species that we had examined up to that time. Inquiry at the Zoölogical Garden from which the blood was received showed that the animal recorded as being subjected to a *post-mortem* examination on the date when the blood was collected was a species of the genus *Felis*, but not one of which we had previously examined the blood. Other similar cases of incorrect labelling of specimens were detected, in which the wrongly labelled blood was one that had been examined and the species known from other specimens.

2. *Specificity in the Crystals of a Genus.*—The crystals of the different species of a genus, when they are favorably developed for good measurement, can usually be distinguished from each other by definite differences of angle, etc.; while preserving their isomorphous character as belonging to a definite genus. In cases where, on account of difficulty of measurement, the differences cannot be given a quantitative value, variations in the habit of the crystals and in their mode of growth will often show specific differences.

3. *The Occurrence of Several Types of Crystals of Oxyhemoglobin in Many Species.*—In some species the oxyhemoglobin is *dimorphous* (crystallizing in two systems or with two axial ratios), in other cases even *trimorphous*. Where several types of crystal occur in this way in the species of any genus, the crystals of *each type* may be arranged in an isomorphous series. In other words, certain genera are isodimorphous or isotrimorphous.

4. *The Constant Recurrence of Certain Angles, Plane or Dihedral, in the Oxyhemoglobin, Hemoglobin and the "Methemoglobins" of Various Species, even when these Species are Widely Separated Zoölogically and when their Crystals Belong to Various Crystal Systems.*—This appears to indicate a common substance in hemoglobins or a common structure in the various hemoglobin molecules.

5. *The Constant Recurrence of Certain Types of Twinning in the Hemoglobins, and the Prevalence of Mimosie in these Crystals.*—This also indicates a common structure in the various hemoglobin molecules.

6. *Differences between Oxyhemoglobin and Reduced Hemoglobin in Certain Species.*—Undoubted differences between the crystals of these two substances in the same species have been observed.

We have gathered additional evidence that other corresponding proteins, as well as certain fats and carbohydrates, will be found to exhibit similar specificities.

UNIVERSITY OF PENNSYLVANIA.
April 23, 1908.

# INFLUENCE OF PRESERVATIVES AND OTHER SUBSTANCES ADDED TO FOODS UPON HEALTH AND METABOLISM.

By HARVEY W. WILEY, M.D.

(*Read April 25, 1908.*)

In connection with studies of food adulteration, which have been conducted during the past twenty-five years under my direction in the Bureau of Chemistry, frequent evidence was obtained of the addition of certain preserving agents and coloring matters to food products. These bodies are not of the character known as condimental; on the contrary, as a rule, they possess neither appreciable taste nor odor in the quantities in which they are employed.

In so far as preservatives are concerned, therefore, the consumer would have no certain knowledge of their presence, and in respect to coloring matters, he would likewise be ordinarily deceived, since such coloring matters are often used to imitate the natural tints found in food products. Thus there would be practiced upon the consumer a fraud in that in the purchase and consumption of foods he was buying and consuming articles which are distinctly not foods and the presence of which is a just cause of suspicion.

The use of chemical preservatives and artificial colors in foods is of quite recent date. I think I may say with safety that if one could go back thirty, or at most, forty years, he would find a food supply practically free, both from chemical preservatives and artificial colors. The rapid development of organic and tinctorial chemistry during the past forty years has made it possible to offer to manufacturers chemical preservatives of high potency, and colors of great beauty and persistence, at prices which make it entirely possible to use them freely in food products. Inasmuch as the use of these bodies, whatever the claims may be in regard thereto, has for its chief purpose either to cheapen the product itself or to sell it at a higher price than it really should command, it is evident that unless the pecuniary conditions attending the use of these bodies were favorable they would not be employed.

When the claims which are made by manufacturers respecting the use of these substances are carefully considered, we find that most of them are without foundation. In regard to the supposed general preference for artificial color, I would say that an experiment performed on a large number of totally unbiased people has convinced me beyond any reasonable doubt that the great majority of American consumers would prefer uncolored foods. The experiment mentioned was made on about sixty different men during a period of five years to determine whether or not they preferred an artificially colored food or one in its natural tint. Butter, which is perhaps the one food product most universally colored in this country, was used. The subjects on whom the experiment was tried had been in the habit of using nothing except colored butter, hence, if there was any prejudice existing in their minds it must have been in favor of the article which they had constantly consumed. Moreover, the test was made in the winter time when the uncolored butter has the least tint of the whole year, being almost white. No attempt was made to inform the men of the nature of these products. The natural butter and the colored butter were moulded in the same forms and placed upon the same plate, and offered without comment of any kind. At first very few of the men would do more than look at the uncolored butter. A very common expression was, "This is oleomargarine." A few made a trial of its properties. Little by little, without any propaganda of any kind, the whole attitude of these men changed. In the course of four or five months nine tenths of them were using the uncolored butter and they expressed a most decided antipathy to the use of the colored butter when at certain times the supply of the uncolored butter was exhausted.

I believe that this completely refutes the arguments of those who claim that they color butter to meet the demand of the consumer. In point of fact, the color in butter has been almost from the first a fraudulent process. It is a common belief that the best butter of the year is produced during the early spring months, and especially in June, when the cows have access to the succulent pastures. During this time, owing to the oxidation of the chlorophyll of the grass, a xanthophyll is produced, imparting to the cream a rich golden, or yellow, tint which is, of course, perpetuated in the butter. During the winter months, when the chlorophyll is withdrawn practically from the diet of the cow, this natural coloring matter is absent. The use of the artificial color, therefore, is to simulate for winter butter the color of the butter in June, and thus to conceal what is at least believed to be inferiority.

Again, in experimental observations of a less extended character, I have found that the American consumer does not prefer his foods preserved with chemical preservatives. In a large number of instances which have come under my own personal observation the consumer has stopped eating an article as soon as he has found that it contains a chemical powerful enough to inhibit fermentative action. The users of chemical preservatives, however, do not as a rule claim that they use them at the demand of the consumer. A careful study of manufacturing data made by one of the most conscientious manufacturers in the West shows that it costs more to make a food product without a preservative than it does with a preservative. In very extensive practical experiments on tomatoes this manufacturer found that it was necessary to charge from fifteen to twenty cents more for ketchup per case made without a preservative than with a preservative. Thus I think it is well established by this experimental study that the real reason which the manufacturers have for using chemical preservatives is to cheapen the cost of production. This of itself would be a most worthy object, because presumably the cheapening of the cost of production would lower the price to the consumer. If, therefore, a food product of equal nutritive value and equal wholesomeness could be produced with the aid of chemical preservatives, such a process should meet with the approbation of all. But a very serious problem of a different kind is presented here. A chemical preservative is effective usually by reason of its inhibitive action on fermentation. Very extensive studies of this action of chemical preservatives have led to the general conclusion that while these bodies inhibit the fermentative action giving rise to the ordinary evidences of decay and putrefaction, and, as a rule, stop most effectively those fermentations which produce alcohol and carbon dioxid, they do not have the same restrictive influence on those processes resulting in the general degradation and decay of organic matter, due chiefly to that class of chemical reactions which is represented by the term hydrolysis. In other words, the ferments which break down, for instance, nitrogeneous tissues into more soluble and finally more dangerous forms of combination, are not so particularly inhibited as is the first class of ferments mentioned.

This fact might well be used, however, as a justification of the employment of chemical preservatives, since if they prevent the ordinary processes of fermentation which produce evident indications of decay and putrefaction, it might be held that they would not interfere with that other class of fermentations or hydrolytic processes peculiarly exercised by the digestive ferments. It will probably not be contested at the present time that there is some justification for this plea, since it has been well established that an amount of a preservative which will for instance prevent alcoholic fermentation will not interfere in anything like so serious a manner with the action of such ferments as the diastatic ferments of the saliva, of the stomach, and of the pancreas. On the other hand, it is well established that in any notable quantities these preservatives do interfere with even the latter class of ferments.

But the problem which is of most importance in this connection is, What is the chief effect of these preservatives upon the health of those who constantly use them and upon the metabolism resulting from the normal functions of the body? To answer this question, there was begun in an experimental way in the Bureau of Chemistry, under my direction, a few years ago, a series of studies having for their purpose the elucidation of this problem. The general plan of the experimental work was extremely simple. It contemplated the selection of a number of young men between the ages of twenty and thirty, in excellent health, who had suffered from no serious disease in the immediate past, who were of steady habits, who were not addicted to the use of alcohol, and whose character was such as to warrant especial confidence and trust in their veracity and general conduct. Such young men evidently are to be found among those who pass the examinations for the civil service of the United States. In these examinations the very qualities which were looked for in the young men in question must be present or they could not receive the vouchers for character and conduct which are necessary to entitle them to compete in the examinations. These young men were subjected to a careful physical examination similar to that exercised upon those who apply for policies in life insurance companies. This examination showed them free from organic diseases and not to have suffered within a year, usually not at all, from any serious disturbance of health. The subjects were placed upon their honor, by a formal pledge, that they would obey all the rules established for the experimental work and abstain from any form of food and drink except that offered in the regular course of the investigation. Those who used tobacco, tea and coffee were permitted to continue to do so in the regular manner so as not to change the habits of their previous daily life. They were also limited by their pledge to a regular course of exercise which they undertook to follow without variation, and also regular hours of work and sleep. As a justification of the faith and confidence reposed in these young men I think it is sufficient to say that, although during the five years of the experiments we have had about sixty young men under observation, only three have been found to have violated their pledges.

The subjects so selected were first placed on a generous diet of the kind and character to keep them in equilibrium; that is, to maintain the weight of their body without notable changes. The part of the experiment devoted to this purpose was known as the "fore period." Each one was allowed to determine, within certain limits, the character of the diet from the foods offered; that is, a relative amount of meat, bread, potatoes, butter, milk, coffee, tea, etc., to suit his taste and to conform with his previous habit of life. Only in those cases where an excess of some particular kind of food seemed to be preferred was any restriction placed upon this matter. This fore period, therefore, enabled us to determine the magnitude of the ration which would preserve the body equilibrium and presumably be in entire conformity with the normal digestive functions.

The study of the food ingested and of the excreta secured established a chemical control whereby it would be easy to determine any variation in the quantity of food consumed should any of the young men attempt to evade the conditions of their pledge. Having thus established the normal conditions of the body and ascertained the normal metabolic processes, there was introduced into the same ration varying quantities of the preservative which was to be studied. It was thus evident that any change taking place in health or metabolism could be due only to the one factor which was varied in the method of life, namely the injection of the chemical preservative. This period, during which a drug was used, was known as the "preservative period," and lasted, according to circumstances, from twenty to sixty days, depending upon the character and magnitude of the effects produced. As soon as any decided disturbance of health was produced, clearly traceable to the administration of the preservative, its future use was discontinued since it was not the purpose to seriously or permanently affect the health of the subject, but only to secure positive diagnostic data. Then followed an "after period," during which the chemical, or drug, was withdrawn from the food and the normal ration continued as in the fore period, the object being to correct, if possible, any disturbances of metabolism which had been produced and restore the subject again to normal conditions of health and digestion and also to study the after effects of the preservative should such persist. This period of observation was called the "after period." Thus each series of experimental investigations were divided into these three periods.

During the progress of the experiment the following substances were added to the foods for the purposes mentioned above: Boric acid, borates, salicylic acid, salicylates, benzoic acid, benzoates, sulphurous acid, sulphites, formaldehyde, sulphate of copper and potassium nitrate. There is given in the accompanying table a condensed statement of the effects which were produced in these various cases. It is not the purpose of this paper to go into the experimental detail of this matter. The amount of chemical analysis incident to this study was enormous. A great many chemists gave their entire time during the whole period of observation to these analytical problems,

HEALTH AND METABOLISM AS INFLUENCED BY PRESERVATIVES.[1]

| Administration of Preservatives. | | | | Medical and Clinical Notes. | Body Weight | Urine Determinations. | | | | Red Blood Corpuscles. | Metabolism. | | (Percentage of Total Excretion.) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Substance. | Number of Days. | Daily Amount Grams. | Total (Maximum). Grams. | | | Volume. | Albumin. | Acidity. | Microscopic Bodies. | | Nitrogen. | Phosphoric Acid. | Sulphur. | Fat. | Solids. |
| Borax | (3 series) | 0.5–3.0 | 79.5 (minimum 13) | Loss of appetite, nausea, headache, depression | — | o | — | + | o | o | — | + | ......... | o | + (very small) |
| Boric acid | 30 to 70 | 0.5–5.0 | | | — | o | + | + | o | o | | | | | |
| Salicylic acid and salicylates | 30 | 0.21–2 | 30.85 | Hunger, slight headache, and abdominal pain; symptoms not general. | — | o | o (Special study) | o (Special study +) | + | + | Total — (slight) Urine + | — | — | — | Total — Urine+ |
| Sulphurous acid | 20 | 0.171 –0.4 | 6.856 | Headache, dizziness, pain in stomach; weakness; depression. | o | + (more marked) | + (slight) | + | + | — (very marked) | + (especially in feces) | Total + Urine — | Total + Feces— | + (very slight) | + |
| Sodium sulphite | | 0.223 –0.762 | 12.565 | | — | + | + (slight) | + (more marked) | | — (very marked) | + (especially in feces) | Total + Urine — | Total + Feces— | + (very slight) | + |
| Benzoic acid | 20 | 1–2.5 | 35[2] | Nausea, headache, lassitude. | — | — (slight) | ............. | ............. | + (slight) | — | + | + | + | — (very slight) | + (very slight) |
| Benzoates | | | | | — | — (slight) | | | | + | | | | | |
| Formaldehyde | 15 | 0.1–0.2 | 2.5 | Headache, abdominal pains; sometimes nausea and rash. | — | + | o (+ very few cases) | o (— very few cases) | + (very slight) | — (not conclusive) | — | Total + Feces — | — | — (very slight) | Total — Urine+ |
| Copper sulphate | 19 | 0.05 –0.15 | 1.9 | Pains in stomach and abdomen; nausea, indigestion; headache; nervousness. | — (very slight) | o | o | o | + (slight) | — | Total — (Feces +) | — (marked) | Total o (Feces —) | — (slight) | — |
| Potassium nitrate | 60 | 0.15 –.60 | 12 | Slight headache, pains in epigastrium. | — (slight) | — (Summer) | o | + | + | + | — | — (marked) | + (slight) | ......... | ......... |

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[1] Plus sign signifies a gain, minus sign a loss, and zero practically no change in the preservative period as compared with the fore period.

[2] Only three subjects took the maximum amount.

and in addition to that a number of calculators were employed to tabulate, classify, and average the data. The experimental data which were obtained are published in Bureau of Chemistry Bulletin 84, which when completed will contain the entire series of studies. Part I, of Bulletin 84, is devoted to the detailed study of the effect of borates and boric acid upon health and metabolism. This part of the Bulletin consists of 477 pages. Part II is devoted to the study of salicylic acid and salicylates and contains 283 pages. Part III contains the data relating to sulphurous acid and sulphites, and contain 281 pages, making a total of published matter of 1,041 pages.

CHANGES IN THE URINARY NITROGEN AND SULPHUR COMPOUNDS.[1]

| Preservative. | Dose. [Grams per Day.] | Urea. | Uric Acid. | Kreatinin. | Ammonia. | Xanthin. | Neutral. | Total Sulphates. | Inorganic Sulphates. | Ethereal Sulphates. |
|---|---|---|---|---|---|---|---|---|---|---|
| Borax | 0.5 –3.0 | ........ | ...... | ...... | ...... | ........ | ...... | ...... | ...... | ...... |
| Boric acid | 0.5 –5.0 | ........ | ...... | ...... | ...... | ........ | ...... | ...... | ...... | ...... |
| Salicylic acid and salicylates | 0.21–2.0 | — | — | + | — | 0 | + | + | + | + |
| Sulphurous acid | 0.17–0.4 | — | — | 0 | — | 0 | + | + | + | + |
| Sulphites | 0.22–0.76 | | | | | | + | + | + | 0 |
| Benzoic acid | 1.0 –2.5 | ........ | ...... | ...... | ...... | ........ | — | + | + | 0 |
| Benzoates | 1.0 –2.5 | ........ | ...... | ...... | ...... | ........ | — | + | + | 0 |
| Formaldehyde | 0.1 –0.2 | — | ...... | ...... | ...... | ........ | 0 | 0 | 0 | 0 |
| Copper sulphate | 0.05–0.15 | — | + | ...... | ...... | + | + | — | 0 | — |
| Potassium nitrate | 0.15–0.6 | — | 0 | 0 | — | ........ | — | 0 | + | 0 |

The data relating to benzoic acid and benzoates are in press. These data, together with those relating to the other parts of the study which have been completed and submitted for publication, will make a volume of approximately 2,100 pages. All that I can give in this paper will be the general conclusions relating to each part of the study.

## CONCLUSIONS.

*Boric Acid and Borates.*—In the consideration of the action of preservatives of a mineral nature, such as borax and boric acid, it must be remembered that the animal as well as the plant possesses

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[1] Minus and plus signs indicate decreased or increased total excretion in preservative period as compared with the fore period.

a certain mineral hunger. In other words, mineral substances play a double role in animal and plant nutrition: First, they may serve as real foods, necessary to the formation and nutrition of the tissue. In the animal economy this is especially true of phosphoric acid and lime. In the second place, they are necessary to the functional activity of the various organs of the body, irrespective of any part they may take in direct nutrition.

The necessity of saline solutions in the blood is known to every physician and physiologist. If the blood were deprived of all of its saline constituents the circulation would be impeded, restricted, or stopped, and death would result. In cases of collapse in disease saline injections in the blood are often used as a restorative measure. These salts in solution stimulate the heart's action and undoubtedly are active in the osmotic operations of the cells. This is one of the facts which show the intimate relation existing between physical chemistry and physiology.

Common salt is the most frequent and most abundant of the saline constituents of the blood, but the alkalinity of the blood is not due of course to the common salt, which is a neutral substance. The existence of alkaline carbonates or other alkaline salts is necessary to the vital functions. While it is true that the digestion in the stomach takes place in an acid solution, it is likewise true that any excessive acid must be neutralized and enough of alkali added in the small intestine in order that the further digestion of the food may properly take place. That saline bodies other than common salt or the alkaline carbonates may be useful, however, in the performance of the vital functions cannot be denied, though it might be difficult to demonstrate their absolute necessity. Hence the introduction of saline bodies, which may or may not be of an antiseptic character, may, within certain limits, have a favorable influence upon health and digestion. At the same time it should not be forgotten that all excess of such bodies imposes upon the excretory organs an additional burden, which, while it might not impair their efficiency even for a number of years, might finally produce a condition of exhaustion which would be followed by serious consequences. Especially is this remark true of the kidneys, which appear to be a general clearing house for all the surplus of saline matters, ingested in the foods.

The most interesting of the observations which were made during the progress of the experiments was in the study of the direct effect of boric acid and borax, when administered in food, upon the health and digestion. When boric acid, or its equivalent in borax, is taken into the food in small quantities, not exceeding half a gram (7½ grains) a day, no notable effects are immediately produced. The medical symptoms of the cases, in long-continued exhibitions of small doses or in large doses extending over a shorter period, show in many instances a manifest tendency to diminish the appetite and to produce a feeling of fullness and uneasiness in the stomach, which in some cases results in nausea, with a very general tendency to produce a sense of fullness in the head, which is often manifested as a dull and persistent headache. In addition to the uneasiness produced in the region of the stomach there appear in some instances sharp and well-located pains, which, however, are not persistent. Although the depression in the weight of the body and some of the other symptoms produced persist in the after periods, there is a uniform tendency manifested after the withdrawal of the preservative toward the removal of the unpleasant sensations in the stomach and head above mentioned.

The administration of boric acid to the amount of 4 or 5 grams per day, or borax equivalent thereto continued for some time, results in most cases in loss of appetite and inability to perform work of any kind. In many cases the person becomes ill and unfit for duty. Four grams per day may be regarded, then, as the limit of exhibition beyond which the normal man may not go. The administration of 3 grams per day produced the same symptoms in many cases, although it appeared that a majority of the men under observation were able to take 3 grams a day for a somewhat protracted period and still perform their duties. They commonly felt injurious effects from the dose, however, and it is certain that the normal man could not long continue to receive 3 grams per day.

In many cases the same results, though less marked, follow the administration of borax to the extent of 2 grams and even of 1 gram per day, although the illness following the administration of borax and boric acid in those proportions may be explained in some cases by other causes, chiefly grippe.

The administration of borax and boric acid to the extent of one half gram per day yielded results markedly different from those obtained with larger quantities of the preservatives. This experiment, Series V, conducted as it was for a period of fifty days, was a rather severe test, and it appeared that in some instances a somewhat unfavorable result attended it. On the whole, the results show that one half gram per day is too much for the normal man to receive regularly. On the other hand, it is evident that the normal man can receive one half gram per day of boric acid, or of borax expressed in terms of boric acid, for a limited period of time without much danger of impairment of health.

It is, of course, not to be denied that both borax and boric acid are recognized as valuable remedies in medicine. There are certain diseases in which these remedies are regularly prescribed for both internal and external use. The value which they possess in these cases does not seem to have any relation to their use in the healthy organism except when properly prescribed as prophylactics. The fact that any remedy is useful in disease does not appear to logically warrant its use at any other time.

It appears, therefore, that both boric acid and borax, when continually administered in small doses for a long period or when given in large quantities for a short period, create disturbances of appetite, of digestion, and of health.

*Salicylic Acid and Salicylates.*—In the conclusions based upon the general observations the same conservatism must be observed and the same general reservations made as are found in Part I concerning boric acid and borax. While, as described in the borax report, the attempt has been made to control as far as possible, all the conditions of the experimental work, the difficulties attending the task are so enormous that it is not possible that complete success should be secured. There has, however, been no attempt made to discriminate in the choice of data, all the observations being recorded and the discussion of the individual data based upon the tabular statements being without prejudice and without bias. The general assumption has been made, as in the previous cases, that, by reason of the regular habits of life which were imposed upon the subjects, the amount of energy developed and the quantity of nourishment expended therein are reasonably constant throughout the experimental period. If these factors vary, as they necessarily must to a certain degree, it is evident that they vary uniformly above or below the average, and hence these variations could not possibly produce any notable effect upon the final result.

There has been a general consensus of opinion among scientific men, including the medical profession, that salicylic acid and its compounds are very harmful substances, and the prejudice against this particular form of preservative is perhaps greater than against any other material used for preserving foods. This is due not only to the belief in the injurious character of salicylic acid, but perhaps is especially due to the fact that it has in the past been so generally used as an antiseptic. That salicylic acid should be singled out especially for condemnation among preservatives does not seem to be justified by the data which are presented and discussed in this bulletin. That it is a harmful substance, however, seems to be well established by the data taken as a whole, but it appears to be a harmful substance of less virulence than has been generally supposed. There is no doubt of the fact that salicylic acid is a drug which is often indicated in diseases well established and also perhaps in certain conditions which, while verging on disease, might still be regarded as a state of health. But the administration of salicylic acid as a medicine should be controlled exclusively by the medical profession, and while it is a remedy well established in the Pharmacopœia and especially prized for its effect upon rheumatism and gout, it does not seem that there should be any warrant in this fact for its promiscuous use in foods, even if it were harmless.

The data show very clearly that salicylic acid and salicylates appear to exert an exciting influence upon the activities which take place in the alimentary canal, stimulating the organs to greater effort, and this stimulation leads at first to increased solubility and absorption of the foods which are introduced into the stomach. In the light of the data which are exhibited salicylic acid may be said to increase the solubility and absorption of the food in the alimentary canal, so that larger parts of the nutrients taken into the stomach actually enter the circulation.

The data which show the effect just noted also indicate that the general effect upon the system is depressing, in that the tissues are broken down more rapidly than they are built up, and thus the normal metabolic processes are interfered with in a harmful way. The administration of the salicylic acid is attended by a gradual decrease in the weight of the subjects, although the quantity of food elements administered during the preservative and after periods is slightly increased, which fact, together with the greater degree of absorption of the food elements, should have resulted in a slight increase in weight. This increase in weight, however, does not occur, and the disturbing influence of the salicylic acid upon metabolism, although not very great, is specifically demonstrated.

The final conclusion in this matter, therefore, is that the unenviable position which salicylic acid has heretofore held among preservatives, in being regarded as the most injurious of all, is to a certain extent undeserved. Like other ordinary preservatives, it is not one which can be classed as a poison in the usual sense of the word. When used as a medicine in many cases of derangement of health it is like the other chemical preservatives, often highly beneficial when properly prescribed by a competent physician. It is when used in the food at first an apparent stimulant, increasing the absorption and solubility of the common food elements from the alimentary canal. It soon, however, loses its stimulating properties and becomes a depressant, tending to break down the tissues of the body more rapidly than they are built up. It disturbs the metabolic processes, in most cases producing conditions which are not normal and which, apparently, are not beneficial. It has a tendency to diminish the weight of the body and to produce a feeling of discomfort and malaise, which, while not marked, is distinctly indicative of injury. In some cases these symptoms of malaise approach illness, and while not always diagnostic are sufficiently common to point unmistakably to the salicylic acid as their origin. It places upon the excretory organs, especially the kidneys, an additional burden which they are not able to bear and which cannot possibly result in any good, but on the contrary must necessarily finally result in injury, though perhaps with the use of very small quantities of the preservative these organs would continue to perform their function for many years before finally breaking down.

This work is offered as an unbiased study of all the data recorded, both of those which appear to be in favor of the use of salicylic acid and those which appear to be against its use, and leads to the inevitable conclusion that salicylic acid is a substance which, when added to foods even in small quantities, exerts a depressing and harmful influence upon the digestion and health and the general metabolic activities of the body. Further, there appears to be no necessity for its use, as food can be preserved in unobjectionable ways without its aid. Its indiscriminate use would tend to carelessness in the quantities employed, thus increasing the dangers to which the consumer is subjected. Also its use in the preservation of foods tends to induce carelessness and indifference on the part of the manufacturer, as when a chemical antiseptic is employed many of the processes necessary to the proper selection, cleaning, and preservation of foods may be omitted.

The addition of salicylic acid and salicylates to foods is therefore a process which is reprehensible in every respect, and leads to injury to the consumer, which, though in many cases not easily measured, must finally be productive of great harm.

*Sulphurous Acid and Sulphites.*—From a careful consideration of the data in the individual cases and the summaries of the results, it appears that the administration of sulphurous acid in foods, either in the form of sulphurous acid gas in solution or in the form of sulphites, is objectionable and produces serious disturbances of the metabolic functions and injury to health and digestion. This injury manifests itself in a number of different ways, both in the production of clinical symptoms which indicate serious disturbances, malaise, or positive suffering, and also by inducing certain changes in the metabolic processes which are not manifested in the way of ordinary clinical symptoms, and are only detected by careful chemical and microscopical study of the excretory products. It can safely be said from the evidence adduced that the administration of sodium sulphite and sulphurous acid as above indicated produces a marked influence of an unfavorable character on metabolism. As a result of this action an assimilation of food materials containing organic phosphorus is retarded, while there is evidence of increased sulphur katabolism. The sulphur balance sheets show what an immense burden has been added to the already overworked kidneys, which are called upon in this case to remove nearly all, if not quite all, of the added sulphur from the body, previously converted, in great part to sulphuric acid. It is not possible that placing upon the kidneys this increased work of excreting sulphur can result in anything but injury. The fact that the microscopic crystalline and amorphous bodies in the urine are increased in number under the influence of the added sulphur, is another indication of the extraordinary demands made upon the kidneys in such circumstances.

This increase is interesting in respect of the effect which the continued exhibition of sulphurous acid must eventually have upon the structure of the kidney. It is reasonable to suppose that the continued use of a body which produces such results would cause lesions of a histological character which eventually would develop conditions which would give serious apprehension. In the nature of these experiments it was not possible to examine the organs of the body histologically and hence the above conclusion is only based upon experience of a similar character where the organs in question have been subject to such examinations. While there might be no distinguishable lesion of the kidneys produced during a period of twenty or thirty days, or even longer, it is plain that sooner or later lesions of a very serious character producing organic diseases, possibly of an incurable type, would be induced. The further observation that there is a marked tendency to the production of albuminuria, although of an incipient character, is an indication of the unfavorable results of the administration of the sulphurous acid. It is, therefore, evident that by increasing the burden upon the excretory organs, the administration of sulphur in the form mentioned is highly detrimental to health.

All of these tendencies cannot be interpreted as being other than of a decidedly harmful nature. Another effect which the administration of the sulphur produced, and one of a more serious character still, is found in the impoverishment of the blood in respect of the number of red and white corpuscles therein. The administration of a substance which diminishes by a notable percentage these important component particles of the blood must be regarded in every sense as highly prejudicial to health. Some of the most important functions of the blood, as has been well established by careful physiological studies, are intimately connected with the number and activity of both the red and white corpuscles. The bleaching effect of the sulphurous acid upon the color of the blood is a matter of less consequence and no great effect is produced upon the hemoglobin, but the diminution of the number of red and white corpuscles is a matter of serious concern.

The variations of the metabolic processes from the normal, as indicated in this series of experiments, were never of a character favorable to a more healthy condition of the system, but, on the other hand, all these variations, in so far as the effect of the changes could be distinguished, are of a prejudicial character. There is no evidence whatever that the sulphur added to the foods in the form of sulphurous acid, or sulphites, takes any part in the nutrition of the tissues of the body containing sulphur, namely, the proteids; hence, no claim of food value can be established for these bodies. The evidence all points to the fact that they are purely drugs, devoid of food value, having no favorable effects upon the metabolic processes, but, on the other hand, exerting deleterious and harmful effects. The conclusion, therefore, is inevitable that, as a whole, the changes produced in metabolic activity by the administration of sulphur in the forms noted above in the comparatively short time covered by the experiments are decidedly injurious.

The verdict which must be pronounced in this case is decidedly unfavorable to the use of this preservative in any quantity or for any period of time, and shows the desirability of avoiding the addition of any form of sulphurous acid to products intended for human food.

*Benzoic Acid and Benzoates.*—From a careful study of the data in the individual cases and of the summaries of the results, it is evident that the administration of benzoic acid, either as such or in the form of benzoate of soda, is highly objectionable and produces a very serious disturbance of the metabolic functions, attended with injury to digestion and health.

As in the case of boric acid, salicylic acid, and sulphurous acid, this injury manifests itself in a number of different ways, both in the production of unfavorable symptoms and in the disturbance of metabolism. These injurious effects are evident in the medical and clinical data which show grave disturbances of digestion, attended by phenomena which are clearly indicative of irritation, nausea, headache, and in a few cases vomiting. These symptoms were not only well marked, but they were produced upon healthy individuals receiving good and nourishing food and living under proper sanitary conditions. It is only fair to conclude, therefore, that under similar conditions of administration of benzoic acid or benzoate of soda in the case of weaker systems, or less resistant conditions of health, much more serious and lasting injury would be produced.

It was also noticed that the administration of benzoic acid and benzoate of soda was attended with a distinct loss of weight, indicative of either a disturbance of assimilation or an increased activity in those processes of the body which result in destruction of tissue. The production of a loss of weight in cases of this kind must be regarded as indicative of injurious effects.

The influence of the benzoic acid and benzoate of soda upon metabolism was never of a character indicative of a favorable change therein. While often the metabolic changes were not strongly marked, such changes as were established were of an injurious nature. It is evident that the administration of these bodies, therefore, in the food tends to derange metabolism in an injurious way.

An important fact in connection with the administration of these bodies is found in the efforts which nature makes to eliminate them from the system. In so far as possible the benzoic acid is converted into hippuric acid. There is a tendency usually manifested, however, to retain the benzoic acid in the body for a notable length of time, and this is much more marked in the case of benzoate of soda than in the case of benzoic acid.

While the administration of both these bodies, therefore, is undoubtedly harmful, the injurious effects are produced more rapidly in the case of benzoic acid than they are in the case of benzoate of soda; the data, however, will show that the total harmful effect produced in the end is practically the same in both cases, hence there appears to be no reason for supposing that the administration of the preservative in the form of benzoate of soda can be justified by any argument relating to the less injurious effect thereof upon health.

The occurrence of microscopic bodies in the urine is undoubtedly increased under the administration of benzoic acid in all its forms, thus showing conclusively the tendency to stimulate the destructive activities of the body.

Coming to the final consideration of all these different phases of the subject, there is only one conclusion to be drawn from the data which have been presented and that is that in the interests of health both benzoic acid and benzoate of soda should be excluded from food products. This conclusion is reached independently of any consideration of the conditions which it is alleged surround the processes of manufacture and which result in the demands of manufacturers to be allowed to continue the use of this body. This is a subject which must be discussed from an entirely different point of view and has no bearing whatever upon the general conclusions which have been reached, namely, that both benzoic acid and benzoate of soda are bodies which, when added to foods, are injurious to health.

*Formaldehyde.*—A general study of all the data leads to the conclusion that the admixture of formaldehyde with food is injurious to health, even in the case of healthy young men. It is fair to conclude, therefore, that in the case of infants and children the deleterious effects would be more pronounced. The metabolic functions are disturbed in a notable way, both by the retardation of the nitrogen and sulphur metabolism, and the acceleration of phosphorus metabolism. There seems to be a tendency to an increased absorption from the alimentary canal, especially in the cases when the formaldehyde had stood in contact with the milk, and hence it is fair to presume that in so far as the enzymic action in the intestinal canal is concerned, transforming solid food into soluble materials which may enter the circulation, there is evidently a stimulating effect produced.

There are, however, many varying conditions which must be considered in properly interpreting the data. The uniformly increased absorption of the proteid elements of the food, and also of the sulphur and phosphoric acid, accompanied in the first two instances by a decrease in the metabolized elements excreted and in the last instance, namely, phosphoric acid, by a pronounced increase in metabolism, makes the explanation of the data rather difficult. Attention should be called to the fact that while the variations from normal metabolism are not very wide, the individual data are remarkably uniform and consistent.

The conditions which are noted in the case of the proteins would lead one to expect a gain in the body weight. This expectation, however, is not realized for either class of subjects, although the losses in weight are so slight as to be practically negligible. The ratio of the food weight to the body weight was uniformly maintained throughout the experiment, and, hence, if no variations in metabolic activity had occurred a fair presumption would have been that the body weight would remain constant. That the change of weight was slight in the view of the disturbances of the metabolic functions may be accounted for by the inhibiting or retarding influence of the preservative upon the nitrogen and sulphur katabolism, or by the slight increase in water in the urine and feces. It cannot be maintained, however, that a retarded katabolism is beneficial to health. On the contrary a more rapid renewal of the tissues within the limits of healthy activity would be more likely to preserve a normal condition. The old tissues cannot be expected to functionate as perfectly as those which are newer, and hence, within reasonable limits, a change of the tissues of the body must be considered as necessary to a healthy condition, and the maintenance of a normal vitality.

The medical data indicate plainly that formaldehyde, even when given in small quantities, is an irritating substance to the mucous membrane, and, therefore, the normal organs are at first actively stimulated to rid themselves of the irritating foreign substance. It is not strange, therefore, that this preservative had a marked stimulative action on those organs and cells secreting the various digestive juices. It is evident that when the digestive and excretory organs of the body are excited to unusual activity by such an extraneous body having neither food nor condimental value, they act in self defence, and it would be wholly illogical to conclude from this increased excitation that these bodies were helpful to digestion and conducive to health. The nature of the investigation made it impossible to determine whether any organic change took place in the various organs affected, but it may be assumed that any such change which these organs had undergone in the limited time was not sufficient to disturb in any notable way their normal functions which they would perform until the continued administration of the drug produced disease due to the excessive stimulation.

In the case of phosphoric acid, the increased katabolic activity is difficult of definite interpretation, though it is established beyond doubt that such an effect is produced. The formaldehyde may exert a selective action for those proteid bodies high in phosphorus, rendering them insoluble, but in this case there would be an excess of phosphorus in the feces, which is not found. Or the formaldehyde may induce a change in the process of digestion whereby the phosphorus of the food is changed into a soluble and easily excreted form without passing through the tissues of the body. This might easily be the case if in the process of digestion the glycerol-phosphoric acid formed is transformed into soluble inorganic salts, which are readily excreted. Whatever may be the explanation, the changes indicated in normal metabolism, accompanied as they are by the development of the symptoms described, can only be considered as prejudicial to health.

The general tendency to produce a slight decrease in the temperature of the body, assuming for the moment that the data warrant the conclusion that such a condition of affairs existed, might well be due to the inhibition of cell activity shown by the retardation in the breaking down of tissues. The normal functions of the body would doubtless be disturbed by such a condition, aside from the irritating and other disturbing influences exerted by the exhibited drug.

The tendency of the preservative to produce albumin in the urine, while not well marked, is at least worthy of attention. The fact that only slight changes take place in the body weight is sufficiently explained in the data and cannot be urged in favor of the exhibited preservative.

Apart from the injurious effects of formaldehyde itself, its use as a food preservative would be especially inadvisable in milk or cream, because its addition in dilute solution prevents the growth of acid-forming bacteria, but has no effect in retarding the action of many harmful organisms; in other words, the milk is prevented from becoming sour and thus indicating its age and the danger signal is thus removed, while the other organisms which are capable of producing disease continue to multiply in the milk with practically the same degree of rapidity as if the formaldehyde was not present.

The final conclusion, therefore, is that the addition of formaldehyde to foods tends to derange metabolism, disturb the normal functions, produce irritation and undue stimulation of the secretory activities, and, therefore, it is never justifiable.

*Sulphate of Copper.*—The data which have been collected in the course of this experiment have led to the conclusion that the administration of sulphate of copper even in the extremely small quantities in which it has been given has a very distinctly unfavorable effect upon health and digestion, as indicated by the ordinary clinical and medical summaries. Severe pains are produced in the stomach accompanied often with nausea and sometimes with vomiting, there is a general tendency to malaise, often a development of headache, and other unfavorable symptoms of a more or less persistent and uniform character. Further than this, the symptoms which are usually not developed for about a week continue in some instances for a number of days into the after-period after the sulphate of copper has been withdrawn. The data indicate that copper, like many other metals, is likely to produce a cumulative effect, and that its administration in even much smaller quantities than those indicated, or less than those which would be ingested in the regular consumption of coppered vegetables, is attended with more or less danger on this account.

There was a very small loss of weight in nine of the subjects, while the three who showed the greatest tolerance of the copper sulphate gained in weight. No definite conclusions can, therefore, be formed respecting the general effect upon the weight of the body, except that in the cases where uniform effects are produced there is a slight loss of weight.

The copper salt which was used in this experiment differs from other chemicals which have been used in this series of investigations in that its excretion falls only partly upon the kidneys. The effect produced on the urine, therefore, cannot be ascribed directly to the copper salt employed, but only to such derangements of the metabolism due thereto as would incidentally affect the composition of the urine.

The effect upon the general metabolism is of a character which, though not very pronounced, is indicative of a retardation of normal metabolic processes. Inasmuch as a small quantity of sulphur was introduced into the system through the copper salt, the quantity of this sulphur must be taken into consideration in studying the effect on metabolism. There is seen to be quite a uniform tendency to derange the ratio of the metabolized sulphur and nitrogen.

The apparent increase in the relative quantities of sulphur excreted is due rather to the diminution in the nitrogen than to an actual increase in the sulphur over that which would be expected from the ingestion of the sulphuric acid in the copper salt. The most marked change in the sulphur compounds is in the case of neutral sulphur, which shows a decided and uniform increase during the administration of the copper salt and in some cases for several days thereafter.

The effect produced upon the metabolism of nitrogen is more important. Under the administration of sulphate of copper there is a marked and constant decrease in the excretion of urea, which is a matter of great significance. Such a decrease can only be regarded as an indication of a retarding effect on nitrogen metabolism. At the same time the quantity of uric acid and xanthin bases are increased during the administration of the copper salt and the increase in xanthin is still very marked in the after-period. These two important observations indicate that the nitrogen metabolism is disturbed in a way which must be considered injurious to health.

There is also a notable effect produced upon the phosphoric acid metabolism. There is a marked decrease in the total metabolized phosphorus, and, while the non-metabolized phosphorus is less uniformly affected, there is a decided tendency shown to decrease the total excretion of phosphoric acid under the influence of the copper sulphate.

The final conclusion, based on the medical and clinical data and on the study of the effect of the copper sulphate upon metabolism, is that the administration of this salt is prejudicial to health.

*Potassium Nitrate.*—It is evident that the administration of small quantities of potassium nitrate induce only slight disturbances in the metabolic processes, and indicate only to a slight degree harmful or deleterious effects as noted in the medical and clinical data. It is evident moreover that with the exception of one instance, namely, the increase of the number of red corpuscles in the blood, that no beneficial effect can possibly be attributed to the exhibition of this chemical.

While the data are in this case far less conclusive than those in any of the preceding cases, they are of a character to warrant the suggestion that so far as health and digestion are concerned it is safer to omit a body of this kind from the food. There are some foods which naturally contain small quantities of potassium nitrate. Its very poisonous action when taken in large doses, however, is a warning which should cause great care in its use even in small quantities and deter any one charged with the protection of the public health from expressing any favorable opinion in respect to its use.

It is evident that potassium nitrate in the quantities used has neither a preserving effect nor has it any condimental value. Whatever may be said to the contrary, it is perfectly evident that the sole purpose of its use is the intensification of the red color of meats after preservation. Whatever may be the ethical principle underlying this use of potassium nitrate is a question which is not the subject of discussion in a bulletin of this kind, but it is only due to the consumer that the real purpose of using potassium nitrate in the curing of meats should be revealed.

The further question arises as to whether or not the coloring of preserved meats in this way in order that they may have the color of fresh meats is a violation of the Food and Drugs Act, which forbids the coloring of food products for the purpose of concealing damage or inferiority.

While, therefore, the data which have been accumulated are not such as to warrant a sweeping condemnation of potassium nitrate in foods, they are sufficiently indicative to justify the conclusion that its presence in foods is undesirable and open to suspicion.

## General Considerations.

Having thus set forth the general results of this long and laborious study, it is seen that if the conclusions based upon the experimental data are correct that there can be no justification of the process of adding chemical preservatives to human foods. Successful manufacturing establishments have demonstrated beyond peradventure that better, more wholesome, and more permanent forms of food products can be produced without the aid of any preservative whatever. Sterilization will preserve sweet cider better than benzoate of soda. Proper care in handling fruits and in conducting the manufacturing processes for preserves, jams and marmalades will make a more palatable product and one that keeps better than the use of salicylic acid. Careful curing of meats and proper care in transportation will preserve these meats better than boric acid. The natural color of the pea kept in a sanitary can where its color is not lost by action due to imperfections of the tin will make a far more palatable article than will the use of sulphate of copper, and so on to the end of the list. There is no single food product which is not more palatable and of equal if not better keeping qualities when made carefully without the use of preservatives. There is, therefore, absolutely no commercial necessity for the use of these bodies, but it is urged by those who employ them that even though considerable quantities of these bodies are injurious to the health, which no one denies, yet in the minute quantities in which they are used in foods they can not be regarded as in any way deleterious. It is easy to show that such an opinion is without scientific basis. It is quite impossible for any expert who holds this opinion to indicate to any jury, much more to the great jury of the American people any point in the addition of the preservative to food at which it remains harmless, or the point at which it begins to be harmful. Unless such a point could be fixed and demonstrated upon reliable experimental data, it is evident that no scientific reason can be urged for the use of limited quantities of a preservative, which is acknowledged to be harmful, on the ground that in such quantities it is not injurious.

Inasmuch as a preservative is not a food, and as it does not in any way take part in the nourishment of the body nor in the restoration of waste or growth; and further as it is necessarily eliminated, either unchanged or in other forms which may be even more harmful than the original, by the excretory organs of the body, thus imposing upon them an unnecessary and injurious burden and affecting more or less the constitution of the ultimate cells thereof in an unfavorable way, it is evident that the argument which would permit their use in small quantities is wholly illegitimate.

The fallacy of the argument that small quantities of an injurious substance are not injurious may perhaps be best represented graphically. The chart which accompanies this discussion shows theoretically the normal and lethal dose of a food and a drug or, as in this case, a chemical preservative. The chart shows two curves, one representing a chemical preservative and one representing a food. The normal dose of a food is that quantity of food which maintains a healthy adult body in equilibrium. It is represented on the right of the chart by the number 100. If the quantity of food necessary to maintain the equilibrium in a healthy adult body is slightly diminished, no apparent change is at first experienced and possibly even no discomfort. If, however, the quantity of food be still further diminished progressively, as indicated by following the curve down to the left, the point is finally reached when no food is given at all and death ensues, represented by zero on the left hand of the diagram designated "lethal dose." As the curve begins to deviate from the perpendicular on the right the degree of injury is very readily noticed and starvation or symptoms of starvation are set up. Thus, if you follow the perpendicular on the right downward to the point 80, the divergence of the corresponding point of the curve is already measurable. As you descend to zero the magnitude of the measurement increases. It requires but very little further illustration to show how easily the effect of diminishing the normal dose of a food can be measured immediately after the curve begins to vary appreciably from the perpendicular on the right.

Let us now consider the perpendicular on the left, which is marked at the top under the term "lethal dose," viz.; a quantity of the added preservative sufficient to destroy life. The normal dose of such an added chemical preservative is 0, and is shown at the base line to the right marked "normal dose." If you add a very minute quantity of a chemical preservative, the curve representing it varies

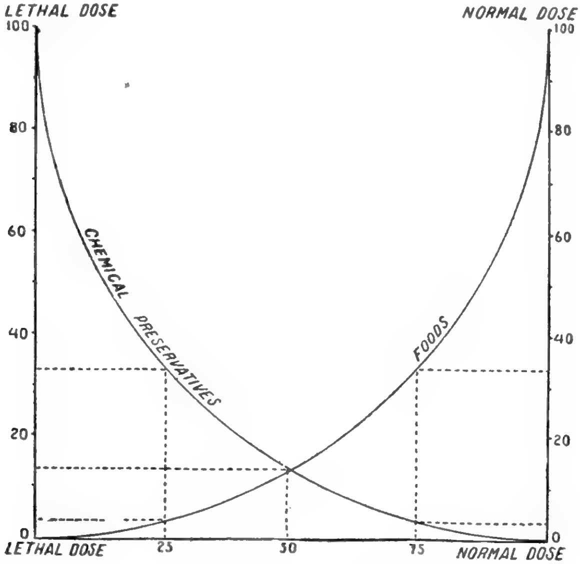

FIG. 1. Graphic chart representing the comparative influences of foods and preservatives.

so slightly from the horizontal base as to be impossible of measurement by ordinary means. If we follow along to the number 75, on the horizontal base, we see the deviation of the curve is sufficiently great to measure. At 50 it is still greater, at 25 still greater, while at the left of the basic line it is a maximum, extending from 0 to 100, or the lethal dose. It is easy to show by mathematical data that no matter how small the quantity of an injurious substance or preservative is, it will still produce an injurious effect, which may be infinitely small if the dose be infinitely small. It follows then, as a mathematical demonstration, that any quantity of an injurious substance added to a food product must of necessity be injurious, provided it is in the nature of a drug and the body is in a perfectly healthy normal condition.

Hence the argument which has been so persistently urged in favor of a chemical preservative that if in small quantities it is harmless is shown to be wholly untenable. Where there is no necessity for the addition of a harmful substance, where no particular benefit is secured thereby, and where there is no disturbance of the normal state of health there can be no possible excuse of a valid nature to offer for the exhibition of even minute quantities. That these minute quantities would not be dangerous, in so far as producing any fatal effect is concerned, is conceded, but that, in the end, they do not produce any injury, even in these small quantities, is certainly to be denied.

The course of safety, therefore, in all these cases is to guard the opening of the door. If the use of small quantities is permitted, then there can never be any agreement among experts or others respecting the magnitude of the "small quantity," and continued litigation and disagreement must follow. On the other hand, when the harmfulness of any substance which it is proposed to add to food is established and no reason for its use can be given other than the convenience, carelessness, or indifference of the manufacturer, the exclusion of such bodies entirely from food products follows as a logical sequence and a hygienic necessity.

# THE HUMMING TELEPHONE,

## A Contribution to the Theoretical and Practical Analysis of its Behavior.

By A. E. KENNELLY and WALTER L. UPSON.

(*Received July 20, 1908.*)

The following paper describes the salient features of an experimental research on the humming telephone, conducted in the Graduate School of Applied Science of Harvard[1] University during the year 1907–08, and discusses an elementary mathematical theory which the observations appear to indicate and support.

*Definition.*—A "humming telephone" is a connection of:

1. A telephone receiver, or ordinary hand 'phone.

2. A telephone transmitter, or ordinary carbon microphone.

3. A source of electric power, such as a voltaic battery and telephone induction coil, with the receiver in such electric and acoustic relation to the transmitter, that it is able to emit a sustained note or hum. This auto-excited hum may be so loud as to be heard in a distant room through several partitions.

*Historical Outline.*—The fact that a telephone receiver held, either in contact with, or close to, the face of its transmitter may cause the production of a hum or singing tone, appears to have been first observed by Mr. A. S. Hibbard.[2] This experimental fact is now well known to telephonists. In many cases, it is only necessary to lift a subscriber's telephone from its hook, and hold it face to face with its transmitter, in order to produce a loud hum.

The only published investigation of the humming telephone that the authors have succeeded in finding is an important paper by Mr.

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[1] "Investigation of the Phenomena of 'The Humming Telephone,'" by Walter L. Upson, a thesis towards the degree of master of science in electrical engineering, Harvard University, 1908.

[2] September, 1890. See Gill's paper hereafter referred to.

F. Gill,[3] read before a meeting of the Dublin Local Section of the Institution of Electrical Engineers in April, 1901. Very briefly, the salient experimental facts reported in this valuable paper are:

1. The reversal of the telephone receiver connections in the circuit alters the pitch of the auto-excited tone, the pitch being higher for one direction, and lower for the other direction, of connection.

2. The pitch of the tone may also be altered by changing: (*a*) the inductance, capacity or resistance of the circuit, or circuits; (*b*) the strength of current in the microphone transmitter; (*c*) the distance between the receiver and transmitter diaphragms; (*d*) pressure on either of the diaphragms.

The Gill paper does not discuss the theory of the subject beyond suggesting that the phase retardation of the acoustic impulses reaching the transmitter from the receiver has a controlling influence on the pitch of the tone.

The research reported in this paper may be regarded as extending the investigation from the stage reached in Gill's paper to a stage which admits of a first approximation theory. A large amount of research remains, however, to be carried on in the future, before the experimental and theoretical analysis of this fascinating but complex phenomenon can be regarded as satisfactorily nearly complete.

*Method of Observation Employed.*—As pointed out in Gill's paper, the pitch of the note emitted by the humming telephone, although substantially constant under fixed conditions, is affected by almost any change in the apparatus, in a seemingly most intricate manner. In order, therefore, to study the effect of varying one particular variable at a time, the device was hit upon of acoustically connecting the receiver and transmitter diaphragms in a definitely controllable way by means of telescoping tubes fitting on to the receiver and transmitter faces. These tubes, and also the standard electric connections employed, are indicated in Fig. 1.

The transmitter was kept stationary, with one end of the tube covering and secured to its cone. The receiver was fastened, on a sliding wooden carriage, to the other end of the telescoping tube.

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[3] "Note on a Humming Telephone," by F. Gill, *Journal of the Institution of Electrical Engineers,* 1901–02, Vol. XXXI., No. 153, pp. 388–399.

The distance between the faces of the two instruments could be varied at will by pulling out, or pushing in, the telescoping tube-sections. The average current in the primary circuit was measured with a Weston d.c. milliammeter. The pitch of the humming note was measured approximately by the ear, with the aid of a number of short organ pipes, and, in some instances, with the aid of a violin. The voltaic battery used consisted of a selected number (from two to nine, but usually four) of 25-ampere-hour lead storage cells. The reversing switch in the secondary circuit enabled the receiver terminals to be reversed at will.

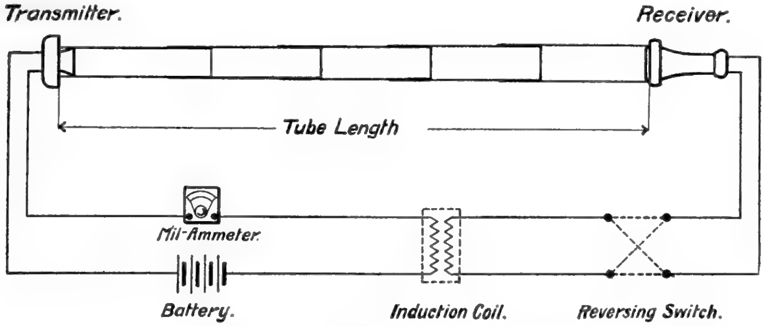

FIG. 1. Diagram of Humming Telephone Connections.

*The Telescoping Tubes.*—The tubes were made of heavy wrapping paper. Their internal diameters varied from 5 cm. (2 in.) to 6 cm. ($2\frac{1}{3}$ in.). They were used in lengths of 65 cm. ($25\frac{1}{2}$ in.), with a few shorter and longer sections for special measurements. The substance of which the tubes was composed did not appreciably affect the observations. It was found, however, that if the telescoping sections did not fit fairly tightly, erratic results were obtained. Closely fitting sections were used.

*The Transmitters.*—The transmitters used were of the standard Western Electric Co. type and manufacture. The diaphragm in these instruments was of aluminum, 6.32 cm. (2.49 in.) in total diameter, and 0.55 mm. (0.022 in.) thick, over a coating of Japan varnish on one face. The diaphragm was loaded at its center with one of the disk electrodes of the carbon microphone. The diaphragm was damped by being clamped between rubber rings to an internal diameter of 4.8 cm. (1.9 in.), and also by the application of a pair of rubber-tipped flat metal springs to areas between the center and edge. The resistance of the microphone varied between the approximate limits of 20 ohms when quiescent, and 110 ohms when in powerful vibration.

*The Receivers.*—The receivers used in most of the measurements were of the standard bipolar Western Electric Co.'s type, known as No. 122, having poles 1.4 × 0.2 cm. (0.55 × 0.08 in.), separated by 0.82 cm. (0.325 in.). They had a resistance of 210 ohms, and an inductance of 0.025 henry, at a frequency of 1,000 ∼. With steady currents, their resistance, at 15° C., was about 70 ohms. The diaphragm of varnished ferrotype iron had an external diameter of 5.5 cm. (2.17 in.), a clamping diameter of 4.95 cm. (1.95 in.) and a thickness, over varnish, of 0.292 mm. (0.0115 in.). Its weight was 4.0 grammes.

*The Induction Coil.*—The induction coil used was of the standard Western Electric Co.'s type, known as No. 13. Its resistances and inductances were taken as follows:[4]

TABLE I.

| Frequency Cycles per Second. | Resistance at 18° C. | | Self-Inductance. | | Mutual Inductance, Henrys. |
|---|---|---|---|---|---|
| | Primary Ohms. | Secondary Ohms. | Primary Henrys. | Secondary Henrys. | |
| 0 | 1.62 | 20.3 | | | |
| 1,000 | 3.2 | 48.1 | 0.0044 | 0.0765 | 0.0172 |

The principal dimensions of the coil were: Length over all 8.2 cm. (3.16 in.). Interflange 6.3 cm. (2.5 in.). Diameter over outside cover 2.5 cm. (1 in.). Internal diameter of core tube 0.75 cm. (0.296 in.). Diameter of iron wires in core 0.0356 cm. (0.014 in.). Total number of iron wires in core about 75.

*Observation Series No 1. Effect of Shortening the Tube.*—Commencing with the connections of Fig. 1, a battery of 8.6 volts, and a tube length of 267 cm., as indicated in Fig. 2 on the scale of abscissas, a loud steady note between G″♯ and A″ (850 ∼) was sustained in the telephone. The pitch of this note is shown at *P* on the

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[4] The data for the coil at 1,000 ∼ were kindly supplied by the engineering department of the Western Electric Co.

upper ziz-zag line *I*. The current strength, on the d.c. milliammeter, as shown at *p* on the lower ziz-zag line *I*, was 130 milliamperes. When the telescopic tube was gradually shortened, the pitch of the note steadily rose, until it reached *Q, at* A″♯ (920∼), with 240 cm. of tube-length, and a primary current strength *q* of 200 mas. The intensity of the note near 920 ∼ was ordinarily somewhat weaker than when near 825 ∼. On continuing to shorten the tube, the pitch suddenly broke from *Q*, at 920 ∼, to *R* at 825 ∼. Pushing in the tube further, the pitch would again climb steadily to *T*, at 201 cm., with a new maximum of current. Beyond this point, the pitch would break suddenly to *U* at 810 ∼. Again it would climb to *W*, at 170 cm. and suddenly collapse to *X*. Continuing in this manner, the pitch would alternately rise to maxima and break suddenly to minima, along the pitch zig-zag *I*. At the breaks of pitch, the current would sometimes break to a lower value, as at *t, u;* or break to an upper value, as at *w, x;* or vary suddenly in rate of change, without discontinuity in magnitude, as at *q*. Repeating the experiment, the zig-zag lines of pitch and of current would be repeated, not exactly but substantially, the variations being due not

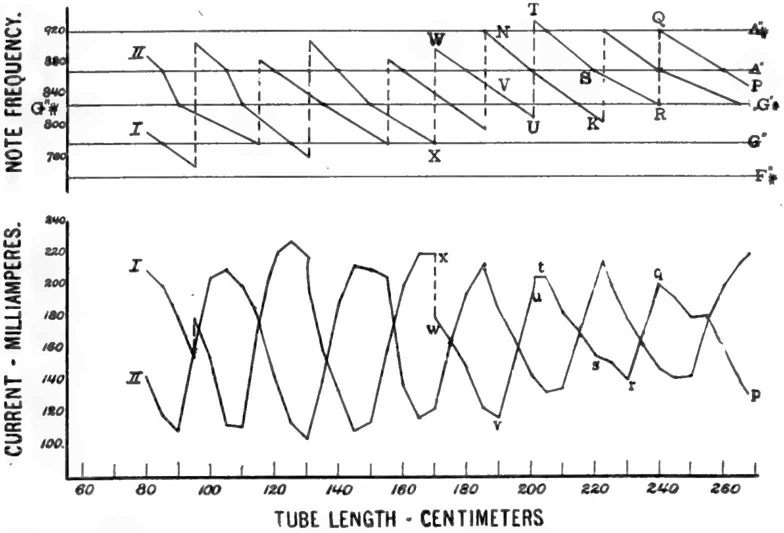

Fig. 2. Effect of Shortening Tube, and of Reversing Receiver Connections.

merely to observational error, but also to variations in the behavior of the transmitter.

The zig-zag pitch line *PQRST* is found to be somewhat irregular. The slants are by no means regularly parallel. The breaks *QTW* are neither regularly elevated, nor regularly spaced. The only substantial regularity is in the spacing along the pitch line G″♯ of 825 ∼. The intersections of the ascending branches with this line lie approximately 40 cm. apart, at 110, 150, 190, 230 and 270 cm., or in accordance with the series $30 + 40m$ cm., where $m$ is any positive integer.

As regards the current curve *pqrst,* its points of minima *p, r, v,* etc., correspond fairly well to the ascending intersections of the pitch line with the line of G″♯ 825 ∼. The points of maxima *q, t, x,* etc., occur near to the breaks in the pitch *Q, T, W,* etc. Minimum primary current was noticed to be associated with maximum microphonic activity of vibration. Feeble action in the microphone, on the other hand, was found to be associated ordinarily with increase of primary current.

*Observation Series 2. Effect of Shortening the Tube with Reversed Receiver Terminals.*—Curves *II,* in Fig. 2, represent the behavior of note pitch and primary current, as the tube was shortened from 265 cm. to 80 cm., with the terminals of the receiver reversed. Their general characters are similar to those of curves *I.* The two sets of curves indicate the effect which would be produced by reversing the receiver terminals at any particular tube-length within the above range. Thus, at *S,* or 220 cm., a reversal would lower the pitch from 870 ∼ on curve *I* to *K,* at 810 ∼, on curve *II.* On the other hand, a reversal made on curve *I,* at *V,* of 825 ∼, would raise the pitch to *N* of 900 ∼ on curve *II,* so that whether the reversal produces a rise or fall of pitch depends, in general, upon whether the reversal is effected above or below the mean pitch of G″♯, 825 ∼.

The only apparent regularity in the pitch line *II* lies in the spacing of the ascending intersections with the line of mean pitch G″♯ (825 ∼). These occur near to 90, 130, 170, 210 and 250 cm. of tube-length, or according to the series $10 + 40m$ cm. On the mean-pitch line, the ascending intersections of one curve lie approximately 20 cm. from, or midway between, those of the other curve.

The note frequencies and primary current strengths for tubes of less than 60 cm. in length are given in Fig. 3, commencing at 60 cm. and shortening down to about 1 cm., when the receiver face came into contact with the transmitter face (cone removed), and so prevented closer approach. Curves *I* and *II* of Fig. 3 correspond to curves *I* and *II* of Fig. 2, respectively, and indicate the effect of reversing the receiver terminals. It may be observed that following the pitch line *I*, the ascending branch intersects the mean frequency line of 825 ~, at a tube-length of 30 cm., for the last time.

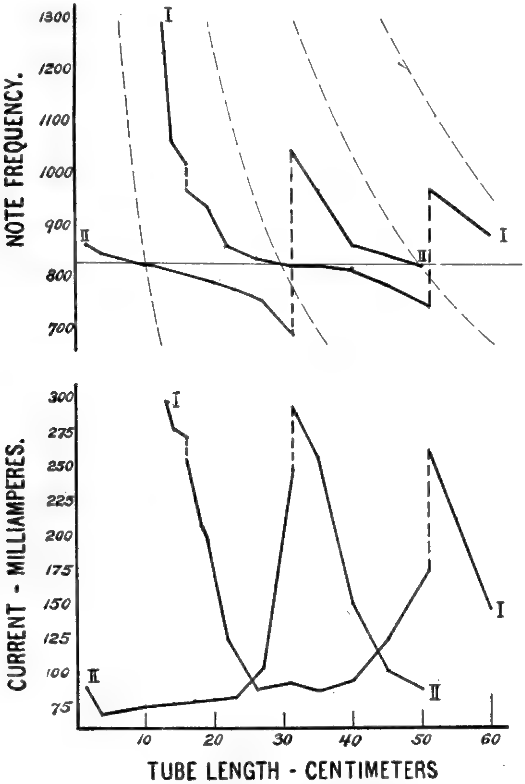

FIG. 3. Humming Note Frequencies and Primary Current Strengths with Short Tubes.

Shortening the tube beyond this point, the pitch rises until it reaches e‴ of 1,300 ∼, at 12.5 cm., and at a primary current strength of 300 mas. Here the note breaks without descending to a new low note. There is silence with this connection of the receiver between 12.5 cm. and 0 cm. With the transmitter and receiver touching each other, it was possible to produce almost any note between 620 ∼ and 1,300 ∼, by giving suitable opening to the air at one side. If, however, the outside air was shut off, and the air between the transmitter and receiver diaphragms was cylindrically enclosed, by bringing their faces into full opposition and contact, no note could be obtained.

If we follow pitch curve *II*, we find that the ascending branches intersect the mean-frequency line at 50 cm. and at 10 cm. The pitch 866 ∼ was obtained steadily when the transmitter and receiver faces were in full contact, corresponding to a "tube-length" of 1 cm. With this connection of receiver terminals, no other note, or variety of notes, could be obtained at contact.

A telescoping tube of 9 meters (29.5 ft.) total length was used in one series of measurements, and the results appear in Fig. 4. They were all obtained with diminishing tube-lengths, or with compression of the telescoping tube. The small crosses indicate discontinuities produced at the removal of sections of tube when finished with. In regard to the pitch line, it will be seen that it corresponds to curve *I* of Figs. 2 and 3. That is, it crosses the mean-frequency line of 825 ∼ ascendingly at $30 + 40m$ cm. with a fair degree of precision. With the shortest tube, the range in pitch-frequency was from 740 ∼ to 1,060 ∼, or through 320 ∼. At the full length of 9 meters, this range fell to 75 ∼. The ultimate limit tended apparently to the mean-pitch frequency of G″♯ 825 ∼. The average note was above this pitch; but this was probably because the tube was being compressed. Reference to Fig. 5 will show that, when shortening the tube, the average pitch lies above the mean of 825 ∼; while in lengthening the tube, the average pitch lies below.

The primary current strength in Fig. 4 tends, in general, to minima at the mean-frequency pitch of 825 ∼, and to maxima at the breaks. The differences in current strength become, however,

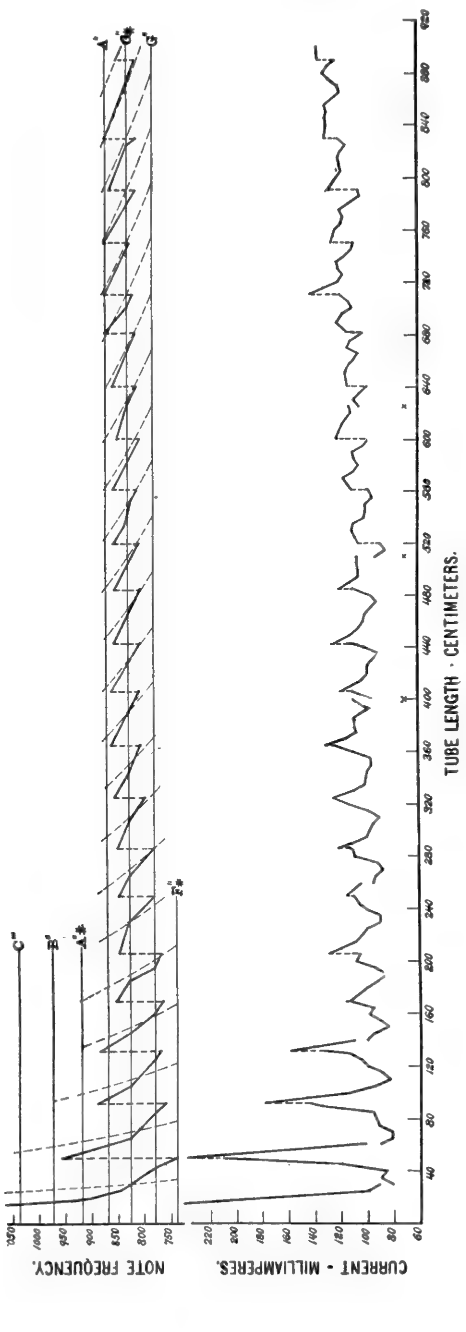

Fig. 4. Frequency and Primary Current Curves for Tube-lengths up to 920 cms. Steadily Reduced in Length, 8.6 Volts in Primary Circuit.

less marked as the tube is longer, the minimum currents rising, as the length increases, by about 40 mas. in 9 meters, indicating steadily reduced action in the transmitter with increasing distance. Since the current rose to 260 mas. when the transmitter diaphragm was entirely out of action, we should expect, at this rate, to be able to sustain the humming note to a total tube-length of 40 meters; but no tests were actually made beyond 9 meters.

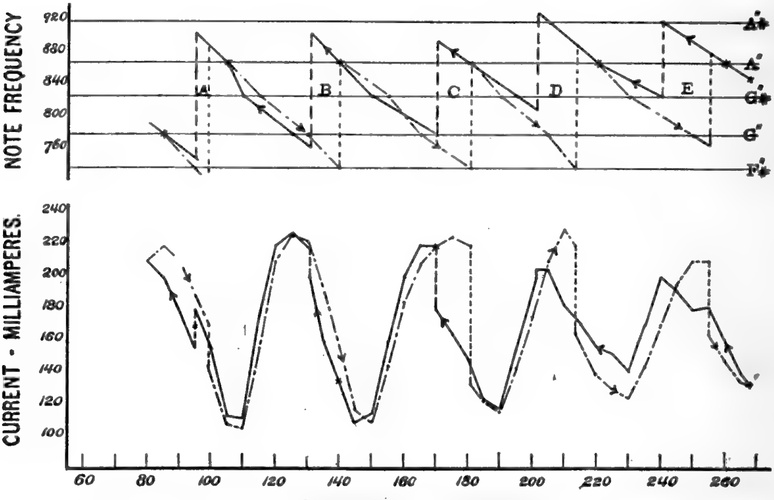

Fig. 5. Effect of Lengthening and Shortening the Tube.

*Observation Series 3. Effect of Lengthening the Tube.*—Fig. 5 indicates the relative effects produced by lengthening, as compared with shortening, the telescoping tube joining the transmitter and receiver in Fig. 1, using the same apparatus and connections as in Figs. 1, 2, 3 and 4. The heavy or continuous lines in Fig. 5 show the effects of shortening the tube, or correspond to curves *I* in Fig. 2. The broken lines show the effects of lengthening the tube. It will be observed that the points of maximum and minimum current agree fairly well. The ascending intersections of the pitch lines with the mean-frequency line of G″♯ 825 ~, lie near together, and approximately conform to the series $30 + 40m$ cm. of tube-length. The points of break in pitch do not, however, agree, and the distances between corresponding pairs of breaks in pitch increase as the tube-length is greater, being 4 cm. at A, 9 at B, 11 at C, 13 at D, and 15 at E. Although not shown in Fig. 5, owing to limitations of space, it was found that these distances between corresponding breaks continued to increase until they reached about 20 cm., after which they shortened again to commence a new expanding series.

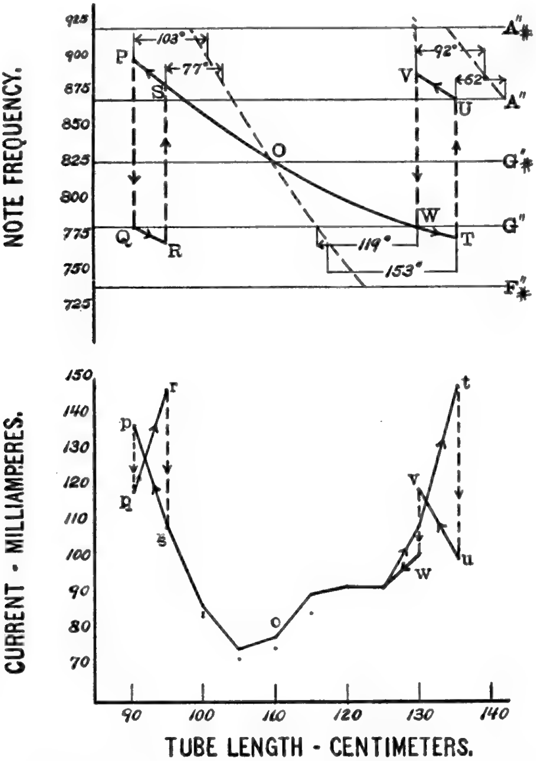

FIG. 6. Humming Cycles with Cyclic Changes in Tube-length.

*Observation Series 4. Effect of Alternately Reversing, or Reciprocating, the Motion of the Tube. Humming Cycles.*—If, when compressing the telescopic tube, and when the note broke from a higher to a lower pitch, the tube was immediately extended again, the note would continue to lower in pitch for a little while, and then break back to a higher pitch. By moving the tube in and out, like a concertina, over this range, the pitch would break to and fro in a very regular way. The corresponding reverse action would also occur if the motion commenced with extension. These conditions are shown in Fig. 6. Commencing at the point $O$, with 110 cm. of tube-length, on the mean frequency of 825 ~, if we shorten or compress the tube to 90.5 cm., we reach $P$ at 900 ~, near A″♯. The note then breaks to $Q$ at 780 ~. Increasing the tube-length back to 95 cm., we reach $R$ at 770 ~. The note then breaks upwards to $S$ at 880 ~. This humming cycle $PQRS$, could be repeated indefinitely with a considerable degree of precision as to pitch and tube-length; but with a more moderate degree of precision as to primary current strength. Similarly, the cycle $TUVW$, of 10.5 cm. amplitude in length, and 100 ~ amplitude in pitch, might be repeated indefinitely. The amplitudes and areas of these humming cycles vary at different breaking points.

*Purity of Humming Tone.*—With the greater tube-lengths, shortly before the break of pitch occurred, there was frequently noted an appearance of the new tone in advance. As the breaking point was approached, the old tone dwindled, while the new tone strengthened. At the break, the old tone, already faint, would suddenly cease. Consequently, before breaking, both the old and new tones might be recognized, forming a sort of trill, or combination tone. This association of simultaneous tones had the effect of maintaining the primary current strength more nearly uniform. With the shorter tube-lengths, which involved a greater jump of frequency at the breaks, these combination tones were rarely heard, and the old note would break suddenly into the new note without any suggestion of a trill.

In some of the observations, the notes, aside from the abovementioned trilling near to the breaking points, gave acoustical evidence of multiple tones. Occasionally, the principal tone was accompanied by an octave overtone. The octave might be either the first octave below, or the first octave above, the principal tone. Such overtones were comparatively faint. At other times, the superposed tone, instead of being harmonic to the principal tone, appeared to differ therefrom by only about one tone on the musical scale. This inharmonic superposed tone was also relatively faint with respect to the principal tone. Generally, however, no superposed tones could be discerned, and the note was clear and flute-like in quality. Irregularities in the fitting of the telescoping tube-sections, or in other acoustic connections, were found to be productive of superposed notes.

## EFFECTS OF ELECTRICAL CHANGES.

*Observation Series 5. Effect of Resistance in Primary or Secondary Circuit.*—In this test a single tube of constant length (86.5 cm. or 34 in.) was used. It was of pasteboard, had an internal diameter of 5.1 cm. (2 in.) and weighed 113.5 gm. This length happens to be about midway between the ascending intersections of pitch lines *I* and *II* in Fig. 2 measured on the mean-frequency line of 825 ∼. That is, the tube-length selected favored each of the lines *I* and *II* nearly equally. The battery e.m.f. of 8.6 volts was the same as in all the above described measurements. The same telephone receiver and induction coil were also used. Substantially non-inductive resistance was introduced, by rheostat, into either the primary, or the secondary, circuit at will, leaving the connections of Fig. 1 otherwise unchanged.

After starting the loud humming note with no extra resistance in either circuit, resistance was gradually inserted into the primary circuit until the note, diminishing in amplitude, finally disappeared. The extra resistance in the circuit at the extinction of the tone was recorded, under the name of "*extinguishing resistance.*" Resistance was then withdrawn from the primary circuit, and, after the loud note had been reëstablished, was introduced gradually into the secondary circuit, until again the note was extinguished. The secondary extinguishing resistance was likewise recorded. The same tests were repeated with the telephone receiver terminals reversed.

It was found that both the primary and secondary extinguishing resistances repeated themselves very fairly (within about 5 per cent.) in successive trials. In order to obtain the best comparative results in successive tests, it was found desirable to tap the transmitter gently when approaching the condition of extinction.

The pitch of the tone when enfeebled almost to extinction by extra resistance, in either the primary or secondary circuit, was always close to the mean frequency of 825 ∼.

The amount of either the primary or secondary extinguishing resistance was found to depend upon the adjustment and operative condition of the transmitter, keeping the receiver, tube-length and all other conditions unaltered. This led to a trial of this method as a practical test of microphone transmitters.

*Observation Series 5a. Test of Transmitter by Hum-extinguishing Resistances.*—A number of transmitters, some good and others imperfect, were tested under the conditions above outlined. These transmitters were kindly loaned for this purpose by the Western Electric Co. Twelve were regular standard instruments that had already satisfactorily passed the factory tests. These were labelled $T_1$ to $T_{12}$ respectively. Four more were marked defective and "down in volume." They were labelled $T_{13}$, $T_{15}$, $T_{16}$ and $T_{24}$. Four more were marked defective and "thick in quality." These were labelled $T_{14}$, $T_{17}$, $T_{22}$ and $T_{23}$. Yet another four were marked defective and "burning." These were labelled $T_{18}$, $T_{19}$, $T_{20}$ and $T_{21}$. Defective transmitters "down in volume" are recognized as weak. Those which are of "thick quality" are strong but defective in articulation. Those which are "burning" produce slight arcing, at or near the electrodes, when subjected to normal conditions of operation.

The results of the tests on these 24 transmitters are given in the accompanying table; where $R$ represents the primary, and $r$ the secondary, extinguishing resistance, when the transmitter was gently tapped. Care was taken that the observer in this test did not know the label number, or reported condition, of the transmitter under trial. It will be seen that with the good transmitters, the mean primary extinguishing resistances were all included between 26.5 and 58.5 ohms, their mean secondary extinguishing resistances being between 1,925 and 4,150 ohms. All of the defective transmitters lay outside these limits, the "down in volume" being low, and the "thick quality" high, in their extinguishing resistances; except two of the "burning" type, which fell within the good secondary extinguishing resistance limits. It would seem, therefore, that this resistance method constitutes a possible practical application of the humming telephone to transmitter testing; except that "burning" transmitters may require a separate test for their detection.

The results recorded in the last two columns of Table II. are presented graphically in the target diagram of Fig. 7. The square includes all the good instruments and none of the bad. The mean of the good transmitters is indicated by the solid black circle.

TABLE II.

*Table of Comparative Hum-Extinguishing Resistances for 12 Good and 12 Defective Transmitters.*

| Quality of Transmitter. | Transmitter. | Extinguishing Resistances. | | | | Average. $R$. | Average. $r$. |
|---|---|---|---|---|---|---|---|
| | | 1st Position of Rec'r. | | 2d Position of Rec'r. | | | |
| | | $R$ (Pri.). | $r$ (Sec.). | $R$ (Pri.). | $r$ (Sec.). | | |
| OK. | $T_1$ | 43 | 3,100 | 50 | 2,300 | 46.5 | 2,800 |
| | $T_2$ | 23 | 3,050 | 44 | 3,000 | 33.5 | 3,025 |
| | $T_3$ | 55 | 4,300 | 43 | 4,000 | 49 | 4,150 |
| | $T_4$ | 25 | 2,300 | 31 | 1,900 | 28 | 2,100 |
| | $T_5$ | 45 | 3,900 | 40 | 2,600 | 42.5 | 3,250 |
| | $T_6$ | 31 | 3,000 | 69 | 3,800 | 50 | 3,400 |
| | $T_7$ | 27 | 2,600 | 26 | 1,600 | 26.5 | 2,100 |
| | $T_8$ | 30 | 2,600 | 30 | 1,700 | 30 | 2,150 |
| | $T_9$ | 31 | 2,700 | 44 | 2,300 | 37.5 | 2,500 |
| | $T_{10}$ | 47 | 3,900 | 46 | 3,900 | 46.5 | 3,900 |
| | $T_{11}$ | 43 | 4,100 | 74 | 3,800 | 58.5 | 3,950 |
| | $T_{12}$ | 33 | 2,600 | 21 | 1,250 | 27 | 1,925 |
| | Mean | 36.1 | 3,180 | 43.2 | 2,696 | 39.6 | 2,937 |
| Down in Volume. | $T_{13}$ | 10 | 750 | 10 | 700 | 10 | 725 |
| | $T_{15}$ | 6 | 390 | — | — | 6 | 390 |
| | $T_{16}$ | 6 | 900 | 12 | 1,000 | 9 | 950 |
| | $T_{24}$ | 17 | 1,400 | 20 | 1,500 | 18.5 | 1,450 |
| | Mean | 9.75 | 860 | 14 | 1,070 | 10.9 | 879 |
| Thick Quality. | $T_{14}$ | 62 | 4,900 | 66 | 2,300 | 64 | 3,600 |
| | $T_{17}$ | 50 | 9,000 | 70 | 10,000 | 60 | 9,500 |
| | $T_{22}$ | 52 | 7,000 | 75 | 8,000 | 63.5 | 7,500 |
| | $T_{23}$ | 66 | 5,300 | 78 | 6,700 | 72 | 6,000 |
| | Mean | 57.5 | 6,550 | 72.5 | 6,750 | 64.75 | 6,650 |
| Burning. | $T_{18}$ | 54 | 3,800 | 68 | 3,400 | 61 | 3,600 |
| | $T_{19}$ | 61 | 4,700 | 93 | 6,900 | 77 | 5,800 |
| | $T_{20}$ | 82 | 5,300 | 102 | 5,000 | 92 | 5,150 |
| | $T_{21}$ | 60 | 3,900 | 61 | 2,900 | 60.5 | 3,400 |
| | Mean | 64.25 | 4,425 | 81 | 4,550 | 72.6 | 4,487 |

*Observation Series 6. Effect of Varying the E.M.F. in the Primary Circuit.*—Among so many variables and variations as are displayed in preceding diagrams, it is comforting to find one variable which produced relatively little effect within certain practical limits. Fig. 8 shows the frequencies and primary currents for tube-lengths

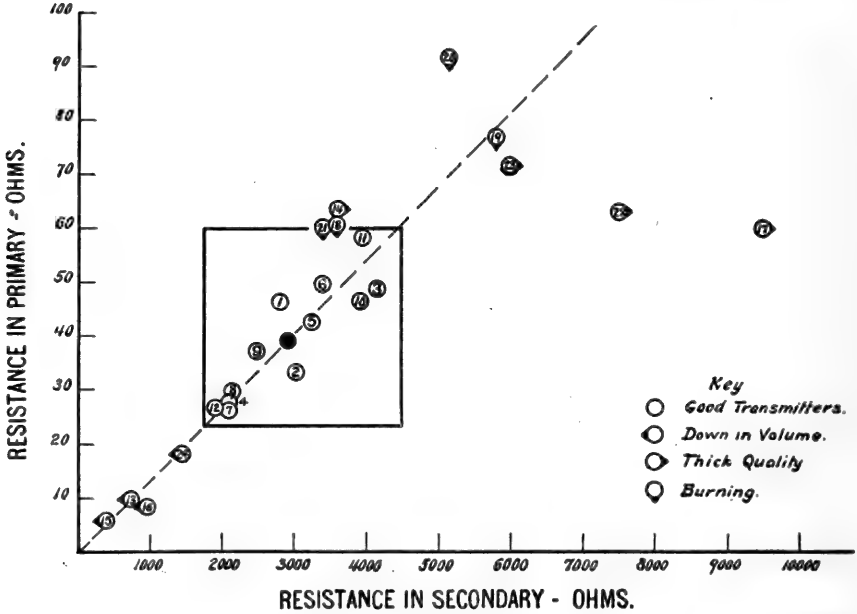

FIG. 7. Target Diagram of Transmitter Tests by the Method of Hum Extinguishing Extra Resistance.

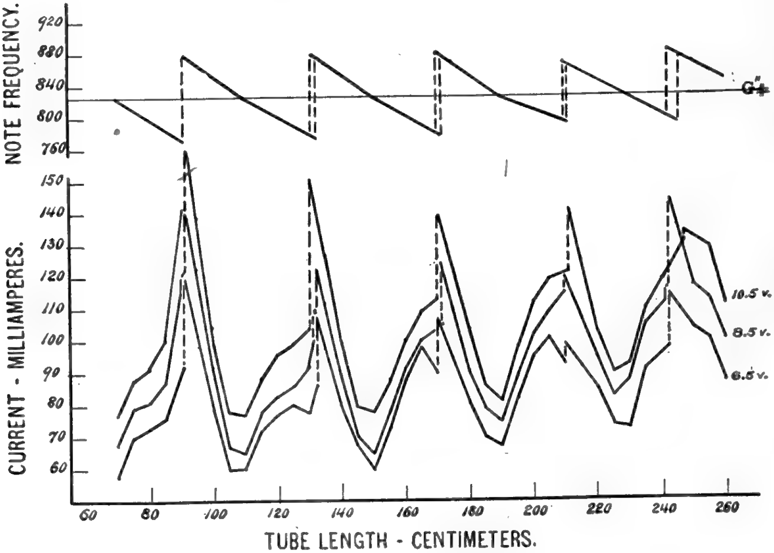

FIG. 8. Frequencies and Primary Currents for Different Primary E.M.F's.

steadily reduced from 260 to 70 cm., with batteries of 3, 4 and 5 storage cells, respectively, in the primary circuit (6.5, 8.5 and 10.5 volts). The transmitter, induction coil, receiver and transmitter were all as in Figs. 1 to 6. It will be seen that the primary currents have their respective maxima and minima in substantial agreement, the range of variation being naturally greatest for the largest battery, and least for the smallest. The ascending intersections of the frequency line with the mean-frequency line of 825 ~ are the same throughout, and conform to the series 30 + 40*m* cm., in agreement with line *I* of Fig. 2. The breaks in pitch do not all coincide; but the differences in this respect are not great, nor can it be said that the biggest battery always produced the most retarded break. Moreover, excepting perhaps the break at 240 cm., the variations in breaking points are within the limits of variation obtained in successive series with one and the same battery.

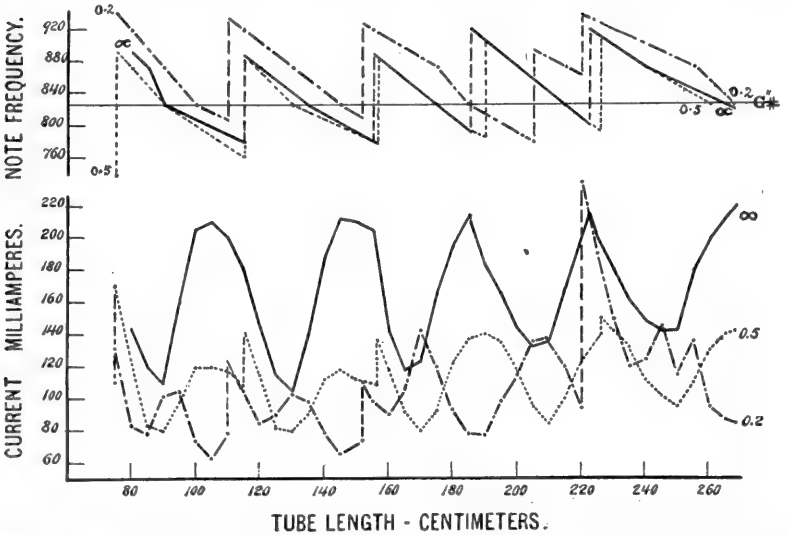

Fig. 9. Frequencies and Primary Current Strengths for Different Condensers in Secondary Circuit.

*Observation Series 7. Effect of a Condenser in the Secondary Circuit.*—It was found that a certain magnitude of condenser capacity inserted in series in the secondary circuit had a marked effect on the behavior of the humming telephone. The results are indicated in Fig. 9, for a tube-length commencing at 270 cm. and steadily reduced to 75 cm., with 8.6 volts in the primary circuit and the same instruments as before. Three sets of curves are given, for 0.2 $\mu$f. (microfarad), 0.5 $\mu$f., and $\infty$ $\mu$f. (condenser short-circuited), respectively. Referring to the pitch lines, it will be seen that there is not much difference between the cases of $\infty$ and 0.5 $\mu$f. The ascending branches of the zig-zags cut the mean frequency line of G″♯ at 90, 132.5, 175 and 210 cm. or fairly in conformity with the series $10 + 40m$, as in curve *II* of Fig. 2. With 0.2 $\mu$f., however, the intersections with this line are at 100, 145 and 185 cm., or more nearly in conformity with the series $22 + 40m$ cm.; that is, at points displaced about 12 cm. further along the tube. Moreover, the breaks occur at higher frequencies by about 40 ∼.

As regards primary current strengths, the minima in each series occur at substantially the points where the pitch line intersects ascendingly with the G″♯ line. That is, the minima of $\infty$ and 0.5 $\mu$f. are fairly close together; while those for 0.2 $\mu$f. are displaced about 12 cm. further along the tube. Maximum currents occur near breaking points, as usual.

## EFFECTS OF MECHANICAL CHANGES IN INSTRUMENTS.

*Observational Series 8. Effects of Modifying the Transmitter.*—In order to study the influence of changes in the transmitter upon the humming note, three similar Western Electric transmitters were selected, of standard type and quality, already referred to as $T_5$, $T_8$ and $T_{11}$, in connection with Fig. 7. The receiver, induction-coil, battery and connections were as in previous tests. The comparative results with these three transmitters are shown in Fig. 10, for tube-lengths steadily reduced from 260 to 70 cm. It will be noted that the ascending intersections of the pitch lines all intersect the mean-frequency line of 825 ∼ in substantial conformity with the series $30 + 40m$, or in accordance with curve *I* of Fig. 2. The breaking points do not agree, No. 8 always breaking last at a higher pitch, No. 5 next at a medium pitch and No. 11 first at a lower pitch. It may also be noted that in the hum-extinguishing resistance-test of these three transmitters, as given in Table II., and in Fig. 7, their order of succession was the same.

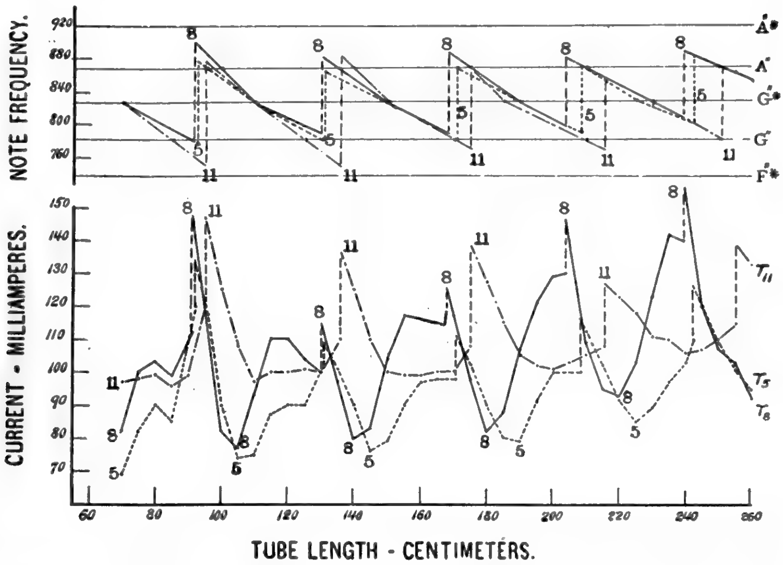

FIG. 10. Comparative Behavior of Three Regular Standard Transmitters with Reduced Tube-lengths.

The test indicates, therefore, that different standard transmitters in normal adjustment do not alter the mean-frequency tube-lengths; but that variations in breaking lengths may be expected within certain limits.

A further test was made of the effect of modifying the transmitter, by selecting for experiment a particular Western Electric Co.'s standard type of transmitter which had been used in the laboratory for some years, and was not in the best adjustment. A test was made with this instrument (using the same receiver, coil, battery and connections as in preceding tests), first without any extra load on its diaphragm, second with a load, and third with the load removed. The load consisted of a small brass disk 1.5 cm. (0.59 in) in diameter, and 0.2 cm. (0.079 in.) thick, clamped at its center between the two small nuts at the center of the external surface of the diaphragm. This added a mass of 2.7 gm. to the vibrating system of the transmitter. The results are seen in Fig. 11. Curves 1 and 3 represent the behavior of the system unloaded, before and after loading respectively, the tube-length being steadily diminished from 200 to 80 cm. Curves 2 represent the corresponding behavior when the diaphragm was loaded. The primary currents were all unusually large, probably owing to the imperfect adjustment of the transmitter.

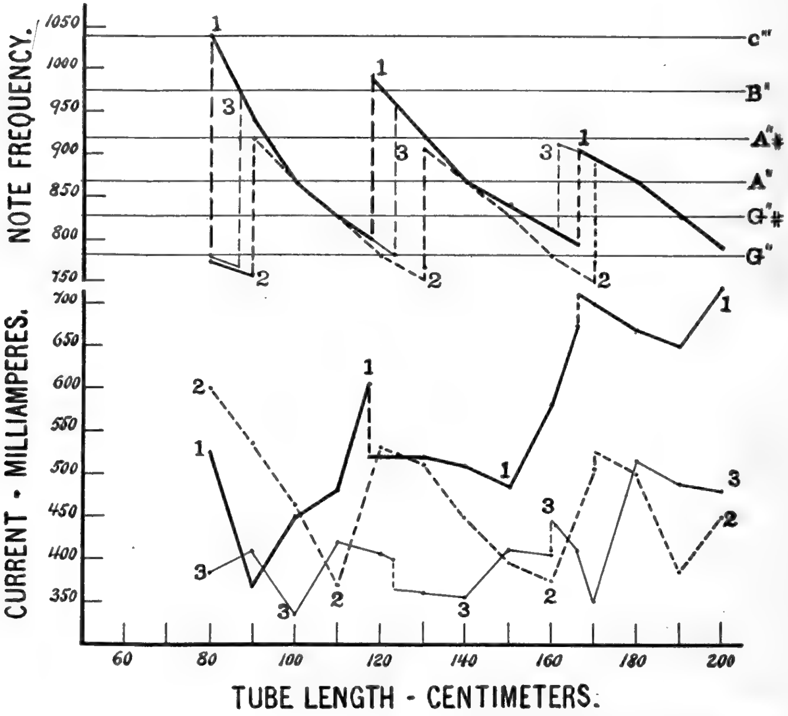

FIG. 11. Test of a Transmitter with its Diaphragm Loaded and Unloaded.

It will be observed that the loading did not appreciably alter the ascending intersections of the pitch lines with the G"# mean-frequency line, which occur in conformity with the series $20+40m$ cm. The loading seems to have somewhat lowered the range of pitch as a whole; or to have modified the conditions at breaking, without materially affecting the conditions at mean-frequency (825 ~).

A number of trials with further modifications of the transmitter diaphragm substantiated the above stated results. In one case, a new experimental diaphragm of tinned sheet iron, 0.38 mm. thick

(0.015 in.), with parallel and opposite symmetrical sectors sliced off, was substituted for the regular diaphragm in the test transmitter. The primary current strength during activity was thereby increased; but the G″♯ tube-lengths remained substantially unchanged at $30 + 40m$ cm. Adding loads, altering the damping-spring pressure, or varying the other mechanical adjustments of the transmitter produced either complete silence; or else the usual G″♯, at $30 + 40m$ cm.

The tests showed that modifying the transmitter alters the range and limits of pitch variation, as well as the primary current strengths; but does not sensibly alter the tube-lengths for mean-frequency.

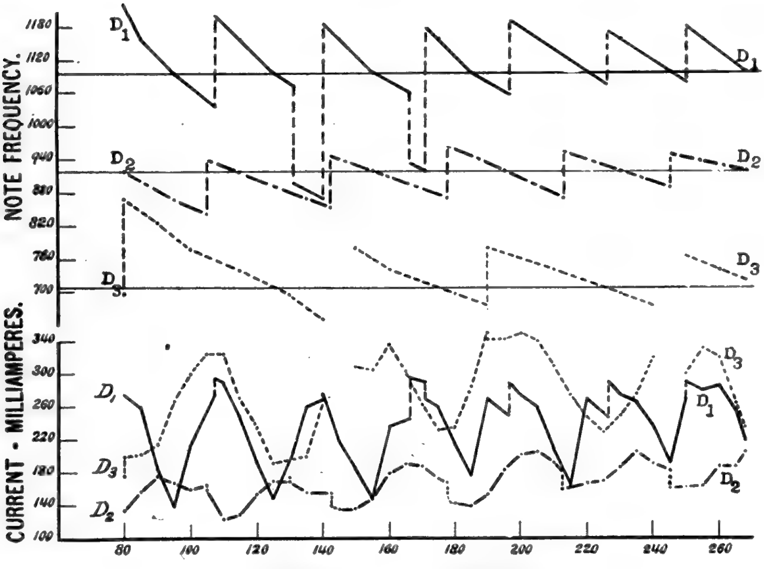

FIG. 12. Comparative Frequencies and Currents with Three Different Receiver Diaphragms.

*Observation Series 9. Effect of Altering the Receiver.*—In order to determine the influence of the telephone receiver diaphragm on the hum, three special receiver diaphragms were made up, each of soft transformer steel, 0.355 mm. (0.014 in.) thick, and 5.5 cm. (2.16 in.) in diameter, labeled $D_1$, $D_2$ and $D_3$ respectively. $D_1$ was left circular, $D_2$ and $D_3$ had symmetrical sectors cut from opposite sides, reducing their width to 4 cm. (1.57 in.) and 3 cm. (1.18 in.) respectively. In clamping these strip diaphragms in front of the bipolar magnet of the standard receiver, their angular position did not appear to affect the system appreciably.

The results obtained with these three diaphragms are indicated in Fig. 12, for tube-lengths diminished steadily from 270 to 80 cm. It will be seen that the receiver diaphragm influences the hum profoundly. Thus, the circular diaphragm $D_1$ developed a mean-frequency of 1,100 ∼ or c‴♯, judging by the points of minimum primary current, and its pitch zig-zag formed ascending intersections with this line at 95, 125, 155, 185, 215 and 245 cm., approximately, in conformity with the series $5 + 30m$ cm. The sectored diaphragm $D_2$ developed a mean-frequency of A″♯, at 920 ∼, with ascending intersections nearly in conformity with the series $36m$ cm. The narrowest diaphragm $D_3$ developed a mean-frequency of F″, at 705 ∼, and ascending intersections in substantial conformity with the series $33 + 47m$ cm.

It will be observed that there are double breaks in pitch on zig-zag $D_1$. This tendency was found to follow irregularity in the diaphragm, or in its mounting. Thus, the ordinary standard diaphragm used in all the preceding tests was observed to develop similar double breaks when the clamping screw-cover was slackened, so as to leave the diaphragm somewhat loosely clamped.

The pitch zig-zag of $D_3$ shows gaps. These gaps seemed to be due to the enfeebled condition of the electromagnetic vibrating system in the receiver when used with the experimental diaphragm $D_3$. A very marked case of such gaps is presented in Fig. 13, which indicates the frequencies and currents obtained with a particular single-pole telephone receiver, the remainder of the apparatus being unchanged, and the tube-length being steadily reduced from 165 to 80 cm. The line of mean-frequency is at 1,025 ∼, and the ascending intersections with this line are formed at points conforming with the series $28 + 32m$ cm. Only short pieces of the zig-zag were, however, obtainable, and these only with the aid of a condenser in the secondary circuit. The dotted segments *RS* and *TV* were obtained with the receiver terminals reversed, and correspond approximately to ascending intersections of the series $13 + 32m$ cm.

Various other modifications of receiver and receiver diaphragm were tried. Loading the diaphragm with a small central mass lowered the mean humming frequency. By selecting suitable diaphragm dimensions, the mean-frequency of the hum could be varied between wide limits.

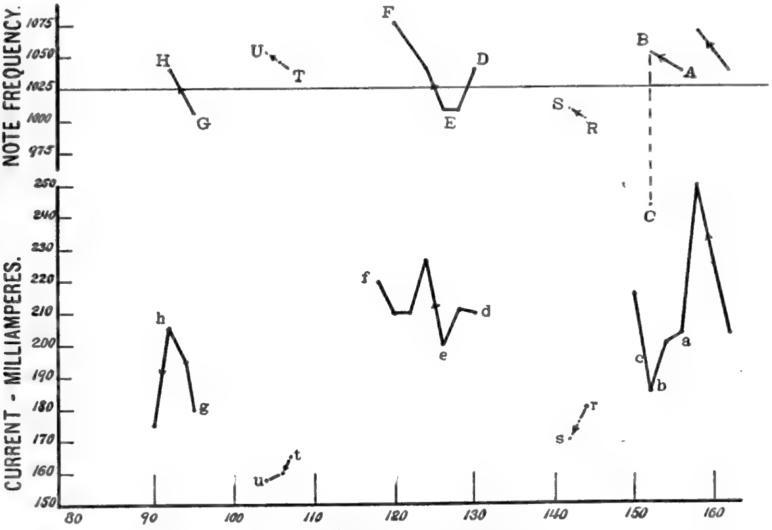

FIG. 13. Discontinuous Frequencies, or Large Gaps in Curves, for Case of Singe-pole Receiver.

*Conclusions Directly Derivable from the Experiments.*—The following more prominent conclusions are indicated by the experiments themselves, independently of any theory:

1. The mean-frequency of the humming-telephone note is determined solely by the receiver diaphragm, and its natural free rate of vibration.

2. The ascending intersections of the frequency zig-zag with the mean-frequency line will be formed approximately at tube-lengths of $(\frac{3}{4} + m)\ v/n_0$ cm. for one connection, and of $(\frac{1}{4} + m)\ v/n_0$ cm. for the other connection, of the receiver; where $v$ is the velocity of sound in air (33,000 cm. per sec. nearly), $n_0$ is the mean frequency in cycles per second, and $m$ is any positive integer, within

the working range of the tube. The constants $\frac{3}{4}$ and $\frac{1}{4}$ may be modified by the presence of condensers, and other circumstances.

3. The range of pitch variation, and the breaking positions, are determined by the transmitter, and by the reinforcing capability of the system. For systems that are weak, either electrically or acoustically, the range of pitch, above or below the mean, will be small.

4. The primary current, as measured by a d.c. instrument, is ordinarily a minimum at the mean frequency, and a maximum at a break.

5. Transmitters may be tested for effectiveness, by measuring their hum-extinguishing resistances in the primary or secondary circuit. The tube-length should be such as to produce mean frequency if one connection of receiver only is used, but should favor both connections equally, if both connections of receiver are used.

## Outline of Theory of the Humming Telephone.

*Preliminary Considerations. Simple Orbital Motion and Simple Unretarded Vibration.*—Let a particle of mass $m$ grammes describe a simple plane circular orbit *zab*, Fig. 14, about the center $O$. Let the radius $Oz = r$ cm., and let $OX$ be the initial line of reference. At time $t = 0$ seconds, let the particle occupy the position $z$; so that its initial radius vector is $Oz$. Let $\omega$ be the uniform angular velocity of the particle about the center $O$, in radians per second. Then, after the lapse of $t$ seconds, the particle will occupy a point in the plane defined by the vector displacement

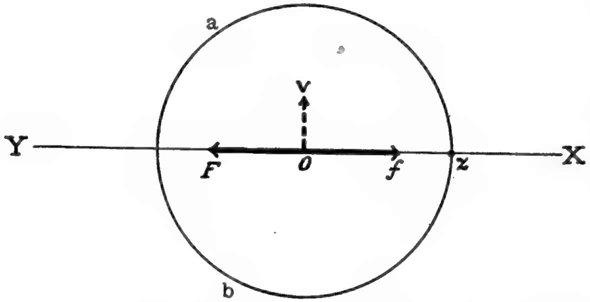

Fig. 14. Vector Diagram of Free Undamped Vibration.

$$\xi = r\epsilon^{j\omega t} \qquad \text{cms.} \ \angle \qquad (1)$$

where $j = \sqrt{-1}$, and $\xi$ is the displacement of the particle in cms. from $O$ at the angle $\omega t$, measured positively, or counter-clockwise, from the initial line $OX$.

Let the particle be acted upon by a centrally directed elastic force

$$F = -A\xi = -ma\xi = -mar\epsilon^{j\omega t} \qquad \text{dynes} \ \angle \qquad (2)$$

proportional to and opposing the displacement, as represented by the vector $OF$ in Fig. 14. Let there be no other forces except those of inertia, acting on the particle; so that the movement is frictionless. Then the velocity of the particle at any instant $t$ will be

$$v = \dot{\xi} = j\omega r\epsilon^{j\omega t} \qquad \text{cms./sec.} \ \angle \qquad (3)$$

The direction of the velocity will, therefore, be perpendicular to the radius vector, or parallel to the instantaneous tangent, as indicated by the dotted line $Ov$, 90° ahead of $Oz$ in phase displacement.

The acceleration of the particle will be, at any instant $t$,

$$c = \dot{v} = \ddot{\xi} = -\omega^2 r\epsilon^{j\omega t} \qquad \text{cms./sec.}^2 \ \angle \qquad (4)$$

That is, the acceleration will be directed oppositely to the displacement. Thus at time $t = 0$, represented in Fig. 14, the acceleration will be directed along $OY$. The virtual reactive force of inertia will be

$$f = -mc = -m\ddot{\xi} = m\omega^2 r\epsilon^{j\omega t} \qquad \text{dynes} \ \angle \qquad (5)$$

In Fig. 14, this reactive force of inertia is represented by $Of$.

In order that the circular orbital motion shall be stable, the sum of the forces $OF$ and $Of$, of elasticity and inertia must be zero; or

$$OF + Of = 0 \qquad \text{dynes} \ \angle$$

$$\therefore \quad -mar\epsilon^{j\omega t} + m\omega^2 r\epsilon^{j\omega t} = 0 \qquad \text{dynes} \ \angle$$

whence

$$\omega = \sqrt{A/m} = \sqrt{a} \qquad \text{radians/sec.} \qquad (6)$$

If, therefore, the angular velocity of the motion be numerically equal to the square root of elastic force per unit of mass, the orbit will be circular and stable, and Fig. 14 may represent its vector diagram. The particle $z$ rotates about $O$, at constant radius with uniform angular velocity $\omega$, and the pair of equilibrating forces $OF$ and $Of$ rotate in synchronism with it. The entire system, Fig 14, may be imagined as pivoted about an axis through $O$ perpendicular to the orbital plane, and spun about this pivot with uniform angular velocity $\omega$.

By a well known proposition connecting simple harmonic vibration with circular orbital motion, the displacements in the former are the projections of the displacements in the latter, upon a straight line passing through the center of the system. In other words, to every case of simple circular orbital motion in two dimensions corresponds a case of simple harmonic vibration, its projection in a single dimension. Consequently, at time $t$, we have for the displacement in the case of simple vibration,

$$\xi = r\epsilon^{j\omega t} \qquad \text{cms.} \qquad (7)$$

measured along the initial line $OX$ by projection. The real part only of $\xi$ is retained, and the imaginary part ignored. Similarly, the vibratory velocity will be

$$v = \dot{\xi} = j\omega r\epsilon^{j\omega t} \qquad \text{cms./sec.} \qquad (8)$$

taking only the real part of the equation, or the projected value along $YOX$. Again, the vibratory acceleration will be

$$c = -\omega^2 r\epsilon^{j\omega t} \qquad \text{cms./sec.}^2 \qquad (9)$$

retaining only the real or projected part. Similar reasoning applies to the forces of elasticity and inertia. The same equations appear as in the circular orbit case; but only their real, or horizontally projected values, are retained. Consequently, we deduce that the vibration of a particle possessing elasticity and inertia without frictional retardation will be stable and self sustained under the condition

$$\omega = 2\pi n = \sqrt{A/m} = \sqrt{a} \qquad \text{radians/sec.} \quad (10)$$

where $n$ is the frequency of the vibration in cycles per second.

If, for example, the diaphragm of a telephone receiver had simple elasticity and inertia without frictional retardation, such that the elastic intensity $a = 26.87 \times 10^6$ dynes per cm. of displacement and per gramme mass, then any displacement released would be followed by an indefinitely sustained angular velocity

$$\omega = \sqrt{26.87 \times 10^6} = 5{,}184$$

radians per second, corresponding to $n = 825$ cycles per second. If the initial displacement were $r = 0.01$ cm., the corresponding simple circular orbit, Fig. 14, would have a radius of 0.01 cm., an angular velocity of 5,184 radians per second, an orbital velocity of 51.84 cm. per second, and an acceleration of 268,700 cm. per second. If the elastic force $A$ were $1.3435 \times 10^6$ dynes per cm. of displacement and the effective mass were 0.05 gm., the elastic force $OF$ would be 13,435 dynes, and the centrifugal force $Of$ 13,435 dynes, the two being equal and in complete opposition.

*Case of Free Vibration Damped and Unreinforced. Spiral Orbital Motion.*—In the case of the particle moving about a center, let the motion be retarded by a force $f'$, proportional to the velocity, defined by the relation

$$f' = -\Gamma v = -2m\gamma v \qquad \text{dynes} \angle \quad (11)$$

Then the orbital displacement at any time $t$ becomes

$$\xi = r\epsilon^{(-\gamma + j\omega)t} \qquad \text{cms.} \angle \quad (12)$$

The orbital velocity is

$$v = \dot{\xi} = r(-\gamma + j\omega)\epsilon^{(-\gamma + j\omega)t} \qquad \text{cms./sec.} \angle \quad (13)$$

The orbital acceleration is

$$c = \dot{v} = \ddot{\xi} = r(-\gamma + j\omega)^2\epsilon^{(-\gamma + j\omega)t} \qquad \text{cms./sec.}^2 \angle \quad (14)$$

Each of the above equations defines an equiangular spiral, an inwardly directed spiral in which the curve makes a constant direction $-\gamma + j\omega$ with the radius vector.

The vector diagram for this case is indicated in Fig. 15. Let

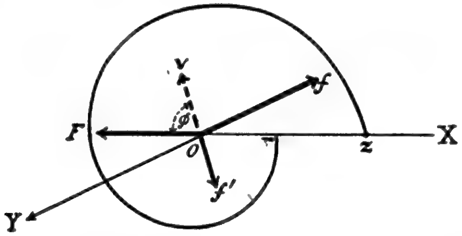

FIG. 15. Vector Diagram of Free Damped Vibration.

$z$ be the position of the particle at any instant. The velocity at this instant will have the vector $OV$, parallel to the tangent at $z$, where

$$\tan \phi = \omega/\gamma \qquad (15)$$

The acceleration at the same instant will be directed along $OY$, the angles $XOV$ and $VOY$ being each equal to the supplement of $\phi$. The virtual force of inertia will be directed along $Of$. The retarding force, opposing the velocity, will be directed along $Of'$. At any instant the vector sum of the three forces of elasticity, retardation and inertia must be zero. That is,

$$OF + Of' + Of = 0 \qquad \text{dynes } \angle$$

or

$$-mar\epsilon^{(-\gamma+j\omega)t} - 2\gamma mr(-\gamma + j\omega)\epsilon^{(-\gamma+j\omega)t}$$
$$-mr(-\gamma + j\omega)^2\epsilon^{(-\gamma+j\omega)t} = 0 \qquad \text{dynes } \angle$$

whence

$$\omega = \sqrt{a - \gamma^2} = \sqrt{\omega_0^2 - \gamma^2} = \omega_0 \sin \phi \qquad \text{radians/sec.} \quad (16)$$

where $\omega_0$ is the unretarded angular velocity. That is, the angular velocity of orbital rotation has been reduced by the retardation in the ratio of $\sin \phi$, Fig. 15, and the displacement or radius vector $r$ continually dwindles with time by $\epsilon^{-\gamma t}$.

In the corresponding case of free damped vibration, the above equations apply; but their real parts only are taken. In Fig. 15, the projections of the vectors on a straight line through $O$, are selected. The dwindling vibrations of a tuning fork, or the oscillatory discharge of a condenser through a circuit containing resistance and inductance, obey this law. In the last named case, the inductance corresponds to the mass $m$, the reciprocal of the capacity corresponds to the elastic coefficient $A$, and the resistance corresponds to the velocity-resisting coefficient $\Gamma$. The condenser-charge, or electric quantity, corresponds to the vibratory displacement, the electric current to the vibratory velocity, the discharging electromotive force to the elastic force $OF$, the resistance e.m.f. to $Of'$, the e.m.f. of self-induction to $Of$, and the impedance of the discharging circuit to the vector $m\omega_0 \angle \phi$, or $\sqrt{MA} \angle \phi = \Gamma/2 + jm\omega$.

*Case of Retarded Free Vibration Reinforced. Restored Circular Orbit.*—In order to sustain stable orbital motion in a particle retarded with a force proportional to the velocity, it is necessary to supply energy continuously to the particle and to act upon it with a force equal but opposite to the velocity-resisting force. The orbit will then be restored from an inmoving spiral to a simple circle. The displacement, velocity and acceleration of the particle, Fig. 16, will then be severally expressed by equations (1), (2) and (3) applied to Fig. 14.

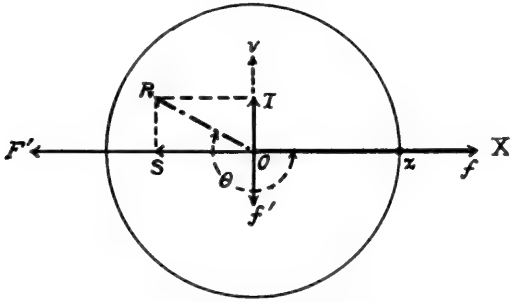

FIG. 16. Vector Diagram of Reinforced Vibration.

Let $OR$, Fig. 16, be an outwardly directed force from the center $O$, the magnitude of $OR$ being some function $m\chi(r)$ of the radius of displacement, and $\theta$ the phase retardation behind the displacement, reckoned positively in the direction indicated, or clockwise. The restoring force $OR \angle\theta$ may be analysed into two components $OT = OR \sin\theta$, and $OS = OR \cos\theta$ along the directions $OV$ and $OX$ respectively. The component $OT$ may be called the velocity component, or $T$ component, since it acts in the direction of the velocity $Ov$, and against the retarding force $Of'$. The component $Os$ may be called the $S$ component, or the new elastic component. It coacts with the elastic force $OF$ that resists displacement.

In order that the circular orbit may be retained, it is necessary and sufficient that the $T$ component of the restoring force shall equilibrate the velocity-resisting force $Of'$; or, if $R$ be the restoring force, that

$$R \sin\theta + f' = 0 \qquad \text{dynes}$$

If the $T$ component should be less than the velocity-resisting force, the system will lose energy. The orbit will spiral inwards until the velocity has been sufficiently diminished to equilibrate the $T$ component, and permit a stable circular orbit of reduced radius to be restored. If, on the contrary, the $T$ component exceeds the velocity-resisting force, the system will accumulate energy, and the orbit will spiral outwards until the radius and velocity of the motion are sufficient to restore equilibrium and permit a circular orbit of enlarged radius to be maintained.

In the condition of equilibrium represented in Fig. 16, we have four forces acting on the particle, forming two separate equilibrating pairs; namely, a pair along the displacement vector $Oz$, which we may call the displacement pair, and a pair perpendicular thereto, which we may call the velocity pair. Both these pairs rotate together at some uniform angular velocity $\omega$, which will in general differ from that which would hold for unretarded motion $\omega_0$, as in Fig. 14, or from that which would hold for retarded unreinforced motion, as in Fig. 15.

Considering the displacement pair, the first member is the elastic force $OF$, modified by the new elastic force $OS$, to $OF'$, Fig. 16. The new virtual force of inertia is $Of$. Consequently

$$OF' + Of = 0 \quad \text{dynes}$$

or

$$-mar\epsilon^{j\omega t} + m\chi(r)\ \cos\theta\ \epsilon^{j\omega t} + m\omega^2 r\epsilon^{j\omega t} = 0 \qquad \text{dynes } \angle$$

whence

$$\omega = \sqrt{a - \cos\theta \cdot \chi(r)/r} \qquad \text{radians/sec.} \quad (17)$$

Considering the velocity pair, the first member is

$$Of' = -\Gamma v = -2m\gamma v = -j2m\gamma\omega r\epsilon^{j\omega t} \qquad \text{dynes } \angle$$

The second member is the $T$ component:

$$OT = -jm\chi(r)\ \sin\theta \cdot \epsilon^{j\omega t} \qquad \text{dynes } \angle$$

For equilibrium

$$Of' + OT = 0$$

or

$$-j2m\gamma\omega r\epsilon^{j\omega t} - jm\chi(r)\ \sin\theta \cdot \epsilon^{j\omega t} = 0$$

From which

$$\chi(r)\ \sin\theta = -2r\gamma\omega \qquad \text{dynes} \qquad (18)$$

and

$$\omega = \sqrt{\omega_0^2 + \gamma^2 \cot^2\theta} + \gamma\cot\theta \qquad \text{radians/sec.} \quad (19)$$

It follows that $\omega$, the new angular velocity under reinforcement, is independent of the force function $R = m\chi(r)$, and depends only on the natural angular velocity $\omega_0$, the phase retardation $\theta$ of the restoring force and the magnitude of the damping coefficient $\gamma$. Some curves of $\omega$ as a function of $\theta$ for four particular values of $\Gamma$ between 50 and 500 dynes per cm. per sec.; *i. e.*, of $\gamma$ between 500 and 5,000 dynes per cm. per sec. and per gm., are given in Fig. 17. It may be seen that for all values of the damping, $\omega = \omega_0$ for $\theta = 270°$. That is, the angular velocity of reinforced motion is the same as that of unretarded motion when the restoring force is applied at 270° of phase lag, or exactly in phase with the velocity, as seen in Fig. 16. If the phase retardation $\theta$ is between 180° and 270°, the new angular velocity will be greater than the natural angular velocity $\omega_0$; but if $\theta$ is between 270° and 360°, must be less than $\omega_0$.

Applying the above principle to the corresponding case of reinforced vibration, by taking the projections or real parts of the rotating vectors, it follows that if any automatically reinforced vibrating system, such as an electromagnetic bell, electromagnetic tuning fork, or humming telephone, is propelled by an elastic force proportional to the displacement, reinforced by a cyclic force some function of the displacement, and damped by a force proportional to the velocity, it is subject to equations (17), (18) and (19) which appear to be new.

In the series of measurements on the humming telephone above

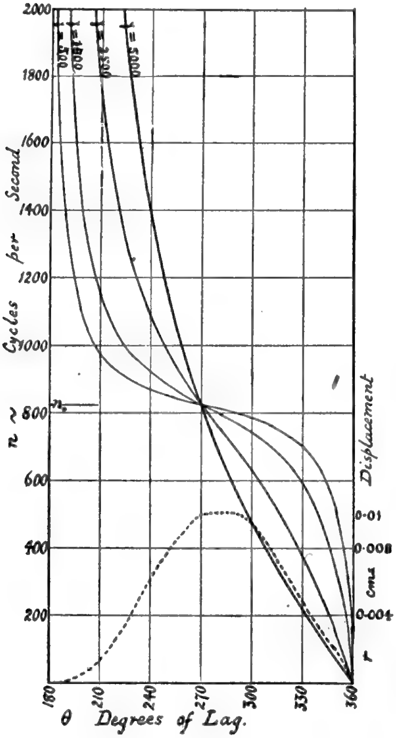

FIG. 17. Reinforced Frequency in Relation to the Phase of the Reinforcement.

outlined, the force function $R = m\chi(r)$ was not measured. The restoring electromagnetic force on the receiver diaphragm, due to the action of the transmitter, will manifestly diminish when the tube-length is increased. For a fixed tube-length, moreover, it cannot increase indefinitely in simple proportion to the displacement of the diaphragm, or to its amplitude of vibration. If we assume provisionally that $R$ increases as the square root of the amplitude of receiver-diaphragm vibration; so that for a fixed tube-length, $R = bm\sqrt{r}$; or $\chi(r) = b\sqrt{r}$; where $b$ is the numerical constant $1.036 \times 10^6$ dynes per gm. and per $\sqrt{\text{cm.}}$; then for the example already considered, if $\Gamma = 100$; or $\gamma = 1{,}000$, we find:

The displacement $r = 0.01$ cm. when $\theta = 270°$.

The reinforced angular velocity is $\omega = 5{,}184$ radians per second; $n = 825$ ~.

The maximum cyclic values of the vibratory—

velocity $v = 51.84$ cm. per sec.
acceleration $c = 268{,}740$ cm. per sec.$^2$
damping force $Of' = 5{,}184$ dynes.
restoring force $OT = 5{,}184$ dynes.
elastic force $OF' = 13{,}435$ dynes.
inertia force $Of = 13{,}435$ dynes.

As the phase $\theta$ of reinforcement changes from 180° to 360°, the line of $\gamma = 1{,}000$ in Fig. 17 shows the change in frequency; while the dotted line indicates the computed amplitude of vibration, which reaches a maximum near 280°.

According to the theory, therefore, if the phase of the displacement is 270° behind the displacement of the receiver diaphragm, the reinforced frequency coincides with the natural frequency. This condition is substantially borne out in all of the observations. For example, in Fig. 2, taking the pitch line No. 1, with a natural frequency of $n_0 = 825$ ~ and a sound-velocity in air of 33,000 cm. per sec., the wave-length $\lambda = 33{,}000/825 = 40$ cm. corresponding to 360° of phase. A lag of 270° would be represented by 30 cm.; so that we should expect the reinforced frequency to be 825 ~ at 30 cm. of tube-length, and at every 40 cm. beyond; *i. e.*, in accordance with the series $30 + 40m$, as was substantially observed. Moreover, by reversing the receiver terminals, the phase of the reinforcement is necessarily changed 180°; so that with this change of connection, 270° of phase lag would be altered to 90° of phase lag, or 10 cm. of tube-length. The natural frequency of 825 ~ should then occur in conformity with the series $10 + 40m$ cm., as was substantially observed.

When the phase retardation $\theta$ of the restoring force (Fig. 16) is less than 270°, we should expect, according to the theory, that the pitch should rise; because the elastic resilience of the diaphragm is virtually increased by the *OS* component of the new force, and when $\theta > 270°$, on the contrary, the pitch should fall. This was always the case in the observations. We have to bear in mind, however, that with any given tube-length, an alteration of pitch involves a change of wave-length, and therefore a change of phase in transmission through the air-column, besides any electrical change in phase due to change in current frequency. In Figs. 3, 4 and 6, the sloping dotted lines are drawn to indicate constant acoustic phase retardation of 270° for all of the frequencies within the range considered. Taking, for instance, Fig. 6, the break at *P* occurred 103° in phase from the dotted line of 270°, and the return at *S* occurred 77° in phase from the dotted line. According to the theory, assuming no electric change of phase, each of these angles should be something less than 90°, since the phase retardation must be something more than 180° on the side of increasing pitch. The discrepancy here is not serious; for the mean of the two angles is 90°. At *T* and *W*, however, the corresponding angles are 153° and 119°, with a mean of 136°, which should be something less than 90°, a greater divergence from the theory than observation errors can explain. While, therefore, the theory accounts for all of the experimental results in a general way, it can only be regarded as a first approximation. For example, it is possible that superposed harmonic currents might have to be considered; or that in estimating the damping forces, the inclusion of higher powers of the velocity than the first might be necessary.

Setting aside unexplained deviations, as the tube-length is shortened from a point of $\theta = 270°$, the phase retardation of the electromagnetic reinforcement on the receiver diaphragm is diminished. This causes the pitch to rise, and incidentally readjusts the phase change to a lower value than if the pitch were kept steady. The amplitude of vibration diminishes until the diaphragm suddenly selects a lower pitch for the same tube-length, to which the amplitude will be greater. In other words, the receiver diaphragm automatically seeks to maintain the greatest amplitude that the conditions of reinforcement will permit. If a lower tone, with a phase lag $\theta$ more than 270°, will give more amplitude than the higher note to which it has been driven, with $\theta$ less than 270°, it will break pitch downwards. This process will continue down to the first wave-length of tube, or 40 cm. in the case examined. For connection *I* of the receiver, it can break to no lower note after passing 270°, and the tone will rise to such a pitch that the amplitude becomes insufficient to excite the transmitter, so that silence should ensue at or near the length 12 cm., as actually observed in Fig. 3. The curve *I* of frequency between 12 and 50 cm. accords fairly well with the curve $\gamma = 1{,}000$ in Fig. 17.

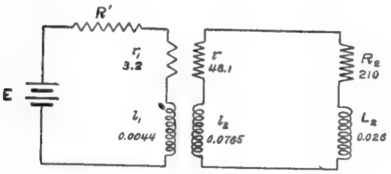

FIG. 18.

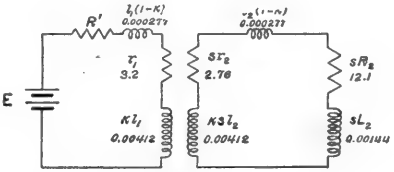

FIG. 19.

FIG. 18. Diagram of Electrical Connections with Step-up Induction Coil.
FIG. 19. Equivalent Diagram of Connections, with Level Induction Coil.

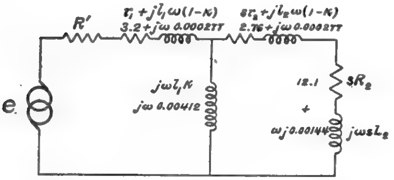

FIG. 20.

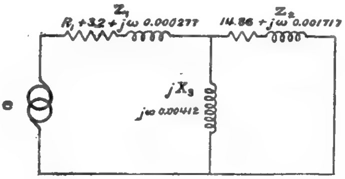

FIG. 21.

FIGS. 20 AND 21. Equivalent Conductive Connections with Level Induction Coil and Alternating E.M.F.

With reference to the influence of capacity in the secondary circuit, Figs. 18 to 21 show the successive steps by which the secondary circuit may be treated as a conductive branch of the primary circuit. Using the constants given in Table I., ignoring any capacity existing between the windings of the coils, and assuming that the effect of the transmitter in the primary circuit is equivalent to an alternating e.m.f. *e*, working through a transmitter resistance *R*, of 50 ohms, we find a coupling coefficient for the coil of $K = 0.937$, and an inductance ratio $S = 0.0575$ between primary and secondary windings. Proceeding in this way, the following table has been arrived at, giving the conductances which when multiplied by the equivalent transmitter e.m.f. yield the current strength in the secondary circuit of Fig. 21.

TABLE III.

| Frequency Cycles per Second. $n$. | Angular Velocity Radians per Second. $\omega$. | Capacity in Secondary Circuit. $\mu$f. | Conductance of Secondary. Mhos. |
|---|---|---|---|
| 637 | 4,000 | ∝ | 0.009 /23° |
| 796 | 5,000 | ∝ | 0.0087 /17° |
| 956 | 6,000 | ∝ | 0.0093 /12° |
| 637 | 4,000 | 0.2 | 0.0054 \140° |
| 796 | 5,000 | 0.2 | 0.0095 \123° |
| 956 | 6,000 | 0.2 | 0.11 \115° |

Although the assumptions employed do not anticipate a high degree of accuracy in the conclusions above tabulated, yet we may safely infer that when no condenser is used in the secondary circuit ($\mu$f. = ∝ ), the secondary current will lead the impressed primary e.m.f. by a small angle, and this current will have substantially the same strength and phase for all frequencies between 600 ~ and 1,000 ~. When, however, a condenser of 0.2 $\mu$f. is inserted in the secondary circuit, the current in the receiver will be advanced in phase about 110° or nearly a third of a cycle; while the strength of this current will be considerably greater at the higher frequencies than at the lower frequencies.

Since the total lag in phase of the restoring electromagnetic force behind the displacement of the receiver diaphragm includes (1) the electric current lag; (2) any hysteretic electromagnetic lag in the receiver cores; (3) any mechanical inertia lag of the transmitter diaphragm; (4) the acoustic lag in the air column of the tube; it follows that the total lag with a condenser of 0.2 $\mu$f. should be about 110° less than with short-circuited condenser; while the higher frequency notes should be favored, and the lower frequency notes disfavored. Fig. 9 shows that both these effects took place, the acoustic lag had to be increased by about 12 cm., or about 110°, in order to produce mean frequency, and compensate for the current lead.

Also the range of frequency is moved bodily towards higher notes.

All of the experimental series of observations appear to be accounted for and explained by the above theory to a first approximation; although in matters of quantitative detail there remains much room for further development.

In conclusion, the authors desire to express their indebtedness to the Western Electric Co. for the loan of apparatus used in the tests.

# ON THE AFTER-IMAGES OF SUBLIMINALLY COLORED STIMULI.

By EDWARD BRADFORD TITCHENER and WILLIAM HENRY PYLE.

(*Received July 23, 1908.*)

We attempt, in the present paper, to answer the question whether a subliminally colored stimulus may arouse a colored, negative or complementary after-image. This question has been answered in the affirmative both for direct and for indirect vision, and in indirect vision for all three of the retinal zones. Our own experiments, on the other hand, have led us to answer it in the negative. Provided that the subliminally colored stimulus appears on a neutral (black, gray or white) background, and provided that the retina is achromatically adapted, we find no trace of the colored after-image in either direct or indirect vision, with either light or dark adaptation.

## PREVIOUS EXPERIMENTS.

1. *Direct Vision.*—In a paper entitled *Das Anpassungsproblem in der Physiologie der Gegenwart* (1904), A. Tschermak compares the course of excitation in the retina with the effects produced by the constant current in a nerve-muscle preparation. The passage is as follows:

> " Haben wir doch gerade in der Anwendung des constanten Stromes auf Nerv und Muskel ein vorzügliches didaktisches Mittel, um die Grundbegriffe der allgemeinen Reiz- und Adaptationslehre zu veranschaulichen und einzuprägen. Am besten demonstrieren wir als Gegenstück zugleich die Wirkung eines mässig satten Farbglases auf das Auge: die Phase der Reizwirkung, individuell verschieden lang, und dadurch erinnernd an die verschiedenrasche Adaptation des Praeparates vom Warmfrosch und Kaltfrosch an den constanten Strom — weiterhin das Stadium der vollendeten Adaptation, endlich den gegensinnigen Oeffnungseffect. Nicht minder lehrreich ist die Parallele des subjectiven und des objectiven Erscheinungsgebietes für das Phaenomen des Einschleichens d. h. des Ausbleibens einer sinnfälligen Reizwirkung, wenn der Reiz so langsam anwächst, dass das Adaptationsvermögen folgen kann — gleichwohl hat auch nunmehr Wegfall

des 'Reizes' eine gegensinnige Oeffnungswirkung. Analoges gilt vom Ausschleichen, also vom Ausbleiben eines sinnfälligen Oeffnungseffectes. Zum optischen Versuche schiebt man zweckmässig eine schwach tingierte Glasplatte vor die andere oder benützt einen Keil farbigen Glases."[1]

The observation here briefly mentioned was apparently made in light-adaptation. The observer, we may suppose, looked through a vertical slit in a cardboard screen towards a window. The thin end of the colored glass wedge, viewed through the slit, appeared colorless. The wedge itself was slowly pushed forward — so slowly that progressive adaptation prevented its color from being perceived. Presently the observer turned his eye to the cardboard screen, and there saw the negative colored after-image, the "gegensinnige Oeffnungswirkung" that followed the "Einschleichen des Reizes."[2]

2. *Indirect Vision.*—In the Studies from the Psychological Laboratory of Mount Holyoke College for 1905, Miss G. M. Fernald reports the arousal of colored after-images in the peripheral or black-white zone of the retina. "A further point worth mentioning"—so the passage runs—"is the fact that, in the case of several colors, exposure, beyond the limits where any color is seen, is followed by a very clear [colored] after-image. This was repeatedly found to be true with red, orange, green and blue and often with yellow [stimuli]. This after-image for the first three and for yellow was blue, and for blue a very clear yellow. This may explain the 'gegenfarbige' zone found by Hellpach in his dark-room work, as under those conditions there would have been no way of telling whether the color came exactly at the time of exposure or immediately afterwards."[3] No further details are given.

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[1] *Archives des sciences biologiques,* XI., Supplément (*Festschrift* for Professor J. P. Pavloff), 82 f.

[2] The procedure is sketched by H. Abels, *Zeits. f. Psychol.,* XLV., 1907, 86. "Man kann . . . einen schwach gefärbten Glaskeil so langsam vor das Auge schieben, von der Kante gegen den Rücken fortschreitend, dass überhaupt keine Farbenempfindung zustande kommt; und dennoch haben wir bei plötzlichem Entfernen desselben und Betrachten einer indifferent gefärbten Fläche die deutliche Empfindung der komplementären Farbe." Abels is here quoting a conversation with Tschermak; there is no evidence that he himself performed the experiment.

[3] "The Effect of the Brightness of Background on the Extent of the Color Fields and on the Color Tone in Peripheral Vision," *Psychol. Review,* XII., November, 1905, 405.

These observations would, no doubt, have been repeated, and their interpretation discussed by other experimenters, had not Baird published, earlier in the same year, his study of the color sensitivity of the peripheral retina. "There seems to be no doubt," Baird had written, "that Hellpach's zone of complementariness is an artifact, and that its discovery is wholly due to the experimenter's failure to avoid retinal fatigue [chromatic adaptation] in his explorations."[4] Nevertheless, one of the present writers (*T*) made in 1906 a fairly long series of campimetrical observations (some 200 in all) with the view of testing Miss Fernald's conclusion. The colored stimuli were Hering papers, R, Y, G and B; the backgrounds were white, neutral gray and black. In no case was "exposure, beyond the limits where any color is seen," followed by a colored after-image, clear or obscure. All four colors, if they gave an after-image at all, gave a colorless image, indistinguishable from the after-images of gray stimuli—as these gray stimuli themselves were indistinguishable from the colored papers. It therefore seemed probable—indeed, it seemed practically certain—that the Mount Holyoke results were due to a defect of method. Since Baird's disproof of the "gegenfarbige Zone" was deemed complete and final, the Cornell observations were not published.

However, in the following year, 1907, a second paper from the Mount Holyoke laboratory reported the same phenomenon. "At the extreme periphery it sometimes happened: (*a*) that a stimulus which was clearly seen produced no after-image. . . . (*b*) On the other hand there were 118 cases in which a subliminal stimulus produced an after-image which was perfectly distinct in color. . . . That this somewhat unusual result was not the outcome of imagination or suggestion seems proved by the fact that these invisible colors gave rise to their appropriate after-images."[5] The authors, the Misses H. B. Thompson and K. Gordon, found no indication of Hellpach's zone of complementarism. They refer the images to the enhancing influence of a light background.

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[4] J. W. Baird, "The Color Sensitivity of the Peripheral Retina," Carnegie Institution of Washington, Publication No. 29, May, 1905, 73.

[5] "A Study of After-Images on the Peripheral Retina," *Psychol. Review*, XIV., March, 1907, 126 f., 129 f.

Again, in 1908, in a continuation of her former study, Miss Fernald writes: "In agreement with the observations already made in our first paper, and later in the work of Miss Thompson and Miss Gordon, our results show that in many cases a characteristic colored after-image follows an unperceived color stimulus. In general this after-image is perfectly clear and distinct. . . . That the phenomena here described are genuine after-images is shown by the fact that the color is in every case the color complementary to the stimulus as [it would be] perceived either in central or in peripheral vision, although the observer was kept in complete ignorance concerning the nature of the stimuli employed, and so had no clew as to what after-image was to be expected in cases in which the [color of the] stimulus was not seen. Moreover, gray and white, though frequently used as stimuli, were never followed by colored after-images."[6] Hellpach here drops out of sight altogether, while the range of the subliminally aroused after-image is extended, from "the extreme periphery," to include both the B–Y and the R–G zones.

## New Experiments.

### I. *Direct Vision: (a) Light-Adaptation.*

*Experiment I.: The Glass Wedge.*—We wished to begin our own experiments by repeating Tschermak's observation with the faintly colored glass wedge. However, the difficulty of finding a suitable glass proved to be so great that this Exp. I. was, as a matter of fact, performed last of all. After many delays we were able, through the kind assistance of Professor J. A. Brashear, to secure a wedge of light blue glass, 5 by 20.5 cm., the thin end of which was almost colorless in clear daylight. Although the color might well have been still fainter, we found it possible, with an observation-slit of 22 by 5 mm., and with a white muslin screen stretched between the glass wedge and the white-screened windows from which our illumination was derived, to take observations of 2 to 5 min. duration, in which the wedge was moved, for the practised observers, from 1.5 to 4 cm., and for the unpractised from 5 to 10 cm.

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[6] "Studies from the Bryn Mawr College Laboratory: The Effect of the Brightness of Background on the Appearance of Color Stimuli in Peripheral Vision," *Psychol. Review,* XV., January, 1908, 33 ff.

We made no long series of tests, since the question at issue had already been answered, so far as we could answer it, by the following Exps. II.–V. The experiments were, however, carefully conducted. The work was done in a long gray-tinted light-optics room, with achromatic adaptation; the observers were the writers (*T, P*), Mr. L. R. Geissler (*G*), assistant in psychology, and two unpractised students, Mrs. G. L. de Ollogni and Mr. E. M. Stevens; and the experimenter had acquired great skill, from Exps. II. and IV., in moving the wedge slowly and steadily forward. In general, the stimulus-background was black, and the field for the projection of the after-image was white, though these relations were occasionally changed.

As we had expected, there was no trace of color in the after-image; this result was uniform. In control experiments, in which (after a period for the recovery of the eye) the glass was exposed for 30 sec. at the point finally reached in the adaptation experiments, the after-image showed a brief period of dirty orange or brownish yellow, followed by gray.

*Experiment II.: The Marbe Color Mixer.*—The observations with Tschermak's wedge could not, in any case, be regarded as more than preliminary. For systematic work we employed, first, the Marbe color mixer, which permits the change of a colored sector during rotation of its discs, and thus gives scope for progressive adaptation.

The observer, head in rest, was seated at a distance of 1 m. from a black cardboard screen. The rotating discs were observed through a circular opening, 2 cm. in diameter, cut in the screen at the level of the eyes. The observation was monocular, and was continued for 5 to 7 min. The discs were made up of white, with a sector of colored paper (Zimmermann R, Y, G, B, V); the color at the outset was subliminal for the achromatically light-adapted eye, and was gradually increased in amount as the observation proceeded. The after-image was projected upon a fixation-point marked on a white cardboard dropped in front of the black screen.[1]

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[1] For comparative purposes, a few observations were taken with a gray screen, and with projection upon a black or gray background. Nothing new resulted.

The regular observers were *T, P, G,* and Mr. T. Nakashima, graduate scholar in psychology (*N*). A few observations were secured from Professor I. M. Bentley (*B*), and from an unpractised observer, Mr. H. J. Bool; single observations were made by several visitors to the laboratory.

In intention, the procedure was without knowledge. In practice, the experimenter found it impossible, in the early stages of the work, to regulate the size of the colored sector in precise accordance with the course of adaptation. The observer was therefore instructed to tap on the table with a pencil whenever he perceived a color in the stimulus. If a tap was given, the experimenter ran the colored sector back through five or ten degrees, and continued the experiment from that point. The results of these interrupted observations varied, according to the frequency of the taps and the insistence of the color in the stimulus. The following are typical records.

*A. No Color Seen in Stimulus.*

| Observer. | Color in Disc. | After-image. | Duration of Obs. |
|---|---|---|---|
| *T* | 205° B | Gray | 7 min. |
| | 180° V | Gray | 6 min. |
| *P* | 120° G | Gray | 5 min. |
| | 140° V | Gray | 5 min. 15 sec. |
| *G* | 135° R | Gray | 6 min. |
| *B* | 190° B | Gray | 6 min. |

After a period for recovery, the stimuli were exposed at their final color-strength for 30 sec., and the after-image was projected as before. The results, in the above instances, were as follows:

| Observer. | Color Seen. | After-image. |
|---|---|---|
| *T* | Blue | Brownish yellow |
| | Bluish violet | Dirty olive yellow |
| *P* | Green | Pink |
| | Bluish violet | Dingy yellow |
| *G* | Red | Gray |
| *B* | Blue | Clear yellow |

*B. Color Seen in Stimulus.*

| Observer. | Color in Disc. | After-image. | Duration of Obs. |
|---|---|---|---|
| *T* | 140° G | Gray | 5 min. |
| *G* | 120° Y | Dark blue | 5 min. |
| | 220° B | ? Orangish | 7 min. |
| *N* | 155° R | Gray | 7 min. |
| | 130° Y | Blue | 6 min. |

The control experiments, with 30 sec. exposure, gave the results:

| Observer. | Color Seen. | After image. |
|---|---|---|
| *T* | Green | Purple |
| *G* | Yellow | Dark blue |
| | Blue | Yellow |
| *N* | Pink | ? Violet |
| | Yellow | Blue |

The general results of these experiments may be summed up in the following propositions.

1. With every one of our observers, regular and casual, we have been able to raise a color-component in the stimulus from a subliminal to a normally supraliminal value, while the stimulus appeared throughout as gray. In no instance of this kind has the observer found the complementary color in the after-image. Our results thus stand in direct opposition to the observation of Tschermak.

2. There are, however, marked individual differences among the observers. In the 7 min. which represented the limit of our observations, it was difficult, with *G* and *N*, to increase the color-component, without detection, to a normally supraliminal amount: with *T*, *P* and *B* there was no such difficulty. The control images, on the other hand, were obtained most readily from *T* and *P*.

The observer *N* is of the subjective type, and is often misled by an "expected" or "imagined" color. Thus a disc containing 175° G was seen as B with a rim of Y; the after-image, after 6 min., was a Y of irregular form, larger than the stimulus. We recur to these "imagined" colors later. The remaining observers were of a distinctly objective type.

3. There were also, as might be expected, marked differences in the "coloring power" of the Zimmermann papers. Experiments of the form *A* were easiest with B, less easy with V; then follow in order R, G, Y. The last-mentioned color, indeed, gave results only with entirely naive and unpractised observers. The R and G, when seen as color, usually appeared first as Y.

4. As a rule, the after-images, whether colored or gray, developed very slowly. The gray images, in particular, might appear only after a blank interval of 15 to 30 sec. They usually showed

two stages, dark and light. The colored images, both of the regular and of the control experiments, passed off as gray.

*Experiment III.: The Color Mixer with Unchanged Discs.*—So far we have followed and systematised Tschermak's method; the amount of color in the stimulus has increased, during the single observation, and has been compensated by a progressive adaptation. In the present experiments the amount of color in the discs is increased from subliminal to normally supraliminal, step by step, in successive observations.

The rotating discs were observed, as before, through a circular opening in a black or neutral gray screen. The discs themselves were made up of neutral gray (identical with that of the screen), with a colored sector (Hering R, Y, G, B). The stimulus was fixated for 1 min., and the after-image was projected upon a neutral gray or black background. *P, G* and *N* served as regular observers: a few observations were also taken from *B* and *T*. The following are typical results.

| Observer. | Color in Disc. | Color Seen. | Color in After-image. |
|---|---|---|---|
| *G* | 4° G | None | None |
| | 10° G | Green | None |
| | 14° G | Green | Pinkish |
| *N* | 9° B | None | None |
| | 12° B | None | None |
| | 20° B | ? Pinkish | None |
| | 50° B | Blue | Yellow |
| *P* | 6° R | ? Ruddy | None |
| | 10° R | Red | None |
| | 30° R | Red | Green |
| *T* | 6° Y | None | None |
| | 12° Y | ? Yellowish | None |
| | 20° Y | Yellow | Dark blue |

In the above observations, the black screen and the neutral gray background were employed. Other arrangements of screen and background gave similar results.

In no case was a colored after-image obtained from a subliminally colored stimulus. On the contrary, the image appeared only when the stimulus-color was distinctly supraliminal.

### (*b*) *Dark-Adaptation.*

*Experiment IV.: The Glass Wedge.*—Besides furnishing the light blue wedge of Exp. I., Professor Brashear supplied us with smaller and more highly colored wedges of claret, red, orange, green and blue glass. With these, or with combinations of them, we proceeded as follows.

A sheet of ground glass was inserted in the Hering window of a large dark-room: the width of the strip could be regulated at will. Some 2.50 m. before the window was a table, on which stood a large screen of white cardboard. Immediately behind a vertical slit in this screen (3 by 25 mm.) lay a grooved strip of wood, in which the wedge or wedges could be moved. Observations were made in dark-adaptation. The thick end of the wedge was first shown; it appeared as black or as dark gray. The wedge was then moved along, very slowly: if the observer saw its color, he tapped with a pencil, and the experimenter withdrew it a trifle, to start again after a few seconds. At a given signal, the observer looked away from the slit to the cardboard screen, or to a black surface directly below the screen, and watched the development of the after-image. The regular observers were *T, P, G* and *N;* a few observations were also made by *B.*

Owing to the difficulty of procuring the large glass wedge of Exp. I., these dark-room observations were the first taken. And, in our desire to do justice to Tschermak's method, we spent more time and trouble upon them than we like to recall. The observer's head was fixed securely in a head-rest; the height of the screen was carefully adjusted; generous time was allowed for adaptation; the admission of light was rigorously controlled, beforehand, by the experimenter; the uniform movement of the wedge was assiduously practised. We were rewarded, however, by the unequivocal character of the results. Though observation might be continued for 5 min.; though during this period the observer might tap his glimpse of color no less than seven times; and though in the control experiments, with immediate observation of the part of the wedge finally exposed, a good complementary after-image might be obtained in

20 sec.: we did not once, in the course of the principal experiments, obtain a record of color in the after-image. Sometimes the after-image failed to appear at all; more often it appeared, and obstinately remained, as gray.

The duration of a single observation varied between the limits of 2 min. 30 sec. and 5 min.; most of the exposures were about 3 min. The number of taps varied from 0 to 7; the average for all observers was 4. The color was thus much more insistent than in Exp. II. — partly, no doubt, because the range of possible movement was only about one-third of that allowed by the Marbe mixer. In the control experiments, *T* and *P* obtained the colored after-image fairly easily; *G, N* and *B* often failed to secure it.

*Experiment V.: Colored Papers.*—These observations were also made in the dark-room and with dark-adaptation. A number of Milton-Bradley colored papers, 4 by 8 cm., were pasted upon white, neutral gray and black grounds. The Hering window was so adjusted that, for the experimenter, the color of the particular paper exposed was just subliminal. The observers (*T, P, G, N* and occasionally *B*) fixated the colored strip at a distance of 1 m. for 40 sec., and projected the after-image upon a white, neutral gray or black surface. All possible combinations of stimulus-ground and projection-ground were employed.

The observer was instructed to report the quality of the stimulus as it appeared at first fixation, and to mention any qualitative change that it might undergo in the course of an observation. In most cases the color was subliminal; and the subliminally colored stimulus never gave a colored after-image. In the cases in which the color of the strip was seen, the after-image was sometimes colored, sometimes gray.

The direct judgment of color under these conditions is extremely difficult, and the observer is sorely tempted to avail himself of secondary criteria—brightness, velvetiness, depth, shimmer, etc. An observer of the objective type soon learns, however, to distinguish between vision and imagination: "I can see nothing," he will say, "but I should guess that it is red" or what not. The guesses were confined—probably from the analogy of the immediately preceding Exp. III.—to the four colors R, Y, G, B; and, as we had the full set of Milton-Bradley papers at our disposal, they were more often wrong than right.[8] Their influence upon the after-image appeared only in the case of the subjective observer *N*. Thus, R seen on W was judged by *N* to be "red or blue"; and the after-image, also on W, was a large irregular disc of yellow. R seen on Bk was judged to be "bluish"; and the after-image, on gray, was green-blue with a vague yellow rim. B seen on W was judged "blue or red"; and the after-image, on gray, was red above and blue below, with a yellow patch between. It is noteworthy that here, as in Exp. II., after-images of the "supposed" or "imagined" color invariably differed in form and size from those of the true color. The observer did not realise the significance of this difference, though in time he would doubtless have learned to use it as a secondary criterion.

## II. *Indirect Vision.*

We have already mentioned the experiments made by *T* in 1906 with the view of testing the conclusions of Miss Fernald's first paper. The observations were rigorously confined to the Bk–W zone, and their outcome was definitely negative. In the meantime, however, the arousal of a colored after-image by a subliminally colored stimulus had been maintained for both the B–Y and the R–G zones. Unsystematic observations made in the Cornell Laboratory failed to confirm this result. It seemed worth while, however, to obtain further testimony; and Professor J. W. Baird, of the University of Illinois, very kindly consented to investigate the subject.[9]

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[8] One of the observers remarked that the experiments showed—what he had never fully understood before—how it is that a case of partial color-blindness may remain undetected both by the color-blind person himself and by the normal persons in his surroundings. In principle, the remark was correct enough; but in practice the observer would have had to revise and extend his criteria very considerably.

[9] All the observations in indirect vision mentioned in this paper were carried out with light-adaptation. Peripheral after-images in dark-adaptation are practically non-existent. In *op. cit.*, 56 f., Baird writes: "After-images—in the ordinary sense of the term—were almost invariably absent from our experiments. They were reported in less than one per cent. of our exposures; and when they did occur, they were aroused by the stimulation of paracentral, never of peripheral, regions of the retina." And in a personal letter he adds: "There is an interesting difference of function in

The experiments were carried out by means of a simplified form of the Zimmermann perimeter, which permitted an accurate record of the degree of eccentricity at which the stimulus was exposed. Exploration was confined to the horizontal nasal meridian of each eye. The stimulus was a beam of light from an electric (16 c. p.) lamp, transmitted through appropriate combinations of gelatines and colored glasses; the colors employed were (non-equated) B and Y, R and G. Six of the most reliable laboratory students[10] acted as observers, and Professor Baird had personal charge of the entire work. The after-images were projected upon white, gray and black grounds. The experiments proper were preceded by a careful determination of the outermost limits of color vision for the stimuli used, and all pains were taken to avoid chromatic adaptation.

The following may serve as a sample of method and results.

*Determination of Outermost Limits of Blue Vision: Observer Bu.*
*Right Eye.*

| Preliminary. | | Series 1. | |
|---|---|---|---|
| 90°–75° | Nothing | 72°–58° | Black |
| 70°–55° | Dark gray | 56°–50° | Bluish |
| 50°–45° | Bluish | 48°– | Blue |
| 40°– | Blue | | |

| Series 2. | | Series 3. | |
|---|---|---|---|
| 75°–63° | Black | 73°–61° | Very dark gray |
| 61°–53° | Bluish | 59°– | Bluish |
| 51°– | Blue | | |

Outermost limit (bluish or blue): 61°.

*Left Eye.*[11]

| | | | |
|---|---|---|---|
| 90°–65° | Nothing | 62°–50° | Black |
| 60°–40° | Dark gray | 48°–44° | Bluish |
| 35°– | Bluish to blue | 42°– | Blue |

| | | | |
|---|---|---|---|
| 60°–48° | Black | 58°–44° | Black |
| 46°– | Bluish | 42°– | Bluish |

Outermost limit (bluish or blue): 48°.

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the peripheral retina in light-adaptation and in dark-adaptation. In the latter case, after-images—both uncolored and colored—are faint or wholly lacking. In the former case they are readily perceptible. Yet even in light-adaptation they are less perceptible than are the primary images aroused by the given stimuli."

[10] The Misses M. Miller, A.B., and B. Scoggin: and Messrs. C. B. Busey, A.B., R. Garrett, O. L. Herndon and A. C. Schertz, A.B.

[11] The visual acuity of the left eye was less than that of the right.

*Perimetrical Experiments.*

| Stimulus. | Duration. | Perception. | After-image. |
|---|---|---|---|
| 90° Right | 30 sec. | Nothing | None |
| 90° Left | 30 sec. | Nothing | None |
| 80° Right | 30 sec. | Nothing | None |
| 80° Left | 30 sec. | Nothing | None |
| 70° Right | 40 sec. | Dark gray | None |
| 70° Left | 40 sec. | Nothing | None |
| 60° Right | 40 sec. | Bluish, then black | None |
| 60° Left | 40 sec. | Gray | None |
| 50° Right | 40 sec. | Dark bluish, then gray | Yellowish, then gray |
| 50° Left | 40 sec. | Trace of bluish, then gray | Gray |

It does not seem necessary to print the full set of results, though the data are at the disposal of anyone who may wish to consult them. The net outcome of the enquiry, in Professor Baird's words, is as follows: "In not a single instance did any stimulus give a colored after-image at a retinal region where it gave an uncolored image," *i. e.*, where it was seen as black or gray. He proceeds: "I have tried every variation of the conditions (with exclusion of chromatic adaptation) which my ingenuity could devise; and the result is in every instance negative, so far as the contention of the Misses Fernald, Thompson and Gordon is concerned."

## CRITICISM AND INTERPRETATION.

1. The positive outcome of Tschermak's observations with the glass wedge must, in our opinion, be explained by the prepossession of the observer and the roughness of the method employed. Had Tschermak been in doubt as regards the after-image, he would have had recourse to a more refined instrument, as the Marbe color-mixer. And had he adopted a better method, we cannot doubt, on our side, that the outcome of his observations would have been negative. We may, perhaps, venture to express the hope that he will now submit his hypothesis to a stricter test.

2. It is less easy to account for the peripheral results. The *experimentum crucis,* in positive regard, would seem to be the production of a colored after-image, in the achromatically adapted eye, at a point lying well beyond the limits of B–Y vision. It must be remembered that in all liminal determinations an unnoticed variation in physical or physiological conditions, or in the conditions of

attention, may lead to a serious variation of numerical result. It is, for instance, exceedingly doubtful if any but the most careful and most highly practised observers can maintain their fixation so accurately as to ensure a precise localisation of the retinal area affected by a given stimulus. Moreover, we are here dealing with a retinal function which tails off gradually from center to periphery: so that a very slight shift of regard, or a momentary lapse of attention, or a minimal change in adaptation or in illumination may be enough to vitiate an observation. An illustration may be taken from the records of the observer *Bu.*, quoted above. The outermost limit of B-vision, in the left eye, was determined as 48°. Nevertheless, the observer reported, in the experiments proper, a "trace of bluish, then gray" with the stimulus at 50°. There was no colored after-image. But suppose a tinge of blue-adaptation: then we might have had a perception of gray, and a yellow after-image; and we should still have been, apparently, beyond the limit of B–Y vision. It was only the care taken to avoid chromatic adaptation that prevented the positive result.

It is, of course, precisely this crucial experiment which is described affirmatively by Miss Fernald in 1905,[12] and which came out negatively in *T*'s experiments of 1906. The question then arises as to the accuracy of determination of the zonal limits. And on this point we may quote specimen results from Miss Fernald's tables.

1. R stimulus on light gray background.[13]

| | |
|---|---|
| 10°–73° | Stimulus uniformly seen as red. |
| 74.5° | *No color seen.* |
| 76° | Red seen in two observations. |
| 80° | Red seen in four, no color seen in two observations. |
| 82.5° | No color seen. |
| 84° | No color seen. |

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[12] We follow the phrasing of the *Psychol. Review* of 1905: "Exposure, beyond the limits where any color is seen, is followed by a very clear after-image." In the *Journ. Philos., Psychol. & Sci. Meth.*, iii., 1906, 352 (Report of Sec. of N. Y. Acad. of Sciences), the report reads: "After-images were perceived, almost without exception, as far out as any color could be distinguished, and in many cases were clearly seen though the stimulus color was not recognised."

[13] *Psychol. Review,* XII., 408. Italics ours.

85.5° Red seen once, no color seen once.
87° *Red seen twice,* no color seen twice.

The conditions can hardly have remained constant from 74.5° to 87°. Again, R on Hering gray no. 7 is seen colorless at 37°, while it is seen red at 39°, 41.5° (twice), and even at 47° (twice).[14] And yet again, G on the same gray is seen colorless at 82°, green at 84°, and once colorless and once green at 87°.[15] Instances of this irregularity might easily be multiplied.

2. If we turn to the special table for the limits of B and Y, we find a greater uniformity of result, but a certain arbitrariness in the selection of the limiting values. Thus, on various backgrounds and for different observers, the limits for Y are taken as

(*a*) 97°, although at 98.5° the color is seen 3 times out of 14,
(*b*) 88.5°, although at 92.5° the color is seen once in 3 times,
(*c*) 95.5°, although at 98.5° the color is seen once in 3 times,
(*d*) 92.5°, although at 95.5° the color is seen 3 times out of 10,

and so on. Similarly, the limits for B are taken as

(*a*) 88.5°, although at 91.5° the color is seen once in 4 times,
(*b*) 97°, although at 99.5° the color is seen once, and one observation is doubtful,
(*c*) 97°, although at 99.5° the color is seen 3 times out of 9, with one observation doubtful,

and so on.[16]

Now in her second paper, of 1908, Miss Fernald states that the paradoxical after-images "are perceived most frequently either just inside or just beyond the regular limits for the color."[17] If this statement may be applied to the limits of color vision at large, *i. e.*, to the work of 1905, we must conclude that the crucial experiment has not been adequately performed; for the limits given are, as we have seen, irregular and arbitrary.

Each, however, if we maintain that *T*'s results are conclusive for the Bk–W zone, we have still to account for the colored after-images of subliminally colored stimuli in the B–Y and R–G zones.[18] Miss

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[14] *Ibid.*, 422.

[15] *Ibid.*, 416.

[16] *Ibid.*, 402.

[17] *Psychol. Review*, XV., 33.

[18] Miss Fernald uses the term "unperceived," not subliminal. The latter word is, however, employed by the Misses Thompson and Gordon, whose results Miss Fernald assimilates to her own. That "unperceived" really means "imperceptible" is shown also by a passage in a letter received from Miss Fernald: "I should be very much afraid of my observer's life, if it depended on his identification of the stimulus color, in all cases in which a clearly colored after-image is seen. In fact, when forced to say what stimulus he thought was used, he guessed at B for O as often as O for O, insisting all the while that he did not see any color."

Fernald has been good enough to send us an account of the conditions under which her observers found the after-image, and to make a special series of observations, with Mr. C. E. Ferree as observer. "The head," she says, "must be held firm (my method is the bit, with the impression of the teeth). The background must be light, and the illumination good. The observer must hold the fixation steadily after the stimulus is removed. The after-image screen must be white to obtain Y or B after-images and black to obtain R after-images. A very slight change in conditions makes a great difference in results, which seem to me to depend wholly on brightness." Professor Baird was acquainted with these conditions before he undertook his perimetrical observations.

The new set of observations is as follows.

*Observer:* C. E. Ferree. Full illumination on bright day (May 17, 1908). Nasal meridian, right. White ground. Projection field white, except in obs. 14–17, when it was black. Stimulus, 13 sq. mm. Distance from eye to stimulus, 25 cm.

| Fixation Point. | Stimulus. | Color Seen. | After-image. |
|---|---|---|---|
| 80° | O | Dark gray | Unsaturated light blue |
| 85° | B | Just dark | Wash of unsaturated yellow |
| 85° | Y | Nothing | Nothing |
| 80° | Y | Tinge of dirty yellow | Very pale blue |
| 80° | Medium gray | Dark | White |
| 80° | O | Indefinite gray | Nothing |
| 80° | Light gray | Dark | White |
| 75° | Y | Reddish yellow | Good blue |
| 75° | B | Good blue | Good yellow |
| 75° | B | Good blue | Good yellow |
| 65° | O | Yellowish red | Unsaturated blue |
| 65° | Y | Reddish yellow | Blue |
| 60° | G | Indefinite greenish gray | Uncertain |
| 65° | G | Greenish yellow | Dark red, more saturated than stimulus |
| 80° | Medium gray | Dark | Nothing |
| 80° | Medium gray | Dark | Nothing |
| 65° | G | No color | Flash of red |
| 65° | R | No color | Blue |

Positive results occur in the two first and two last observations of the series. The former may be explained in terms of chromatic adaptation. If, as the illumination suggests, the observer began the work in Y-adaptation,[19] the first, blue after-image would naturally follow. If the second observation was taken at too short an interval of time, the resulting B-adaptation would show itself as a yellow after-image. The two final observations suggest a shift of conditions. G is seen at 65° as greenish yellow, and as colorless; at 60° as indefinite greenish gray. It is possible that, in the case in which "no color" is reported, the G simply escaped notice; peripheral colors at the limit of vision often appear as momentary flashes. Again, R is reported at 65° as "no color," although "reddish yellow" had been seen as far out as 75°. It is possible that the flash of red escaped notice; it is also possible that R-adaptation, from the preceding after-image, brought out the blue.

The puzzling thing is that the positive outcome should be thus definite in the Mount Holyoke and Bryn Mawr laboratories, while neither Professor Baird nor ourselves—though working with full knowledge of conditions, and though trying various possibilities which have not been reported in detail[20]—are able in a single case to obtain the colored after-image. We can only guess at an explanation; and we offer the following guesses in what seems to us to be the order of their likelihood: (1) chromatic adaptation;[21] (2) the momentary and flash-like appearance of colors at the limit of vision; (3) the phenomenon of "fluctuation of attention"; (4) defective method and unsystematic procedure in the determination

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[19] These observations were taken "after the limits had been roughly determined in previous experiments." If the determination of limits was made at the same sitting, and if the last test-color employed was O, there would be additional reason for an initial Y-adaptation.

[20] Thus, Mr. Ferree wrote to us: "After-images seem to occur most intensively when the stimulus is removed while adaptation is still going on. If one carries the stimulation to a stationary point in adaptation, the after-image will weaken in proportion to the length of time during which the stimulus is regarded before the after-image is evoked. This is true whether one uses intensive or slightly supraliminal stimuli." We thought that it might possibly be true of subliminal stimuli, and accordingly made brief observations both in light and in dark adaptation. But we never saw the after-image.

[21] On chromatic adaptation, see Baird, *op. cit.*, 57 ff., 64 ff., 73 f.; *Journ. Philos., Psychol. & Sci. Meth.*, II., 1905, 21.

of zonal limits; (5) unnoticed variations, physical, physiological or psychological, in the conditions of observation during a series.[22]

We are well aware that negative experiments are logically inconclusive.[23] The fact that we have failed to find the colored after-image does not prove that this after-image is non-existent. We have, however, attempted a positive explanation: for Tschermak's result, in terms of prepossession and inaccurate method; for Miss Fernald's result, in terms (predominantly) of chromatic adaptation. Further experimentation by other observers must show whether our hypotheses are correct.

We are aware, also, that the charge of prepossession is double-edged, and that we may ourselves be accused of an initial bias. We freely confess that we, as well as Professor Baird, approached the peripheral experiments in a sceptical attitude of mind. On the other side, we may point out that the scepticism was positively based upon the results of Baird's Carnegie Institution research, and that the student-observers at the University of Illinois knew nothing of the question at issue.

In the case of Tschermak's observation, however, our initial bias was positive; we were surprised at the uniformly negative character of our results with the Marbe mixer. Tschermak's position seemed to accord well with current visual theory. Moreover, we knew that a contrast-color may be more saturated, may appear more "real," than the inducing, objective color. We knew that Heymans, in his experiments on "psychische Hemmung," had sometimes seen the contrast-color while the inducing color was still unperceived.[24] We knew of Helmholtz' statement, "dass die gesät-

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[22] In a letter to *T* Miss Fernald remarks: "You will see that colored after-images were seen in less than one third of the total number of cases in which the stimulus-color was not seen." In a communication made to Professor Baird, she estimates, roughly, that the phenomenon appeared in about five per cent. of her exposures upon the peripheral retina. This sporadic and fortuitous character of the after-images suggests that they are the product of some variable condition which has not been taken account of in the investigations.

[23] J. S. Mill, "A System of Logic," 1884, 515; W. S. Jevons, "The Principles of Science," 1900, 434.

[24] G. Heymans, Untersuchungen über psychische Hemmung, i. *Zeits. f. Psychol. u. Physiol. d. Sinnesorgane,* XXI., 1899, 328. "Wo mit weisser Sectorenscheiben experimentirt wurde, kam es öfters vor, dass ehe noch der Ring die Farbe des Papierstückes erkennen liess, sich im Hintergrunde schon die Contrastfarbe bemerklich machte."

tigsten objectiven Farben, welche existiren, die reinen Spectralfarben, im unermüdeten Auge noch nicht die gesättigste Farbenempfindung hervorrufen, welche überhaupt möglich ist, sondern dass wir diese erst erreichen, wenn wir das Auge gegen die Complementärfarbe unempfindlich machen."[25] There was, then, no *a priori* reason to doubt Tschermak's result; on the contrary, we thought it probable that under conditions which were unfavorable to the appearance of the stimulus-color, but favorable to the appearance of its complementary, the subliminally colored stimulus would give a perceptibly colored after-image.[26] As a matter of fact, it did not.

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[25] "Physiol. Optik," 1867, 370; 1896, 520. *Cf.* W. Wundt, "Physiol. Psychol.," II., 1902, 146.

[26] This possibility was considered, also, in the peripheral work; so that even for that our bias was not wholly negative.

# ON THE CLASSIFICATION OF THE CETACEA.

By FREDERICK W. TRUE.

(*Read April 24, 1908.*)

In this communication I wish to call attention to the various changes in the generally-accepted classification of the Cetacea proposed by Professor Dr. O. Abel, of the University of Vienna, in connection with his recent study of the Miocene toothed whales—chiefly those obtained from the vicinity of Antwerp, and now in the museum of Brussels.[1] Professor Abel's classification (1905) is as follows:

*Odontocètes*
+Archéocètes
+Squalodontidæ
Physeteridæ
Ziphiidæ
+Eurinodelphidæ
Acrodelphidæ . . . { Argyrocetinæ, Acrodelphinæ, Iniinæ, Beluginæ }
+Saurodelphidæ
Platanistidæ
Delphinidæ

I would call attention particularly to the following features to which my remarks will mainly relate:

1. The use of the term "Odontocètes" for all toothed whales and zeuglodonts.

2. The subordination of the "Archéocètes" to the "Odontocètes."

3. The new family Eurinodelphidæ.

4. The new family Acrodelphidæ (should be Iniidæ).

5. The inclusion of *Delphinapterus* and *Monodon* in this family instead of in Delphinidæ, and the inclusion of *Stenodelphis* and *Pontistes.*

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[1] *Mém. Mus. Roy. Hist. Nat. Belgique,* 1, 1901 and 3, 1905.

6. The new family Saurodelphidæ.

7. The family Platanistidæ, consisting of *Platanista* only.

The zeuglodonts are included in the order Cetacea by the majority of cetologists, though they were rejected from the great "Osteography" of Van Beneden and Gervais, as these authors did not consider them to be cetaceans. Brandt placed them with the squalodonts as families in a tribe subordinate to the Odontoceti,[2] but nearly all other authorities have considered them as a distinct suborder,—Archæoceti, or Zeuglodontes.

It seems to be generally agreed that the zeuglodonts have been proven by the researches of Dawes, Fraas, Stromer, Andrews and others to be derived from the creodonts. I do not know from what particular creodont they are supposed to have sprung, and whether the connection is good in that direction is for those most familiar with the creodonts to decide. The chief argument appears to be that in some zeuglodonts some of the molars are three-rooted.

Whatever may be the truth as regards that connection, various zoölogists have proposed, in more or less definite terms, to unite the zeuglodonts to the ordinary cetaceans through the squalodonts, which are clearly cetaceans, but with two-rooted or three-rooted teeth having serrated crowns. Professor Abel advances the concrete proposition of uniting the zeuglodonts and squalodonts[3] through the small form from the Caucasus, described by Lydekker under the name of *Zeuglodon caucasicus,*[4] and afterward made the basis of a new genus, *Microzeuglodon,* by Von Stromer. Of this only a part of the lower jaw, the humerus and a caudal vertebra, are known. The upward turn of the superior margin of the jaw posteriorly, and the form of the humerus—particularly the quite good articular facets,—appear to me to indicate that this is a zeuglodont, with no very strong leaning toward *Squalodon.* If this be conceded, there is no way at present in which to connect the Cetacea with any group of land mammals.

I would point out in this connection that while *Microzeuglodon* is from the Eocene and is of small size, and *Squalodon* is from the

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[2] *Mém. Acad. Imp. Sci. St. Petersburg,* VII^e Série, XX, 1873, p. vii.

[3] *L. c.,* p. 34.

[4] *Proc. Zool. Soc. London,* 1892, p. 558, pl. 36.

Miocene and Pliocene and is of comparatively large size, there is an American form of squalodont which is either from the Oligocene or Lower Miocene, and is of small size.

This is the genus *Agorophius*. It is based on a skull from South Carolina. It has serrate teeth like *Squalodon,* but what is especially remarkable, the parietals occupy a long area on the top of the skull, while in *Squalodon* and existing cetaceans the frontals and occipital come together at the vertex so as to entirely, or almost entirely, exclude the parietals.[5] The very remarkable conformation of *Agorophius* led Van Beneden and Gervais, and also Cope, to suspect that it might possibly be the progenitor of the whalebone whales. I do not think this is likely, but *Agorophius* appears to indicate that *Squalodon* may have, and probably did, originate from forms very unlike *Zeuglodon.*

It might be supposed that the whole argument concerning the derivation of the Cetacea from the zeuglodonts was negatived by the occurrence of various characteristic forms of Cetacea in the Eocene and even earlier formations, and hence contemporaneously with, or earlier than, *Zeuglodon.* In all such cases, however, so far as I have traced them, the forms reported are really from the Miocene. A notable case is that of the various important forms from Chubut, Patagonia, described by Lydekker in 1893. These include such genera as *Scaldicetus* and *Paracetus,* which certainly occur in the Miocene of North America and Europe, and, indeed, I understand the deposits at Chubut to be assigned at present without dispute to the Miocene.

The matter of the history and development of *Squalodon* is especially important, as Professor Abel derives four families of cetaceans from the squalodonts, namely, Physeteridæ, Ziphiidæ, Eurinodelphidæ and Acrodelphidæ (or Iniidæ), and one of them—the Physeteridæ—directly from *Squalodon* itself. The main argument in the latter case is that the teeth of some species of *Scaldicetus* (or *Physodon*)—an intermediate genus—have a ridge on the crown. This seems an unimportant character relatively, and does not balance the difficulty of deriving the extremely concave skull of *Physeter* from the extremely flat skull of *Squalodon.*

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[5] See True, "Remarks on the Type of the Fossil Cetacean *Agorophius pygmæus* (Müller)," Smithsonian Publ., No. 1694, 1907, with 1 plate.

I think that we shall in the end come to agree with the opinion expressed many years ago by Dr. Theo. Gill,[6] that the origin of the Cetacea dates much further back than is generally believed, and that the forms above mentioned are sideshoots from a stem reaching into a much more remote past.

However it may be as to the origin of the families mentioned, Professor Abel is correct, I believe, in following the course of Gray[7] and Gill[8] in separating the sperm whales and the beaked whales into two families, the Physeteridæ and the Ziphiidæ. Abel's line of development for *Physeter* through *Scaldicetus, Physeterula, Prophyseter* and *Placoziphius* seems excellent, except that it ignores *Hypocetus* Lydek. (or *Diaphorocetus* Amegh.) of North and South America, which is certainly an ancestor of *Physeter* or *Kogia,* and probably the former.

The family Eurinodelphidæ of Abel is quite certainly distinct. While obviously allied to the Ziphiidæ, *Eurinodelphis* has distinctive characters of its own, such as the small pterygoids, very long toothless premaxillæ, a delphinoid prenarial region, etc. I succeeded in discovering a skull of this genus in the Miocene of Maryland last year and thus introducing the family into the American fauna.

Abel's family Acrodelphidæ, which, as Professor Eastman recently pointed out, should be called Iniidæ[9], while not entirely new, is a very interesting assemblage. It comprises the following subfamilies and genera:

Family INIIDÆ Gill (ACRODELPHIDÆ Abel).

| | |
|---|---|
| Argyrocetinæ | *Argyrocetus.*<br>*Cyrtodelphis.*<br>*Pontivaga.*<br>*Ischyorhynchus.*<br>*Champsodelphis.* |
| Acrodelphinæ | *Acrodelphis.*<br>*Heterodelphis.* |

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[6] *Amer. Nat.,* 7, 1873, p. 2.

[7] Cat. Seals and Whales Brit. Mus., 2d ed., 1866, p. 326.

[8] Smithsonian Misc. Coll., 11, 1872, p. 15.

[9] *Bull. Mus. Comp. Zool.,* 51, 1907, p. 86.

| | |
|---|---|
| Iniinæ | *Inia.*<br>*Pontistes.*<br>*Stenodelphis.* |
| Beluginæ | *Beluga.*<br>*Monodon.* |

The partial breaking up of the currently-accepted families Platanistidæ and Delphinidæ here shown is quite radical. Usually *Platanista, Inia* and *Stenodelphis* (the so-called "river-dolphins") are united to form the family Platanistidæ, but Professor Abel leaves only the genus *Platanista* in that family. The limits of the family have always been uncertain, and Sir Wm. Flower, though accepting it provisionally in its usual form, remarked: "There are three distinct genera, which might almost be made the types of families, but it is probably more convenient to keep them together, only regarding them as representing three subfamilies."[10]

*Stenodelphis,* although having separate cervicals and broad lumbar diapophyses like *Inia,* has involuted pterygoids, ossified sternal ribs, and the articulations of the ordinary ribs with the vertebræ as in Delphinidæ. Associated with it is the fossil genus *Pontistes* of South America, which resembles *Stenodelphis* very closely, but is larger. The prenarial region in these genera, as well as the form and position of the nasals and the form of the zygomatic processes, recall *Phocœna* and also *Inia,* but I have been unable to satisfy myself of the importance of these resemblances.

The most radical feature of Professor Abel's classification is the removal of the white whale and narwhal (*Delphinapterus* and *Monodon*) from the Delphinidæ to the Iniidæ, although it is true that these forms had previously been considered as constituting a separate subfamily of the Delphinidæ by Gill, Flower and myself. They agree with *Inia* in having no dorsal fin, a broad pectoral, and separate cervical vertebræ, and the diapophyses of the lumbars are somewhat expanded. On the other hand, the sternal ribs are ossified, the sternum is shaped as in other Delphinidæ, the ribs articulate with the vertebræ in the same manner as in that family, and the enamel of the teeth is smooth. This combination of charac-

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[10] Flower and Lydekker, "Mammals Living and Extinct," 1891, p. 258.

ters recalls *Stenodelphis* rather than *Inia,* although the former has a dorsal fin.

Professor Abel's chief reason for rejecting *Delphinapterus* and *Monodon* from the Delphinidæ appears to be that the cervical vertebræ are separate. He says that on this account they cannot be derived from Delphinidæ.[11] This seems to me illogical, for it must be true that the existing Delphinidæ with extremely thin, more or less rudimentary, and anchylosed cervicals were derived from forms with well-developed, separate cervicals. Hence, one might expect to find some forms still existing in which the cervicals are distinct. I do not think that on that account alone they should be rejected from among the Delphinidæ.

In this connection, the genus *Lophocetus* from the Miocene of Maryland is of interest. This is represented by a skull and cervical vertebræ. The skull, which is long-beaked, is delphinoid in general appearance, especially in the prenarial region, but the temporal fossæ are large and the supraoccipital narrow, and shaped somewhat as in *Inia.* The teeth are lacking, but appear to have had simple cylindrical roots. The cervical vertebræ are separate. They are, however, imbedded in the matrix, so that little can be determined regarding their characters.

This genus has been associated with *Inia* in the Platanistidæ by Cope;[12] and Dr. C. R. Eastman, who has recently given a new description of it,[13] also regards it as allied to *Inia,* while Brandt and Abel have considered it closely allied to *Delphinapterus.* I am myself inclined to the latter view, although conceding that the shape of the supraoccipital is inioid. If this be accepted, we have in *Lophocetus* a Miocene delphinoid form with separate cervicals.

On account of the combination of characters presented by *Stenodelphis, Delphinapterus, Monodon* and *Lophocetus,* three courses are possible as regards their classification. They may be included in the family Iniidæ, or made the basis of a separate family Stenodelphidæ, or included in the family Delphinidæ. The latter course seems to me best at present,

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[11] *Mém. Mus. Roy. Hist. Nat. Belgique,* 3, 1905.

[12] *Amer. Nat.,* 1890, pp. 606 and 615.

[13] *Bull. Mus. Comp. Zool.,* 51, 1907, p. 79.

Professor Abel has described a delphinoid form from the Upper Miocene of Antwerp—*Pithanodelphis*—in which the atlas and axis are united as in existing genera. It would appear, from this and other evidence, that the family Delphinidæ was differentiated as early as the Miocene and that both forms with separate cervicals and forms with united cervicals were then existing.

The family Saurodelphidæ of Abel comprises the single genus *Saurodelphis* Burmeister, from the banks of the Paraná River, Argentina. The geological horizon is understood to be Pliocene. Professor Abel considers that it cannot be associated at present with any group of toothed whales, but it appears probable from Burmeister's figures that the skull has a maxillary hood and other characters resembling those of *Platanista,* and the teeth are also similar in some respects, especially as regards the growth of irregular roots with age, etc. For these reasons, I think it should be assigned to the Platanistidæ, at least provisionally.

The modifications which I have proposed in the classification of the toothed whales are summed up as follows:

CETACEA.

ODONTOCETI.

| | |
|---|---|
| + Squalodontidæ. | |
| Physeteridæ. | Physeterinæ.<br>Kogiinæ. |
| Ziphiidæ. | |
| + Eurinodelphidæ. | |
| Iniidæ. | Iniinæ.<br>Argyrocetinæ.<br>Acrodelphinæ. |
| Delphinidæ | Stenodelphinæ.<br>Delphinapterinæ.<br>Delphininæ. |
| Eurinodelphidæ. | |

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# HEREDITY, VARIATION AND EVOLUTION IN PROTOZOA. II.

## HEREDITY AND VARIATION OF SIZE AND FORM IN PARAMECIUM, WITH STUDIES OF GROWTH, ENVIRONMENTAL ACTION AND SELECTION.[1]

BY H. S. JENNINGS.

(*Read April 24, 1908.*)

TABLE OF CONTENTS.
(See pages 544–546.)

## I. INTRODUCTORY.

The first of this series of studies[2] gave a general introduction to the investigations, and dealt with the fate of new or acquired characters in protozoa, showing that these are as a rule not inherited and that there is no difference in principle on this point between protozoa and metazoa. The present paper takes up heredity and variation in size and form in *Paramecium*.

Our present questions are then mainly as follows: In what respects do the individuals of *Paramecium* resemble each other? In what

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[1] From the Laboratory of Experimental Zoölogy, Johns Hopkins University, Baltimore, Md.

[2] *Journal of Experimental Zoölogy*, Vol. 5, 1908, pp. 577–632.

respects do they differ? What are the causes of the resemblances or differences, as the case may be?

The attempt is made to treat these questions broadly, determining experimentally the different classes of causes concerned, without prejudice as to their relative importance. External and internal factors are therefore equally considered, the purpose of the investigation being to give as complete an analysis of the phenomena of resemblances and differences as possible. Our problem, then, requires an analysis from this point of view of all things which may result in producing, increasing or decreasing the similarities and differences between individuals—reproduction, growth, conjugation, the effects of environment, of selection, and the like.

The investigation will be best introduced by proposing at once what is really the central problem—that concerning *heredity*. Is size inherited in *Paramecium?*

How would heredity of size be shown? If certain individuals differ in size, and the progeny of these individuals, under identical conditions, show corresponding differences, this is what would commonly be called heredity of size. "Heredity is a certain degree of correlation between the abmodality of parent and offspring" (Davenport, 1899, p. 35). Do large individuals of *Paramecium* produce, under the same conditions, larger progeny than do small ones? Is it possible to obtain by selection large and small races of *Paramecia?*

To study this question, we must first examine the variations in size commonly found in *Paramecium.*

## II. PRELIMINARY STUDY OF VARIATION IN PARAMECIUM.

We owe our present knowledge of variation in *Paramecium* mainly to Pearl and his co-workers (see Pearl, 1907; Pearl and Dunbar, 1905). A more extensive work by Pearl on variation in *Paramecium* has been mentioned as in prospect; I learn from personal communication, however, that this is not to appear. I shall therefore publish my own results more fully than I should otherwise have done. Certain points in connection with variation in *Paramecium* have been dealt with by Simpson (1902) and Pearson

(1902); also by McClendon (1908). But we have at present nothing like a thorough analysis of the matter, based on extensive data.

## 1. General Methods of Work; Statistical Treatment and Its Uses.

Before we can study experimentally the nature and causes of the existing variations, we must, of course, know their extent, character and distribution. To this end I have made a statistical study, constructed frequency polygons, and determined the more important constants of variation and correlation. This has, of course, not been done because of belief in any occult virtue in mathematical treatment. Statistical methods have been used in this preliminary survey merely because they form the most natural and direct way of discovering and displaying the problems on which we wish to work; I doubt whether the most determined critic of the use of such treatment in biology could suggest any other way for our material. But I am fully convinced that "crucial evidence is always individual in the last analysis" (Whitman); that the preliminary statistical examination of the facts requires development as soon as possible into precise experimental knowledge. It is valuable to know just how many men out of a thousand will die in a given period, but it is infinitely more valuable to know which ones will die if the conditions are not changed, and why; and the latter knowledge includes the former. I have therefore advanced at once from the descriptive statistical work to experimental treatment. A curve or polygon of variation (such as Diagram 1) or a correlation table (such as Table I.) is to be looked upon as a mass of problems. The place occupied in the polygon or table by any individual is due to certain causes, and it is these causes that we seek.

In seeking these causes by experimental methods, statistical treatment is again found to be of the greatest value for detecting and registering the effects of single factors, under complex conditions. This method may be compared to a microscope; it enables us to detect and deal with causes and effects which we could not handle without it. I am convinced that it is a great mistake to hold that the only or the main use of statistical treatment is for "dealing with the sphere of indefinitely numerous small causes—amenable only to the calculus of chance, and *not to any analysis of the individual instance*." Such treatment is a most valuable instrument for precisely such analysis as will bring out the effects of individual factors when we are unable to experimentally disengage them completely from others; it aids us most essentially in the "analysis of the individual instance." Of this I hope the present paper may furnish illustrations. As Johannsen (1906, p. 98) has well expressed it, the mathematical treatment must, to give valuable results, be "based upon an accomplished sorting of the special facts and a biological setting out of the premises which are to be treated." Davenport (1899) states that "the statistical laws of heredity deal not with the relations between one descendant and its parent or parents, but only with the mean progeny of mean parents." The object of the present work is precisely to discover so far as possible the relation between one descendant and its parent (or other relatives); for this, statistical methods show themselves most useful.

## 2. A Typical Culture.

We will then first examine a typical culture of *Paramecium,* made in the usual way with pond water and decaying vegetation, in a circular glass vessel about nine inches across and three inches deep. This culture we will call *Culture 1.*

Inspection showed that *Paramecia* of markedly different size were found in this culture, so that it seemed a favorable one for a study of inheritance in size. Cursory examination seemed to indicate the existence of two sets of individuals, those of one set being nearly double the length of the others.

Of this culture a large number were killed on April 10, 1907, and four hundred specimens, taken at random, were measured as to length and breadth.

## 3. Methods of Measuring and Recording.

The animals were killed with Worcester's fluid, which is known to cause practically no distortion when properly used. Worcester's fluid consists of ten per cent. formalin saturated with corrosive sublimate. In using it, a large number of the infusoria must be brought into one or two drops of water, then these must be overwhelmed with a considerable quantity of the fluid. If the infusoria are in a larger quantity of water, the killing takes place more slowly, the animals have time to contract, and distortion results.

The measurements were made on the slide, the organisms being either still in the killing fluid or in ten per cent. formalin. Transference to the latter has no effect on the form of the fixed animals. Most of the measurements were made directly with an ocular micrometer. In the case of cultures of large individuals, however, the form was projected on paper with the camera, in the way described by Pearl (1907), the extremities of length and breadth marked with the pencil, then these were measured with a scale made by projection of the ocular micrometer.

Such combinations of lenses were used that one division of the micrometer scale was equal to 4 microns (or in a few cases, which will be expressly noted, to $3\frac{1}{3}$ microns). The measurements were thus recorded in units, each of which was equal to 4 microns, so that the recorded units are multiplied by four to give results in microns. When the measurements fell between two lines of the micrometer, the line nearest the actual measure was that recorded; if the measurement fell just half way between two lines, the higher line was recorded. Thus, the recorded unit 45 included all measurements beginning with $44\frac{1}{2}$, and *less than* $45\frac{1}{2}$. In the tables, the measurements, given in microns, are therefore grouped about such values that each group includes values from two microns below to two microns above the one recorded. Thus, in Table 1, the length 180 includes all the specimens measuring from 178 up to (but not including) 182.

It will be well to summarize here, once for all, the method of treating the data obtained in the measurements. For most of the tables the constants computed (and recorded below the tables) were the following: the mean, standard deviation, and coefficient of variation, for length and for breadth; the mean index or ratio of breadth to length; and the coefficient of correlation. The computation of the constants was based on the well-known formulæ that have been brought together by Davenport (1904) and others. I used as a rule the actual methods set forth so clearly by Yule (1897). The computations were made by the aid of seven-place logarithms and of Crelle's and Barlow's tables. Two independent computations, at considerable intervals of time, were made in each case. While I cannot hope that errors in computation are excluded, I believe that such as may exist do not in any way affect the conclusions to be drawn.

Certain points of detail should be mentioned. While, as will appear, most of the tables do not give symmetrical curves, I have used only the simple statistical methods applicable in strictness to such curves; the methods are quite sufficient as a basis for the comparisons we wish to make.

In computing the standard deviation, Sheppard's correction of the second moment was used throughout. That is, if we employ the method of Yule (1897),

$$\sigma = \sqrt{\Sigma(f\xi^2) - d^2 - .08333},$$

or using the signs employed by Davenport (1904)

$$\sigma = \sqrt{\frac{\Sigma(V - V_0)^2}{n} - r_1^2 - \tfrac{1}{12}}.$$

TABLE I.

*"Wild" Culture 1. Correlation Table for Length and Breadth of a Random Sample*
(See Diagrams 1 and 2, polygons *A* and *a*.)

Length in Microns.

| Breadth in Microns. | 84 | 88 | 92 | 96 | 100 | 104 | 108 | 112 | 116 | 120 | 124 | 128 | 132 | 136 | 140 | 144 | 148 | 152 | 156 | 160 | 164 | 168 | 172 | 176 | 180 | 184 | 188 | 192 | 196 | 200 | 204 | 208 | 212 | 216 | 220 | 224 | 228 | 232 | 236 | 240 | Totals. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 28 | | | | | 1 | 4 | | 5 | 3 | 5 | 2 | 3 | 4 | | | | | | | | | | | | | | | | | | | | | | | | | | | | 27 |
| 32 | 1 | 1 | | | 1 | 3 | 3 | 6 | 9 | 19 | 14 | 17 | 9 | 8 | 4 | 2 | | | | | | | | | | | | | | | | | | | | | | | | | 97 |
| 36 | | | | | | | | | 3 | 2 | 6 | 5 | 9 | 7 | 7 | 3 | | | | | | | | 1 | 1 | | | | | | | | 1 | | | | | | | | 45 |
| 40 | | | | | | | | | 1 | | 1 | | 3 | | 5 | 2 | | | | | 2 | | | | 1 | | 2 | | 1 | | | | | | | | | | | | 18 |
| 44 | | | | | | | | | | 1 | | | 2 | 1 | 2 | | | 1 | | 1 | 1 | 2 | 1 | 2 | 4 | 1 | 3 | 7 | 9 | 5 | 3 | 6 | 4 | 1 | 1 | 1 | | | | | 59 |
| 48 | | | | | | | | 1 | | | | | | | | 1 | | | | | 2 | 1 | 3 | 3 | 1 | 4 | 2 | 7 | 5 | 5 | 4 | 8 | 11 | 5 | 1 | | 1 | | | | 65 |
| 52 | | | | | | | | | | | | | | | | | | | | | | 1 | | | 2 | 1 | 1 | 2 | 3 | 5 | 4 | 4 | 7 | 6 | 7 | 3 | 2 | 2 | | | 50 |
| 56 | | | | | | | | | | | | | | | | | | | | | 1 | | | | 1 | 1 | 2 | 1 | 1 | 3 | 1 | 5 | 1 | 2 | 2 | 4 | 1 | 3 | | 1 | 30 |
| 60 | | | | | | | | | | | | | | | | | | | | | | 1 | | | | | | | | | | 1 | | 1 | | 1 | 1 | 1 | 1 | | 7 |
| 64 | | | | | | | | | | | | | | | | | | | | | 1 | | | | | | | | 1 | | | | | | | | | | | | 2 |
| Totals. | 1 | 1 | 0 | 0 | 2 | 7 | 3 | 12 | 16 | 27 | 23 | 25 | 27 | 16 | 18 | 8 | 0 | 1 | 0 | 1 | 7 | 5 | 4 | 6 | 10 | 7 | 10 | 17 | 20 | 18 | 12 | 24 | 24 | 15 | 11 | 9 | 5 | 6 | 1 | 1 | 400 |

Mean Length, 165.840$\mu$.
Mean Breadth, 48.860$\mu$.
Mean Length of Left Hand Group, 125.420$\mu$: of Right Hand Group, 200.972$\mu$.
Mean Breadth of Left Hand Group, 33.396$\mu$: of Right Hand Group, 49.216$\mu$.

The *mean index* given below the tables is the mean of the quotient $\frac{\text{breadth}}{\text{length}}$: it shows essentially what percentage the breadth is of the length. This mean was found, without computing the index for each individual, by the following formula:

$$i=\frac{A_B}{A_L}(1+C_L^2-rC_BC_L).$$

Where $i$ is the mean index, $A_B$ is the mean breadth, $A_L$ the mean length, $C_B$ the coefficient of variation for breadth, $C_L$ the same for length, and $r$ is the coefficient of correlation between length and breadth.

I am greatly indebted to Dr. Raymond Pearl for assistance in the mathematical treatment of the data.

The results of the measurements of a random sample of 400 of Culture 1 are given in Table I.

It is evident on inspection of this table that the individuals fall into two well-marked groups, one set varying in length from 84 to 144 microns, the other set varying from 164 to 240 microns, while between these groups, in the region from 144 to 164 microns, only two specimens are found. The mean length for the entire sample falls at 165.840 microns, almost precisely in the region where no specimens are found. The smaller set have their mean length at 125.420 microns: the larger set at 200.972 microns.

These results are shown as frequency polygons in the lower portions of Diagrams 1 and 2.

## 4. METHOD OF CONSTRUCTING THE POLYGONS.

In making the polygons for length, three units of measurement (12 microns) were grouped together to make a single unit of the abscissa of the polygon. This was done in order to destroy any irregularities due to unconscious prejudice on the part of the measurer for certain numbers. Thus, in measuring a large number of individuals, it may be found, for example, that few are recorded at 51, while at 50 there are many; or the reverse may occur. This is due only to the fact that in doubtful cases falling between these numbers the measurer unconsciously gives the preference regularly to one of them. The error thus introduced is extremely small (it can hardly be more than one micron in any case), but if the polygon is made without grouping together adjacent classes, there appear extreme irregularities in its outline, irregularities that are quite without significance. When three units are thrown together, any marked irregularities remaining in the polygons are almost certainly due to peculiarities in the material itself. It is of course possible that small peculiarities really existing may be hidden in

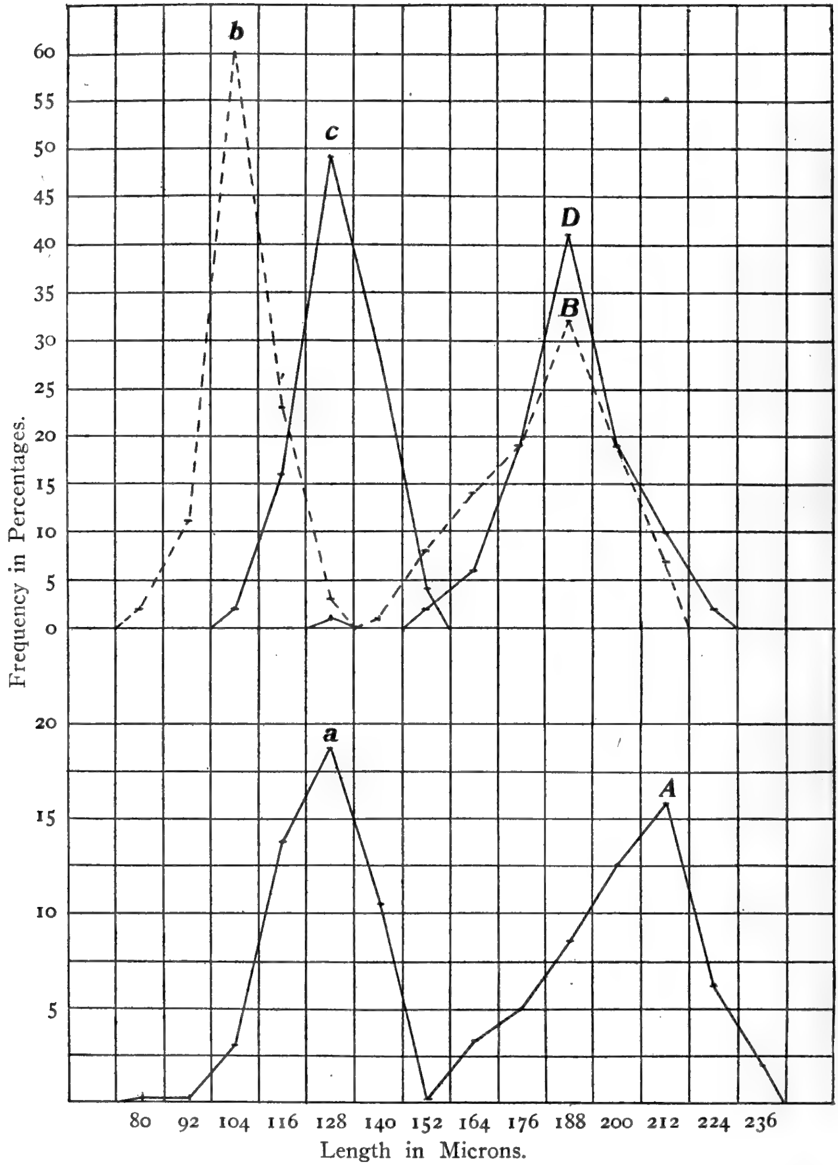

DIAGRAM I. Polygons of variation for length in Culture I and its descendants. *A* and *a* form together the polygon for 400 specimens taken at random from the original culture I, on April 10, 1907. *B*, polygon for 100 descendants of ten of the larger individuals of Culture I. *D*, polygon for 100 descendants of the single large individual *D*, from culture I. *b*, polygon for 100 descendants of fifty smaller individuals from culture I. *c*, polygon for 100 descendants of the single small individual *c*, from culture I.

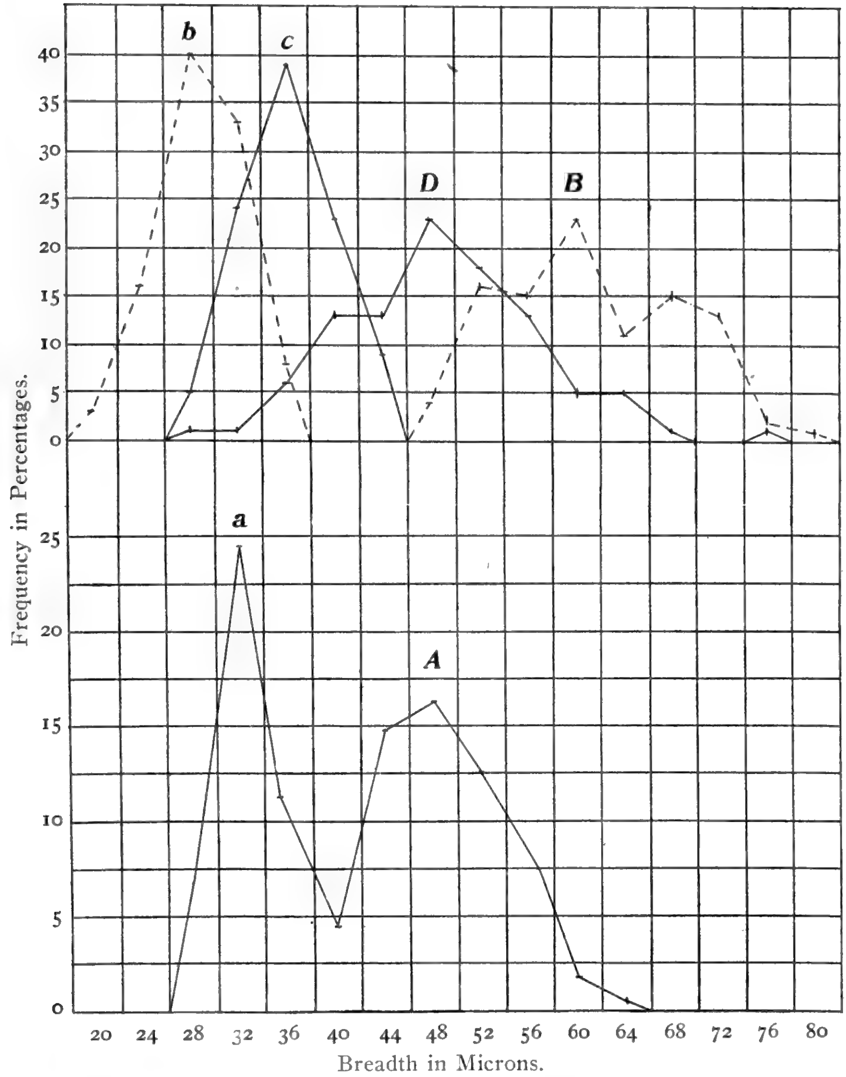

DIAGRAM 2. Polygons of variation for breadth in culture 1, and in its descendants from selected specimens. The letters have the same significance as in Diagram 1.

this way, but it was thought wiser to be conservative in this matter. Thus the space between two perpendicular lines of the polygons includes three of the groups of the correlation table, and is marked at its base with the middle value of the three groups which it includes.

In making the polygons for breadth, it was found that there was little evidence of error due to unconscious preference for certain numbers in making this measurement. This is probably due to the comparatively small numbers of units in the breadth measurement, and to the fact that it is possible to hold both limits of the measurement on the scale sharply in the eye at once, while this is hardly possible in measuring length. In the polygons for breadth, therefore, one unit of the polygon was made to correspond to one unit of measurement (four microns).

In all the polygons the numbers to the left indicate percentages of the entire number, so that all the polygons are of equal area, whatever the number of specimens on which they are based. The only exception to this is in the case of the double polygons *a* and *A*, of Diagram 1, resulting from plotting the random sample of Table I. Since this sample falls into two groups, the entire (double) polygon was made of twice the area of the other polygons. Each half polygon therefore becomes approximately equal to any one of the single polygons of the other diagrams, thus permitting ready comparison.

The numbers at the foot of the diagrams are the dimensions in microns. Each number corresponds to the value of the center of the column beneath which it stands.

### 5. Two Groups of Paramecia.

Thus the *Paramecia* in our natural culture I fall into two groups which are almost completely separated, so far as length is concerned, but which overlap a certain amount in breadth. Characteristic outlines of varied members of the two groups, drawn to the same scale, are shown in Fig. 1.

Are these two groups permanent differentiations, such as might be called distinct species, or are the differences possibly due merely to temporary dimorphism of some sort? To answer this question individuals of the two sizes were isolated and allowed to multiply separately, in cultures made of boiled hay. After varying periods of time 100 individuals, taken at random, were measured from each of these pure cultures, and the frequency polygon derived from these was compared with the two (nearly distinct) polygons from the original culture. The following cultures were made and measured:

1. Fifty of the smaller individuals were selected from the original culture, placed together, and allowed to multiply for twelve days (from April 10 to April 22). The measurements of 100 of this

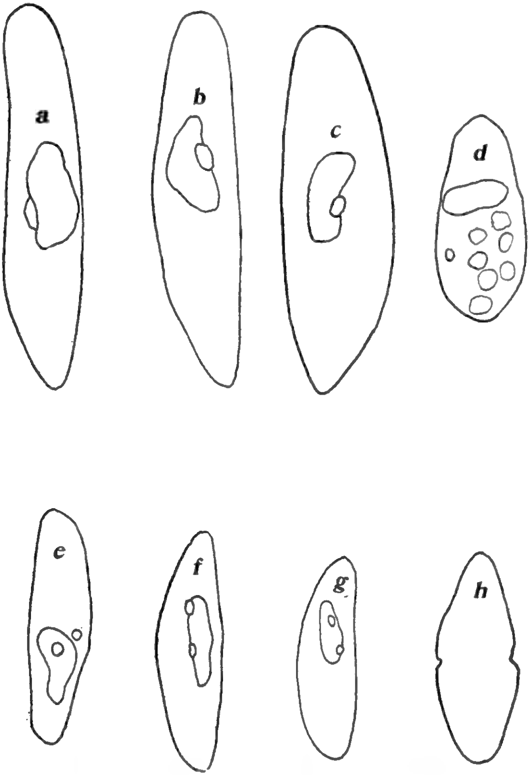

Fig. 1. Outline of characteristic specimens from the original wild culture 1, April 10, 1907. The upper row shows examples of the larger "*caudatum* form"; the lower row examples of the smaller "*aurelia* form." *d*, Young of the caudatum form; *h*, dividing specimen of the *aurelia* form. All × 235.

culture are shown in curve *b* (broken line), Diagrams 1 and 2; their dimensions are given in the correlation Table II. It is evident that this group corresponds in a general way with the smaller group of the original culture, though its mean length and breadth are somewhat lower (96.280 × 29.080 microns instead of 125.42 × 33.396), and it shows a little less variation.

2. Ten of the larger individuals selected from the original culture were likewise allowed to multiply in the same vessel for twelve days, then 100 were measured. The results are shown in curve *B*, Diagrams 1 and 2, and in the correlation Table III. It is evident

TABLE II.

*Correlation Table for Length and Breadth of a Random Sample from Decendants of 50 of the Smaller Individuals from Culture 1, allowed to Multiply for 12 Days. (See polygons b, Diagrams 1 and 2.)*

Length in Microns.

| Breadth in Microns. | 80 | 84 | 88 | 92 | 96 | 100 | 104 | 108 | 112 | 116 | 120 | 124 | 128 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20 | | | | | 1 | | 2 | | | | | | | 3 |
| 24 | | | | | 3 | 3 | 4 | 5 | | 1 | | | | 16 |
| 28 | | | | | 6 | 8 | 10 | 8 | 5 | 1 | 1 | | 1 | 40 |
| 32 | 1 | 1 | 1 | | | 3 | 9 | 8 | 4 | 3 | 2 | 1 | | 33 |
| 36 | | | | | | | | | 1 | 3 | 3 | | 1 | 8 |
| | 1 | 1 | 1 | 0 | 10 | 14 | 25 | 21 | 10 | 8 | 6 | 1 | 2 | 100 |

| | | | |
|---|---|---|---|
| Length—Mean, | 96.280 ± .552μ | Breadth—Mean, | 29.080 ± .212μ |
| St. Dev., | 8.160 ± .388μ | St. Dev. | 3.320 ± .168μ |
| Coef. Var., | 7.678 ± .368 | Coef. Var. | 12.100 ± .585 |

Mean Index, or Ratio of Breadth to Length, 27.428 per cent.; Coef. of Cor., .3768 ± .0579.

that the progeny of these ten correspond to the larger set (*A*) of the original culture, though with slight differences in the means and in the amount of variation.

3. A single smaller individual, *c*, was selected from the original culture. As near as could be measured when alive, this individual

TABLE III.

*Correlation Table for Length and Breadth of a Random Sample from Descendants of 10 of the Larger Individuals from Culture 1, allowed to multiply for 12 Days.* (See polygons B, Diagrams 1 and 2.)

Length in Microns.

| Breadth in Microns. | 144 | 148 | 152 | 156 | 160 | 164 | 168 | 172 | 176 | 180 | 184 | 188 | 192 | 196 | 200 | 204 | 208 | 212 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 48 | | 1 | | 1 | 1 | | | 1 | | | | | | | | | | | 4 |
| 52 | | | 1 | 3 | 1 | 1 | 1 | 1 | 3 | | 1 | 1 | 1 | 1 | | | | 1 | 16 |
| 56 | 1 | | 1 | 1 | 4 | | 1 | 1 | | | 1 | 1 | 3 | | 1 | | | | 15 |
| 60 | | | | | 2 | 1 | 1 | 2 | | 2 | 1 | 8 | 1 | 2 | 2 | 1 | | | 23 |
| 64 | | | | | | | | 2 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | | 1 | | 11 |
| 68 | | | | | | | 1 | | | 1 | 2 | | 3 | 3 | 1 | 1 | 2 | 1 | 15 |
| 72 | | | | | | | | | 1 | 2 | 2 | 1 | 2 | 2 | | 1 | | 2 | 13 |
| 76 | | | | | | | | | | | | | | 1 | 1 | | | | 2 |
| 80 | | | | | | | | | | 1 | | | | | | | | | 1 |
| | 1 | 1 | 2 | 5 | 8 | 2 | 4 | 7 | 5 | 7 | 8 | 12 | 12 | 10 | 6 | 3 | 3 | 4 | 100 |

| | | | |
|---|---|---|---|
| Length—Mean, | 182.760 ± 1.096μ | Breadth—Mean, | 61.360 ± .496μ |
| St. Dev., | 16.264 ± .776μ | St. Dev., | 7.376 ± .332μ |
| Coef. Var., | 8.899 ± .428 | Coef. Var., | 11.912 ± .576 |

Mean Index or Ratio of Breadth to Length, 33.652 per cent.; Coef. Cor., .5288 ± .0486.

was 120 microns in length. It was allowed to propagate in a culture free from all other *Paramecia,* from April 9 to June 11 (thus a little more than two months). Now a random sample gave the polygons shown at *c,* Diagrams 1 and 2; the measurements are given in Table IV. This group corresponds very closely to the smaller group *a* of the original culture, though with slight differences in breadth.

TABLE IV.

*Correlation Table for Length and Breadth of a Random Sample Descended from the single small Individual c, taken from Culture 1 and allowed to Multiply 63 Days.* (See Polygons *c,* Diagrams 1 and 2.)

| Breadth in Microns. | Length in Microns. | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 104 | 108 | 112 | 116 | 120 | 124 | 128 | 132 | 136 | 140 | 144 | 148 | 152 | 156 | |
| 28 | 1 | | | 2 | 1 | 1 | | | | | | | | | 5 |
| 32 | | | | 2 | 6 | 5 | 5 | 3 | 3 | | | | | | 24 |
| 36 | 1 | | | | 3 | 8 | 8 | 7 | 5 | 1 | 4 | 1 | | 1 | 39 |
| 40 | | | | 1 | 1 | 2 | 5 | 3 | 3 | 4 | 3 | 1 | | | 23 |
| 44 | | | | | | 1 | | 1 | 2 | 2 | 2 | 1 | | | 9 |
| | 2 | 0 | 0 | 5 | 11 | 17 | 18 | 14 | 13 | 7 | 9 | 3 | 0 | 1 | 100 |

| | | | |
|---|---|---|---|
| Length—Mean, | 130.120 ± .628μ | Breadth—Mean, | 36.280 ± .260μ |
| St. Dev., | 9.284 ± .443μ | St. Dev., | 3.880 ± .184μ |
| Coef. Var., | 7.134 ± .342 | Coef. Var., | 10.700 ± .516 |

Mean Index or Ratio of Breadth to Length, 27.913 per cent.; Coef. Cor., .5208 ± .0492.

4. A single very large specimen, *D,* approximately 250 microns in length, was isolated from the original culture on April 12 and allowed to propagate freely till June 11 (two months): 100 specimens taken at random then gave the measurements shown in the polygon *D,* Diagrams 1 and 2, and Table V.

Examination of the polygons and tables shows that the two forms retain their essential characteristics when isolated and propagated. The results shown in the diagrams are typical of many others. I have kept distinct strains of each of these groups for periods (at the present time) of more than eighteen months, and measurements made at frequent intervals during that time show that they have always remained quite distinct.

Thus it is clear that these colorless *Paramecia* fall into two distinct groups, which are at least relatively permanent. As is well known, two species of colorless *Paramecia* have long been distin-

### TABLE V.

*Correlation Table for Length and Breadth of a Random Sample Descended from the Single Large Individual D, taken from Culture 1, and allowed to Multiply 60 Days.* (See polygons D, Diagrams 1 and 2.)

Length in Microns.

| Breadth in Microns. | 128 | 132 | 136 | 140 | 144 | 148 | 152 | 156 | 160 | 164 | 168 | 172 | 176 | 180 | 184 | 188 | 192 | 196 | 200 | 204 | 208 | 212 | 216 | 220 | 224 | 228 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 28 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | 1 |
| 32 | | | | | | | | | | | | | 1 | | | | | | | | | | | | | | 1 |
| 36 | | | | | | | | | | | 1 | | 2 | | 1 | 2 | | | | | | | | | | | 6 |
| 40 | | | | | | | | | | | 2 | | | 3 | 4 | 3 | | 1 | | | | | | | | | 13 |
| 44 | | | | | | | | | | | | 1 | | | 3 | 4 | 2 | 1 | 1 | | | 1 | | | | | 13 |
| 48 | | | | | | | 1 | 1 | | | | | 4 | 1 | 3 | 5 | 1 | 2 | 1 | 1 | | 2 | 1 | | | | 23 |
| 52 | | | | | | | | | | 1 | 1 | | 3 | | 2 | 2 | 3 | 2 | | 2 | 1 | | | | | 1 | 18 |
| 56 | | | | | | | | | 1 | | | 1 | | 2 | | | 2 | 2 | 1 | 1 | | 2 | | 1 | | | 13 |
| 60 | | | | | | | | | | | | | | | 1 | 2 | 1 | | | | | | 1 | | | | 5 |
| 64 | | | | | | | | | | | | | 1 | | | | | | 1 | 1 | 1 | 1 | | | | | 5 |
| 68 | | | | | | | | | | | | | | | | | | | | 1 | | | | | | | 1 |
| 72 | | | | | | | | | | | | | | | | | | | | | | | | | | | 0 |
| 76 | | | | | | | | | | | | | | | | | | 1 | | | | | | | | | 1 |
| | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 4 | 2 | 11 | 6 | 14 | 18 | 9 | 9 | 4 | 6 | 2 | 6 | 2 | 1 | 0 | 1 | 100 |

| | | | |
|---|---|---|---|
| Length—Mean, | 188.360 ± .980μ | Breadth—Mean, | 49.000 ± .548μ |
| St. Dev., | 14.532 ± .692μ | St. Dev., | 8.144 ± .388μ |
| Coef. Var., | 7.715 ± .370 | Coef. Var., | 16.618 ± .814 |

Mean Index, 26.029 per cent.; Coef. Cor., .4188 ± .0556.

guished under the names *Paramecium aurelia* Müller and *Paramecium caudatum* Ehr. The two groups we have found correspond to the descriptions heretofore given of the two species, the smaller set representing *Paramecium aurelia,* the larger *Paramecium caudatum.* Besides the differences in size certain other characteristics have been held to distinguish the two species, and these distinguishing characteristics are evident in our two groups. *Paramecium aurelia* is described as having two micronuclei and *P. caudatum* but one; this is true for our larger and smaller groups respectively. *Paramecium aurelia* is said to be more rounded behind, while *P. caudatum* is pointed. In spite of many variations in form within each group, it is clear that our smaller group corresponds in this respect also with *P. aurelia,* the larger one with *P. caudatum.*

Calkins (1906) has brought forward evidence tending to show that the supposed distinction into permanently differentiated forms is not well based, so that there are not two species, the different sizes being merely variants of one. Calkins based his doubts as to the really specific distinctness of *P. aurelia* and *P. caudatum* on the fact that in one of his pedigree cultures of *P. caudatum* the number of micronuclei changed from one to two, remained at two for many generations, and finally changed back again to one.

The results here published tend to indicate that the distinction into two groups is not without some sort of foundation. But it will be best to reserve the discussion of species until we have more data at hand. We may temporarily speak of the smaller set as the *aurelia* group, the larger one as the *caudatum* group. In a later part of the paper the question of distinguishing species will be taken up in detail, in the light of full data.

### 6. Are Differences in Size Hereditary within Each of the Two Groups?

We have found that among the variations of *Paramecium* in size are two groups, limited by internal causes, so that even under the same external conditions they differ in size; these two groups have heretofore been considered two species. But within each of these groups we find likewise many variations in size, so distributed, however, as to produce a curve with a single apex (Diagrams 1 and 2, etc.). These variations are at times very considerable, as will be evident from an examination of the polygons shown in Diagrams 3 and 6 (pages 413, 470), or the tables numbered VII. (page 412) and XX. (page 466). The next question to be considered is: Are the differences in size within such a group hereditary? That is, do the differences in size depend upon internal conditions, of such a character that the differences will persist in the progeny, even when the external conditions remain the same?

The experimental answer to this question is to be obtained by isolating individuals of different size belonging to one of the two groups (either "*aurelia*" or "*caudatum*"), allowing these to multiply and determining whether the progeny show differences in size corresponding to those in the parents. Can we by selection and propagation produce within the limits of a single group races of different mean size?

Experiments designed to answer this question were undertaken in the following way. As representing the *caudatum* group I selected the cultures descended from the individual *D*; while the progeny of *c* represented the *aurelia* group. Now, from each of these groups the largest and smallest individuals were isolated and allowed to multiply, under uniform conditions. Thus, the selected large and small individuals of a given group were all *progeny of a single individual,* forming thus a "pure line"; this fact is of great importance, as the sequel will show.

A large number of experiments gave throughout negative results. The progeny of large and of small individuals (within a given pure line) *showed no characteristic differences in size.* Large specimens of the *caudatum* form produced progeny on the whole no larger than those produced by small specimens of the same form, and the same was true in the *aurelia* group. In many experiments a single large and a single small specimen were isolated, and their progeny compared; in other cases a number of large specimens were placed together in one vessel, a number of small ones in another, and their progeny compared after lapse of a considerable period. Since the results of these experiments were throughout negative, I will give the details of but a single illustrative experiment:

On July 27 ten large and ten small specimens were selected from a lot of the *caudatum* group, all being descendants of a single individual *D*. The ten large specimens measured, as nearly as could be determined while alive, approximately 250 microns each, and were thick in proportion to the length. The ten small specimens were about 150 microns long, and were thin. The two sets were placed in equal quantities of the same culture fluid.

At the end of three days the large set had produced many individuals. Fifty of these taken at random gave a mean length of 189.040 microns, a mean breadth of 60.560 microns.

The smaller individuals did not increase rapidly and five of them died before dividing, so that all the progeny came from six individuals. The six increased in size before dividing. At the end of three days there were twenty-one individuals. The mean length was 205.140 microns, the mean breadth 56.570 microns.

Thus the smaller specimens had produced progeny that were a little longer, but not quite so broad, as those resulting from the larger set. The existing differences are clearly without significance.

In other cases there was more variation in size among the different sets of progeny of *D,* particularly if the measurements were made after but few fissions had occurred. But sometimes the progeny of the large specimens were smaller, sometimes larger, than those of the small specimens. On the whole, both large and small specimens produced progeny of about the mean size for the group, under the given conditions.

Thus it is apparent that the differences in size shown within such a polygon as *D,* Diagram 1, are not due mainly to hereditary internal factors. Before we can determine with certainty whether any such factors are involved, we must make an analysis of the variation polygon, determining so far as possible the different factors, external and internal, which go to make it up.

## 7. Proposed Analysis of the Polygons of Variation.

Our present task is then to determine, so far as possible, what factors produce such polygons of variation as are shown in Diagram 1; to define what the individuals of different sizes and proportions really are, and to what their particular characteristics are due.

There are several sets of problems to be considered; these we may classify as follows:

1. What are the causes and the significance of the variations shown in a single variation polygon, such as *D,* Diagram 1? Why, in a group of *Paramecia* grown under the same conditions, and perhaps all descended from the same ancestor, do certain indviduals show the mean length, while others are larger and others smaller? Each size must have its determining factors.

2. In different polygons from *Paramecia* of the same general group and even when all are progeny of the same individual, the ***mean*** size differs much. Thus, in Diagram 6 (page 470) the mean length for polygon 8 is 146.108 microns; for polygon 11 it is 191.360 microns, though both represent descendants of the individual *D,* of the *caudatum* group. What are the causes of such variations in mean size among different sets of individuals?

3. In different sets of individuals belonging to the same general group, or descended from the same individual, the amount and range

of variation differs much. This is readily evident to the eye on comparing the polygon 8 of Diagram 6 and its correlation table, XIX. (page 466), with polygon 9 (Diagram 6) and its table, XX. In the former the length ranges only from 120 to 176 microns, and the coefficient of variation is 7.003, while in the latter the range of length is from 120 to 220, and the coefficient of variation is 12.767. What is the cause of these great differences in the variation of different groups?

4. In different sets belonging to the same general group the *correlation* between length and breadth differs greatly. Thus, in Table XX. (page 466) the correlation is high and positive, a difference in one dimension being accompanied, with much regularity, by a corresponding difference in the other. In Table XXXI. (appendix), on the other hand, there is almost no correlation, while in Tables XXIX. and XXXII. the correlation is marked, but negative —an increase in length being associated with a decrease in breadth, and vice versa. What are the causes and significance of these differences in correlation found in different sets?

In dealing with these questions, there are three main sets of possible factors to be examined, as follows:

1. *Hereditary Factors.*—Some of the factors concerned may be internal and largely independent of the environment—so that the differences in size are hereditary. The existence and nature of such factors form our main problem, but they can be dealt with only after the other factors are investigated.

2. *Growth.*—Some of the variations in size, and in proportions, may be due to different stages of growth, so that this matter must be carefully examined.

3. *Environmental Influences.*—It appears probable that the differences in the means, the differences in the range and amount of variation, and in the correlation, may depend partly on the nature of the environment.

We shall take up in detail these three sets of factors, beginning with growth.

## III. GROWTH IN PARAMECIUM.

One significant fact was noted in the breeding experiments described in a previous section. Whenever a large and small specimen (belonging to a given group) were isolated at the same time, *the large specimen as a rule divided first.* Often at the end of forty-eight hours the large specimen had produced eight or sixteen progeny, while the small specimen had either not divided at all, or had produced but a single pair.

This suggests that the differences in size may be largely matters of growth; that the small specimens may be young ones, and that the variations shown in the frequency polygons may be largely growth differences. It is clear that a study of growth in *Paramecium* is imperative before intelligent work can be done with variation. The subject of growth in the Protozoa is an interesting one in itself, so that this study will be made as thorough as possible for its own sake, as well as for the light it throws on variation.

Growth was studied by three different methods: (1) By observation of abnormal specimens bearing localized appendages, noting the changes in position during growth; (2) by following the changes of form and size in living specimens; (3) by a statistical examination of the dimensions of individuals of known age.

The observations on growth in abnormal specimens have been described in my first communication (Jennings, 1908). By observations on the living specimen it is not possible to obtain precise measurements. It will be best therefore to begin our account with the statistical examination, taking up the observations on the living specimens by way of control.

### EFFECTS OF GROWTH ON A VARIATION POLYGON.

If our suspicion that growth differences make up an important part of the observed variations in size of *Paramecium* is justified, then cultures rapidly multiplying and growing should be more variable than those that are stationary. To test whether this is true, two lots were removed from a rather old culture of descendants of *D,* in which inspection showed that the individuals were not multiplying rapidly. One of these lots was killed at once, while the other was placed in fresh culture fluid. Twenty-four hours later this second set was found to be multiplying rapidly; a portion of it was then killed. The measurements of the two lots are given in Tables VI. and VII., while the facts are graphically represented in the

TABLE VI.

*Correlation Table for Lengths and Breadths of a Random Sample from a Culture of Descendants of D, in which Multiplication was not in Progress. For comparison with Table VII.* (See also Diagram 3.) (Row 3, Table XVIII.)

Length in Microns.

| Breadth in Microns. | 148 | 152 | 156 | 160 | 164 | 168 | 172 | 176 | 180 | 184 | 188 | 192 | 196 | 200 | 204 | 208 | 212 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 32 | 1 | | | | 2 | | 1 | 1 | 3 | 1 | | | | | | | | 9 |
| 36 | | | | 2 | | 6 | 5 | 1 | 2 | 2 | 2 | | | | | | | 20 |
| 40 | | 1 | | 1 | | 3 | 8 | 4 | 4 | 4 | 3 | 1 | 3 | 3 | | | | 35 |
| 44 | | | | 1 | | 1 | 2 | 2 | 2 | 3 | 3 | 4 | 1 | 3 | | | | 22 |
| 48 | | | | | | | 1 | 1 | 3 | 2 | 1 | 3 | 4 | 3 | 1 | 4 | 2 | 25 |
| 52 | | | | | 1 | | | 1 | 1 | | | 2 | 1 | | 2 | 3 | 4 | 15 |
| 56 | | | | | | | | | | 1 | | | | 2 | | 1 | | 4 |
| 60 | | | | | | 1 | | | | | | 1 | 1 | | 2 | | | 5 |
| | 1 | 1 | 0 | 4 | 3 | 11 | 17 | 10 | 15 | 13 | 9 | 11 | 10 | 11 | 5 | 8 | 6 | 135 |

Length—Mean, 185.008 ± .836μ
St. Dev., 14.420 ± .592μ
Coef. Var., 7.794 ± .324

Breadth—Mean, 43.556 ± .392μ
St. Dev., 6.748 ± .276μ
Coef. Var., 15.490 ± .651

Mean Index, 23.517 per cent.; Coef. Cor., .5955 ± .0375.

TABLE VII.

*Correlation Table for Lengths and Breadths of a Random Sample of Descendants of D, at a Time when Rapid Multiplication was in Progress. For comparison with Table VI.* (See also Diagram 3.) (Row 4, Table XVIII.)

Length in Microns.

| Breadth in Microns. | 104 | 108 | 112 | 116 | 120 | 124 | 128 | 132 | 136 | 140 | 144 | 148 | 152 | 156 | 160 | 164 | 168 | 172 | 176 | 180 | 184 | 188 | 192 | 196 | 200 | 204 | 208 | 212 | 216 | 220 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 32 | | | | | | | | | | | | | 2 | | | | | | | | | | | | | | | | | | 2 |
| 36 | | | | | | | | | | 1 | 1 | 1 | 4 | 1 | 4 | 1 | 1 | 2 | | 1 | | | | | | | | | | | 17 |
| 40 | | | | | | | | 1 | | 1 | 1 | 1 | 2 | 2 | 2 | | 3 | 3 | 5 | 2 | 3 | 1 | 1 | 1 | | | | | | | 29 |
| 44 | 1 | | | | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 4 | 2 | | | 3 | 1 | 5 | 6 | 2 | 6 | 1 | 2 | | | | | | 41 |
| 48 | | | 2 | 1 | | | | | | 1 | 1 | 2 | | | | 1 | 1 | 1 | | 2 | 4 | 5 | 4 | 4 | 4 | 3 | 1 | | | | 37 |
| 52 | | | 1 | 1 | | | | 1 | | | | 1 | | | | | | 1 | 2 | 1 | 5 | 4 | 1 | 5 | 5 | 2 | | | | | 31 |
| 56 | 1 | | | | | | | | | | | | | | | | | 1 | 2 | 3 | 1 | 3 | 2 | 3 | 2 | 4 | 1 | | | | 23 |
| 60 | | | | | | | | | | | | | | 1 | | | 1 | | | 1 | 2 | | | | | 2 | 3 | 1 | 1 | | 12 |
| 64 | | | | | | | | | | | | | | | | | 1 | | 1 | | | | | | | | | | | | 2 |
| 68 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0 |
| 72 | | | | | | | | | | | | | | | | | | | | | 1 | | | | | | | | | | 1 |
| | 2 | 0 | 3 | 2 | 0 | 1 | 1 | 3 | 1 | 4 | 4 | 6 | 9 | 8 | 8 | 2 | 7 | 11 | 11 | 15 | 22 | 15 | 14 | 14 | 13 | 11 | 5 | 1 | 1 | 1 | 19 |

Length—Mean, 176.124 ± 1.128μ
St. Dev., 23.360 ± .797μ
Coef. Var., 13.262 ± .461,

Breadth—Mean, 47.364 ± .344μ
St. Dev., 7.132 ± .244μ
Coef. Var., 15.057 ± .526.

Mean Index, 27.153 per cent.; Coef. Cor., .3945 ± .0408.

polygons of Diagram 3. It is evident that the variability has become much greater in the rapidly growing culture. The range of variation of length in the stationary culture is from 148 to 212 microns; in the growing culture it is from 104 to 220 microns, so that in the latter the range has almost doubled in extent. The coefficient of variation in length has likewise almost doubled, changing from 7.794 when the culture was stationary to 13.262 when it was growing. For breadth the range of variability has likewise increased considerably, though the coefficient of variability shows little change. The correlation between length and breadth has become considerably less in the rapidly multiplying culture, decreasing from .5955 to .3945. The mean length has slightly decreased, the mean breadth slightly increased, in the growing culture.

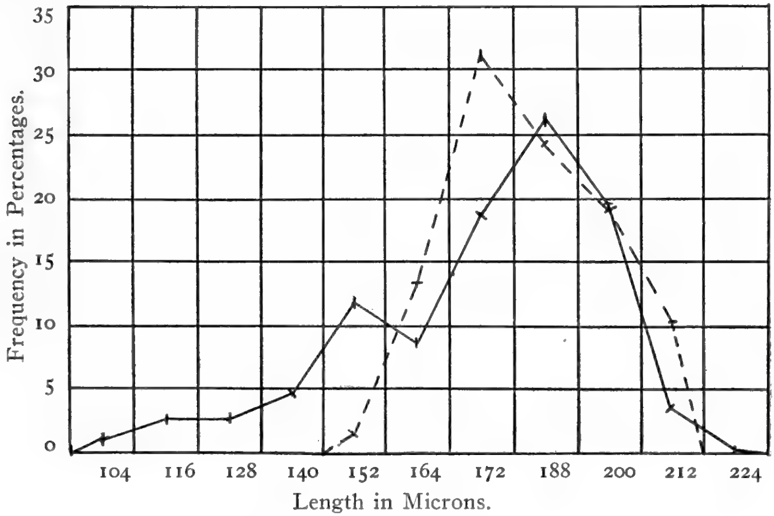

Diagram 3. Polygons of variation in length for (*a*) a culture of descendants of *D* that is rapidly multiplying and (*b*) one that is not. The continuous line represents the rapidly multiplying culture of Table VII.; the broken line the stationary culture of Table VI.

From this example it is clear that growth and multiplication may, and probably do, play a large part in determining the character and distribution of the variations, as well as in determining the mean dimensions and their correlations. We shall now attempt to determine as accurately as possible what this part is by a systematic study of growth.

## MATERIAL AND METHODS OF WORK.

In order to exclude possible differences due to different ancestry, the study of growth was made with the progeny of a single individual for each of the two groups. Of the *caudatum* group a single individual *D* was isolated April 12. This individual was a large one, measuring approximately 250 microns in length. From it many cultures were made under various conditions, and all the results on growth in this group were reached with progeny of this individual *D,* save in cases where the contrary is expressly stated. In the same way the results for the *aurelia* group were reached with the progeny of a single individual *c,* unless otherwise noted.

The method of work in the statistical study of growth was as follows: Numbers of dividing *Paramecia* of known descent were isolated and kept for varying periods, so that the age of the individuals was known to within a few minutes or even less. The individuals were then killed at different ages by the use of Worcester's fluid, and measured. In this way the usual size at various ages was determined, and those variations in size that are due only to varying age of the individuals were excluded. By pursuing this method, an approximate curve of growth is obtained and the part played by growth in the observed variations elucidated; much light is in this way cast on many obscure matters.

To persons who have worked with *Paramecium* it is unnecessary to point out the extremely laborious and time-consuming character of the operations required. Dividing specimens must be sought for with the microscope, among hundreds of their rapidly moving fellows; they must be taken up with the capillary tube, isolated, placed in culture fluid, and the time of capture noted. They must then, after lapse of the proper interval, be killed and measured; this is the smallest part of the work. To thus deal with individuals of known age by the hundred involves an incredible amount of exhausting labor, so that if the mathematical student finds in any stage the numbers employed not always as large as would be ideally desirable, he will realize that there is good reason for this. But it is hoped that the numbers used are amply sufficient, on the whole, for the purposes designed; the results are drawn from the measurement of over 1,500 specimens of known age; together with control cultures of mixed ages in still larger number.

Especially in the study of individuals that are very young (up to the age of half an hour or so), there is very great difficulty in dealing with large numbers owing to the fact that the time required for picking them out is very large in proportion to the amount of time they are to be kept, so that but few can be dealt with at once. Another great difficulty lies in the fact that to be strictly comparable, the sets of different ages must be chosen *on the same day from the same culture;* otherwise differences due to cultural conditions show themselves, confusing our results. No culture remains the same for two successive days, and the differences quickly show themselves in the statistical results. The condition just mentioned cannot be absolutely fulfilled, but much effort was directed toward filling it as completely as possible, and where it could not be fulfilled, strict account of that fact was taken.

The fixing and measurement of the specimens was done by the methods already described (p. 396).

## 1. Description of Different Stages of Growth.

### *First Stage: the Young Before Separation is Complete.*

In the earliest stage recognizable, the young *Paramecium* forms half of a dividing specimen. Before the constriction appears the macronucleus has become band-like, and the mother infusorian is shorter and thicker than the specimens not preparing to divide (see Fig. 2, *a*). The oral groove and other differentiated parts have become less marked. At the first appearance of the constriction the anterior and posterior halves still retain something of their characteristic form, and the body of the mother has extended a little (Fig. 2, *b*). The constriction does not pass squarely across the body, but is a little oblique, being farther back on the oral side (Fig. 2, *c, d, e*). As a result, when the two halves are measured separately, they will seem to differ in length, according to the place where the measurement is taken. Thus, if *d,* Fig. 2, is measured from the ends to the constriction along the oral side, the anterior half measures 96 microns, the posterior half 84 microns, while if the measurements are taken along the aboral side these proportions are exactly reversed. Measurements taken from one of the lateral sides give the same length for the two halves. The *Paramecia* may lie in various positions and this obliqueness of the constricting groove is not always evident. Misled by this fact, I took great pains to measure the precise length of each half in a large number of cases, finding considerable differences, though without any marked preponderance of either half. But I am now convinced that in early stages of fission the most accurate measurements of the young are to be obtained by considering each to be one half the length of the two together.

The breadth of the two halves frequently differs a little, the posterior half being at times slightly broader than the anterior half.

As the constriction deepens, the two halves lengthen (Fig. 2, *b* to *f*; *g* to *l,* etc.). This lengthening progresses with the advancing

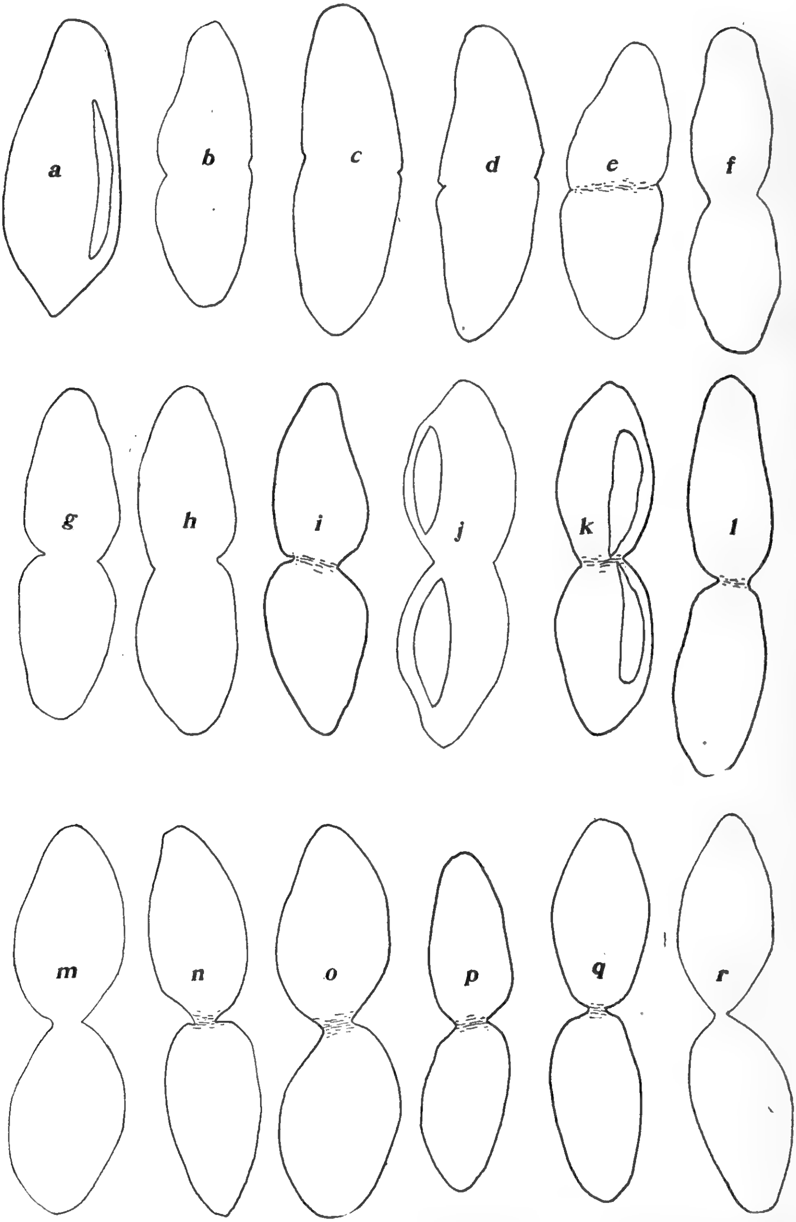

FIG. 2. Dividing specimens of the *caudatum* form, descended from the individual *D*. Note the increase in length and decrease in breadth as the constriction deepens. Anterior ends above. All × 235.

constriction until the two halves separate. This lengthening is clearly evident in the figures and in the correlation table giving depth of constriction with length of body (Table XI., page 441). As Table XI. shows, there is a period at the beginning, before the constriction reaches a depth of about 10 microns, when there is little relation between the length of the body and depth of constriction, showing that in this period the halves have not yet begun to lengthen. We may therefore take the length of the young at this period as that characteristic for the young individuals in their earliest recognizable condition, before growth has begun. By dealing with these alone we are able to compare the variability of the young with that of the adults, or with random samples including all ages. In the further treatment, therefore, the measurements of the unseparated young are divided into two classes: (*a*) those before lengthening has begun; (*b*) those after lengthening has begun.

(*a*) *The Unseparated Halves before Lengthening Has Begun.*—Studies were made of the young of three lots of the *caudatum* group (descendants of the individual *D*), and of two lots of the *aurelia* group (descendants of the individual *c*). Each "lot" included individuals taken on the same day from the same small culture. In most of the lots there were examined: (1) The unseparated young before growth had begun; (2) the unseparated young after growth had begun; (3) a random sample, including all sorts of individuals found in the culture. The results of these measurements are given in Table VIII., page 418.

(1) The *caudatum* Form (Descendants of *D*).—The most thorough study was made of lot 1, of the *caudatum* group; the results there reached are typical, and perhaps more reliable than any others, owing to the large numbers examined. We shall therefore make the results on this lot the basis of our discussion, afterward bringing out points of difference and resemblance shown in the other lots.

From this lot 1, I measured 313 dividing specimens, which, of course, included 626 unseparated young; a random sample of 200 individuals not dividing was likewise measured. A correlation table for the 313 dividing specimens, giving *the depth of the constriction* below the general body surface and the length is given on page 441

TABLE VIII.

*Mean Dimensions and Constants of Variation for Youngest Stages, in Com-* is for convenience of reference in the text. The column headed which fuller data are given on the lot in question. A "Lot" consists of Table X., page 428.

| Row. | A. *Progeny of D (Caudatum Form).* | Number of Individuals. | Table. | Length. | | |
|---|---|---|---|---|---|---|
| | | | | Mean. | Standard Deviation. | Coefficient of Variation. |
| 1 | Lot 1. Young halves, where depth of constriction is 4μ or less ..... | 262 | 9 | 87.848±.278 | 4.716±.197 | 5.368±.224 |
| 2 | Lot 1. Halves, where depth of constriction is more than 4μ.............. | 364 | (62) | 93.033±.355 | 7.104±.251 | 7.636±.271 |
| 3 | Lot 1. Random sample...... | 200 | 14 | 199.960±.740 | 15.528±.524 | 7.765±.263 |
| 4 | Lot 2. Halves, where depth of constriction is less than ¼ breadth....... | 80 | (43) | 82.600±.468 | 4.394±.332 | 5.320±.402 |
| 5 | Lot 2. *All* halves of dividing specimens............... | 124 | (42) | 85.774±.593 | 6.924±.420 | 8.072±.492 |
| 6 | Random sample............... | 200 | 30 | 184.100±.776 | 16.264±.548 | 8.834±.300 |
| 7 | Lot 3. Halves, depth of constriction less than ¼ breadth.................. | 84 | (44) | 83.810±.498 | 4.782±.352 | 5.706±.421 |
| 8 | Lot 3. Adults 24 hours old. | 300 | 41 | 168.532±.419 | 10.768±.296 | 6.389±.175 |
| | B. *Progeny of c (aurelia form).* | | | | | |
| 9 | Lot 4. Halves, where depth of constriction is less than ¼ breadth...... | 132 | (47) | 51.868±.325 | 3.912±.190 | 7.541±.445 |
| 10 | Lot 4. Halves, lengthening begun (constriction more than ¼ breadth).......... | 106 | (63) | 60.692±.527 | 5.684±.372 | 9.365±.613 |
| 11 | Lot 4. Random sample...... | 225 | 49 | 114.163±.784 | 17.443±.555 | 15.279±.497 |
| 12 | Lot 5. Halves, where constriction is less than ¼ breadth...................... | 76 | 48 | 56.666±.425 | 3.889±.302 | 6.862±.533 |
| 13 | Lot 5. Random sample...... | 100 | 50 | 114.033±.820 | 12.140±.580 | 10.646±.513 |
| 14 | Lots 4 and 5. All halves where constriction is less than ¼ breadth (combination of rows 9 and 12)......... ................. | 208 | — | 53.622±.300 | 4.535±.212 | 8.459±.398 |

(Table XI.). In 131 of these specimens the constriction had sunk less than one unit of the micrometer (4 microns) below the surface, while in the other 182 the depth of the constriction was greater. We may take the 131 specimens in which constriction had barely begun

TABLE VIII.—*Continued.*

*parison with Random Samples and Adults.* (The column headed "Row" "Table" gives the number of a table found elsewhere in the paper, in specimens all taken from the same culture on the same day.) Compare

| Breadth. | | | Ratio of Breadth to Length, or Mean Index Per Cent. | Coefficient of Correlation. |
|---|---|---|---|---|
| Mean. | Standard Deviation. | Coefficient of Variation. | | |
| 55.480±.297 | 5.040±.210 | 9.082±.382 | 63.136 | .6546±.0337 |
| 49.540±.215 | 4.296±.152 | 8.671±.309 | 53.592 | —.0938±.0496 |
| 50.220±.308 | 6.468±.218 | 12.877±.441 | 25.114 | .6064±.0302 |
| 50.700±.364 | 3.532±.260 | 6.769±.513 | 61.530 | .1048±.1055 |
| 50.388±.307 | 3.584±.217 | 7.112±.433 | 59.166 | —.1136±.0840 |
| 46.020±.251 | 5.256±.177 | 11.421±.390 | 25.084 | .4282±.0389 |
| 65.716±.706 | 6.784±.499 | 10.322±.768 | 78.563 | .2215±.0999 |
| 40.320±.230 | 5.892±.162 | 14.615±.411 | 23.899 | .5496±.0272 |
| 34.850±.287 | 3.453±.203 | 9.911±.587 | 67.246 | .6502±.0479 |
| 34.590±.383 | 4.147±.273 | 11.989±.797 | 57.296 | .3100±.0837 |
| 34.207±.241 | 5.363±.171 | 15.683±.511 | 30.177 | .6757±.0244 |
| 45.263±.597 | 5.463±.423 | 12.071±.947 | 79.806 | .6744±.0597 |
| 47.300±.437 | 6.490±.310 | 13.720±.667 | 41.455 | .8152±.0226 |
| 38.653±.437 | 6.607±.310 | 17.089±.822 | 71.835 | .7476±.0292 |

as types of the earliest stage of fission, and their 262 halves as young *Paramecia* in the earliest stage. The lengths and breadths of these 262 halves are given in Table IX. The constants derived from the measurements of these, as well as from the measurements of the 364

TABLE IX.

*Correlation Table for Length and Breadth of 262 Unseparated Halves of Dividing Specimens, in which the Depth of Constriction was less than four microns.* All descendants of the single individual *D*, and taken from the same culture on the same day.

Length in Microns.

| Breadth in Microns. | 78 | 80 | 82 | 84 | 86 | 88 | 90 | 92 | 94 | 96 | 98 | 100 | 102 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 44 | | 2 | | 2 | | | | | | | | | | 4 |
| 48 | 2 | 6 | 12 | 6 | 8 | 2 | | 2 | | | | | | 38 |
| 52 | | 2 | 4 | 16 | 12 | 4 | 12 | 2 | 2 | | | | | 54 |
| 56 | | 6 | 4 | 8 | 20 | 14 | 30 | 4 | 4 | 2 | 2 | | | 94 |
| 60 | | | 4 | 2 | 2 | 10 | 16 | 2 | 2 | 4 | 2 | | | 44 |
| 64 | | | | | 2 | | 4 | 6 | 2 | 4 | 4 | | | 22 |
| 68 | | | | | | | | | | 2 | | 2 | | 4 |
| 72 | | | | | | | | | | | | | 2 | 2 |
| | 2 | 16 | 24 | 34 | 44 | 30 | 62 | 16 | 10 | 12 | 8 | 2 | 2 | 262 |

Length—Mean, 87.848 ± 278μ    Breadth—Mean, 55.480 ± .297μ
St. Dev., 4.716 ± .197μ    St. Dev., 5.040 ± .210μ
Coef. Var., 5.368 ± .224    Coef. Var., 9.082 ± .382
Mean Index, 63.136 per cent.; Coef. Cor., 6546 ± .0337.

halves in which lengthening had begun, and of the random sample, are given in the first three rows of Table VIII.[8]

We will for the present limit the discussion to the relations shown by comparing the youngest stages (row 1) with the random sample (row 3) which consists mainly of adults. The following important facts are shown:

1. The mean length of the youngest stages of the new individuals is considerably *less* than one half of the mean length of the individuals that are not dividing. The mean length of the young is 87.848 microns, while that of the individuals not dividing is 199.960 microns, or 24.264 microns more than twice the mean length of the young individuals. This remarkable relation will be taken up later, in discussing the measurements of dividing specimens (page 443).

2. The mean breadth of the youngest stages is slightly greater than that of adults not dividing—55.480 microns, in place of 50,220 microns.

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[8] In Tables VIII. and IX. the measurements were made and the constants were first computed, for the entire dividing specimens. The constants for the halves were of course readily obtained from these; they are the same, save that the mean and standard deviation for length are halved, and the mean index is doubled. The computation of the probable errors was based on the *number of dividing specimens,* not on the number of halves.

3. The mean index, or ratio of breadth to length, is considerably more than twice as great in the young as in the adults; in the former it is 63.136 per cent.; in the latter 25.114 per cent.

4. The variability in length is less in the earliest stages of the young than in the individuals that are not dividing. In the former the coefficient that measures the variability is but 5.368, while in the latter it is 7.765.

5. The variability in breadth is likewise much less in the youngest stages—the coefficient being 9.082 in place of 12.877.

6. The correlation between length and breadth is nearly the same in the youngest stage as in the random sample, being .6546 in the former, .6064 in the latter.

From the other lots smaller numbers were examined. These gave on the whole similar results, though with certain significant differences. The facts are as follows:

From lot 2 (descendants of *D*), 124 halves were obtained. On account of the small number, I threw together all in which the depth of the constriction was less than one fourth the breadth, and considered these the earliest stage (the depth of constriction and length are given for the entire dividing specimens in Table XLII., appendix). There were thus obtained eighty young individuals (dimensions for the entire dividing specimens in Table XLIII., appendix). It is evident that this lot includes individuals varying more in age and growth than in lot 1, since in lot 2 we have included those having a much greater depth of constriction. The results are shown, in comparison with a random sample of the same lot, in rows 4 and 6 of Table VIII. The facts are in the main parallel with those for lot 1. As compared with the random sample, the mean length of the young is less than one half, the mean breadth a little greater, the mean ratio of breadth to length more than double, the coefficients of variation for length and breadth much less. A striking difference between this set and the young of lot 1 is that in the present case the correlation between length and breadth has decreased to such an extent that the coefficient computed (.1048) is without significance, being less than its probable error (.1055). This is due, as we shall clearly see later, to the fact that we have included in the young of row 4 individuals older (constriction deeper) than in those of row 1.

From a third lot of descendants of *D,* 154 halves were obtained; in 84 of these the constriction was less than one fourth the breadth. Unfortunately no random sample of this culture was preserved. But 300 individuals just twenty-four hours old were taken from it for other purposes, and the young halves may be compared with these (rows 7 and 8, Table VIII.).[4] It should be noted, however, that the adults of row 8 had been kept for twenty-four hours in a rather small quantity of water, where food was relatively scarce, so that they were smaller than would have been the case if they had lived throughout under the same conditions as the dividing specimens.

In general, the same relations are shown here as in the other lots. A striking peculiarity is the great breadth of the young halves (65.716 microns), as compared with that of the adults (40.320 microns), so that the ratio of breadth to length (the "mean index") is more than three times as great in the young as in the adults (78.563 per cent. in the former, 23.899 per cent. in the latter). Owing to the inclusion of older halves, in which lengthening has begun, the correlation between length and breadth is again low (.2215 ± .0999).

(2) The *aurelia* Form (Descendants of *c*).—Two lots of dividing specimens of the *aurelia* form were examined, the first including 132 halves in which lengthening had hardly begun, the second 76. The constants for these, in comparison with random samples of those not dividing, are given in rows 9 to 14 of Table VIII. These show the same relations that we have already seen in the *caudatum* group, with one exception. In the smaller collection (lot 5), the mean breadth of the halves was a little *less,* instead of greater, than that of the random sample. In this culture the animals were extraordinarily broad, the mean ratio of breadth to length in the random sample being 41.455 per cent., in place of the usual ratio of about 30 per cent. This was due to the fact that these animals had been placed twenty-four hours before in a rich nutrient solution and had

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[4] The dimensions of the entire dividing specimens of which row 7 are the halves are given in Table XLIV. of the Appendix; the dimensions of the 300 just twenty-four hours old are given in Table XLI.

become very plump. The point of interest is that the breadth of the young individuals in the earliest stages tends toward a constant dimension, becoming greater when the adults are thin, less when the adults are plump. Outlines of dividing specimens, and of those not dividing, from this culture, are shown in Fig. 3, *a* to *f*; the great difference in breadth is noticeable.

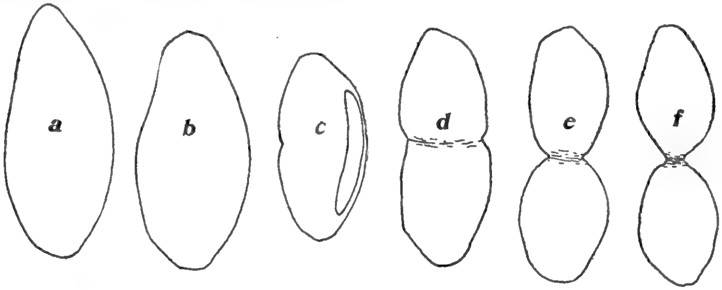

FIG. 3. Outlines of specimens of the *aurelia* form (descendants of *c*), from Lot 5, Table VIII. *c* to *f*, Successive stages of fission. Note the greater breadth of the specimens not dividing (*a* and *b*). Same magnification as Fig. 2. (235 diameters.)

In row 14, Table VIII., are given the constants for all the young halves examined of the *aurelia* group; that is, for the sum of rows 9 and 12. The coefficients of variation are, as might be expected, increased by adding these two dissimilar groups. The fact that the correlation between length and breadth is likewise increased, as compared with what we find in either group taken alone, might not, perhaps, be anticipated. These changes in variation and correlation are environmental effects, to be studied later.

(*b*) *The Unseparated Halves after Lengthening Has Begun.*—As we have already seen, the length of the halves increases as the constriction deepens (see the correlation tables for length with depth of constriction, Nos. XI. (page 441), XLV., XLVI.; compare also the outlines of dividing specimens, Figs. 2 and 3). The coefficient of correlation between depth of constriction and length is, for the 626 halves of Table XI., .6882; with each increase of 10 microns in depth of constriction the length increases 4.30 microns. If we include only the individuals in which lengthening has clearly begun (thus omitting the uppermost row of Table XI.), we find that for these 364 halves the correlation between depth of constriction and length is greater, amounting to .7818; while the increase in length with each 10 microns of increase in depth of the constriction is 5.598 microns.

While the length thus increases, the breadth decreases. This is evident on inspection of Table XII. The correlation between depth of constriction and breadth of body is therefore negative; its coefficient, in the case of Table XII., is —.5232. With each increase of 10 microns in the depth of constriction the breadth of body decreases 2.630 microns. If again we take into consideration only the 364 halves in which lengthening has decidedly begun, omitting thus the uppermost row of Table XII., we find that the correlation decreases to —.3316, and the decrease in breadth for an increase of 10 microns in depth of constriction is but 1.252 microns. This appears to indicate that a large part of the decrease in breadth occurs in the first stages of constriction.

If we compare with the means of the 262 halves in which lengthening has not begun, the means of the 364 in which lengthening has begun (Table VIII., rows 1 and 2), we find that the length has increased from 87.848 to 93.033 microns, while the breadth has decreased from 55.480 to 49.540 microns. If we examine the means at successively older stages, we find, of course, greater differences. Thus, when the constriction has reached a depth of 36 microns, the 10 specimens in that stage show the mean length increased to 101.200 microns, while the mean breadth is but 46.400 microns. Similar relations are to be observed if we compare the means of the younger and older sets of each lot shown in Table VIII.

Since, while the length is increasing, the breadth is decreasing, the growth tends to decrease the correlation between length and breadth or even to make it negative. Thus, while in the stage before lengthening has begun (row 1, Table VIII.) the correlation is .6546, in the 364 specimens of the same lot, *after* lengthening has begun the correlation has decreased to —.0938 (row 2, Table VIII.). In a second lot, containing 124 halves, when we throw all the halves together the coefficient of correlation between length and breadth becomes —.1136 (row 5, Table VIII.). In the *aurelia* form, 106 halves after lengthening has begun give a positive correlation between length and breadth of .3100 (row 10, Table VIII.). Why there should sometimes be a slight positive correlation, sometimes a negative one, at this stage, will be discussed in the section where we deal with the various factors determining correlation.

A variation polygon for the youngest stage of lot 1 of Table VIII. is shown in Diagram 4, p. 440, at *a*.

The changes above set forth from statistical data were in a number of cases observed in living individuals. These observations give a number of additional points of importance, so that they will be described. The facts, as illustrated mainly by a typical specimen of the *aurelia* form, are as follows:

Some time before fission the body thickens and becomes shorter, taking the form shown at *a*, Fig. 2, or *c*, Fig. 3. The form and dimensions differ very noticeably from those of the specimens not preparing to divide. How long before the appearance of the constriction these preparatory changes in form begin it is not possible to say, because it is not possible to distinguish with certainty whether a given specimen is to divide or not until we can see the constriction, and this is at a relatively advanced stage of the process. At the time the constriction first appears the anterior and posterior halves still differ in form, though they are losing their characteristic features.

As the constriction deepens the two halves become longer (Fig. 2, *b* to *f*, Fig. 3, *c* to *d*). A specimen of the *aurelia* form (descendant of *c*) was at about the stage shown at *d*, Fig. 3, at 12.05; each half measured very nearly 80 microns in length.

Ten minutes later (at 12.15) the connecting portion had become smaller, while the two halves had lengthened, so that each measured about 85 microns in length. The anterior half was more pointed and slightly more slender than the posterior half (*f*, Fig. 3); this is regularly the case.

Six minutes later (at 12.21) the posterior half measured about 90 microns, the anterior half 94. The connecting band was now extremely slender.

Five minutes later (at 12.26) the two halves separated. The anterior half was still clearly distinguishable from the posterior one by its pointed, somewhat pear-like form. It measured 100 × 44 microns, while the posterior half was shorter, but thicker, measuring 96 × 52 microns. The succeeding changes of form will be described in the next section.

Thus from the condition shown at *d,* Fig. 3, to the completion of fission a period of twenty-one minutes elapsed. From the earliest appearance of the constriction the time till separation is usually a little more than one half hour.

### *Second Stage: the Young Immediately after Fission up to the Age of Ninety Minutes.*

*Observation of Living Specimens.*—Immediately after separation of the two halves, growth occurs rapidly, and the shape changes, both halves becoming more pointed at both ends. In the specimens of the *aurelia* form under description at the close of the last section, the posterior half had two minutes after fission increased in size from 96 × 52 microns to 104 × 48 microns. Eight minutes after separation both halves measured 112 microns in length, so that they had during that period increased respectively 12 and 16 microns in length. The difference between anterior and posterior individuals was still marked.

Now followed a period of slower growth. At 12.53, twenty-seven minutes after division, each half measured approximately 120 microns in length. They had taken nearly the characteristic adult form and it was no longer possible to distinguish the anterior product from the posterior one.

At 2 P. M. (one hour and thirty-four minutes after separation) the length was about 135 microns and the progeny were similar to the adult specimens of the *aurelia* form.

Thus, at the time of separation the two individuals have somewhat more than half the adult length; they grow rapidly at first, then slowly, and in an hour and a half have reached nearly the adult size. (As later statistical studies show, growth continues for a long time still.)

Observation on the growth of living specimens of the *caudatum* form gave a parallel series of phenomena (see Fig. 4). Thus, in a descendant of *D,* the length of each half at the time of separation was about 120 microns; width 48 microns. Five minutes later the length had increased to 132 microns, while the width was still 48 microns. Nine minutes later the length of the anterior product was 148 microns; that of the posterior product 144 microns. The width had decreased a little; it was now about 44 microns.

After thus increasing in fourteen minutes by nearly one fourth the original length, growth became less rapid. Forty minutes later (fifty-four minutes after separation) the length was about 156 microns. During two succeeding hours no increase in length could be detected. The form was that of the normal adult, though the adult size was not yet reached.

We may summarize as follows: Some time before fission (perhaps a half hour) the body shortens and thickens, so that each half is at first less than half the adult length. As the constriction deepens the two halves grow longer, till at the time of separation they are somewhat more than half the adult length. For five to twenty minutes after separation growth in length is very rapid, while the thickness remains stationary or decreases. Then follows a period of several hours of slower growth, till the adult size is reached.

This somewhat indefinite account, based on the observation of living specimens, will now be supplemented by a statistical investigation of a large number of individuals at various ages. The main results of this statistical investigation are brought together in Table X.

(*c*) *Age 0 to 5 Minutes* (*Table XXIX.*).—A large number of dividing specimens, all descendants of the individual *D* (*caudatum* form), were removed from a rapidly multiplying culture and kept for from 0 to 5 minutes in a watch-glass of culture fluid, then killed and measured. The method of work was to spend five minutes in picking out dividing specimens with the capillary tube and placing them in the watch-glass; at the end of the five minutes the lot was killed. Then other lots were prepared in the same way. In each lot killed, therefore, there occurred specimens that were in the early stages of fission; others that had separated at the moment of removal and were hence just five minutes old; and all stages intermediate between these two. All together, 62 unseparated pairs and 59 separated individuals were secured in this way. The latter set consists of individuals from 0 to 5 minutes old (reckoning from the moment

### Table X.

*Dimensions and Constants of Variation for Paramecia of Various Ages, in*
taken from the same culture on the same day. The lots where identical
column headed "Row" is for convenience of reference. The column
elsewhere, in which fuller data are given on the lot in question.)

| Row. | A. *Progeny of D* (*Caudatum Form*). | Number of Individuals. | Table. | Length. | | | |
|---|---|---|---|---|---|---|---|
| | | | | Mean in Microns. | Standard Deviation in Microns. | Coefficient of Variation. | Range of Variation in Microns. |
| 1 | Lot 1. Youngest unseparated halves, constriction beginning | 262 | 9 | 87.848± .278 | 4.716± .197 | 5.368± .224 | 78–102 |
| 2 | Lot 1. Halves, lengthening begun | 364 | (62) | 93.033± .355 | 7.104± .251 | 7.636± .271 | 80–112 |
| 3 | Lot 1. Random sample | 200 | 14 | 199.960± .740 | 15.528± .524 | 7.765± .263 | 148–240 |
| 4 | Lot 2. From beginning of constriction to 5 minutes after separation | 183 | — | 92.940± .718 | 14.400± .508 | 15.494± .559 | 72–132 |
| 5 | Lot 2. 0 to 5 minutes after separation | 59 | 29 | 107.660±1.296 | 14.780± .916 | 13.729± .868 | 76–132 |
| 6 | Lot 2. Random sample | 200 | 30 | 184.100± .776 | 16.264± .548 | 8.834± .300 | 140–216 |
| 7 | Lot 6. Age 0 to 19 minutes. | 24 | 31 | 128.000±1.908 | 13.856±1.348 | 10.825±1.066 | 108–152 |
| 8 | Lot 6. Age 18 to 28 minutes | 49 | 33 | 143.348± .624 | 6.480± .440 | 4.521± .309 | 132–160 |
| 9 | Lot 6. Age 35 to 45 minutes | 25 | 35 | 149.920±1.012 | 7.512± .716 | 5.010± .479 | 132–160 |
| 10 | Lot 6. Age 75 to 90 minutes | 42 | 36 | 161.524±1.004 | 9.648± .712 | 5.974± .441 | 140–180 |
| 11 | Lot 6. Age 0 to 90 minutes (sum of rows 7–10) | 140 | — | 147.544± .824 | 14.464± .584 | 9.803± .399 | 128–180 |
| 12 | Lot 6. Random sample | 100 | 51 | 184.680± .848 | 12.596± .600 | 6.821± .327 | 156–224 |
| 13 | Lot 7. Age 0 to 19 minutes | 39 | 32 | 134.256±1.663 | 15.394±1.176 | 11.468± .857 | 108–160 |
| 14 | Lots 6 and 7. All 0 to 19 (sum of rows 7 and 13) | 63 | — | 131.872±1.288 | 15.176± .912 | 11.507± .701 | 108–160 |
| 15 | Lots 6 and 8. Age 18 to 28 minutes (sum of row 7, and of 57 of another lot) | 106 | 34 | 143.82 ± .544 | 8.296± .384 | 5.769± .268 | 112–168 |
| 16 | Lot 9. Age 3 to 4 hours | 93 | 37 | 149.636± .688 | 9.856± .488 | 6.587± .327 | 132–176 |
| 17 | Lot 9. Age 4.20 to 5 hours | 95 | 38 | 186.736± .652 | 9.416± .460 | 5.043± .247 | 164–216 |
| 18 | Lot 9. Age 3 to 5 hours (sum of rows 16 and 17) | 188 | — | 168.384±1.028 | 20.904± .727 | 12.415± .438 | 132–216 |
| 19 | Lot 9. Random sample. | 195 | 7 | 176.124±1.128 | 23.360± .797 | 13.262± .461 | 104–220 |
| 20 | Lot 10. Age 12 hours | 73 | 39 | 188.988± .996 | 12.612± .704 | 6.672± .374 | 136–216 |
| 21 | Lot 10. Age 12 hours (same as row 20, but omitting 2 smallest). | 71 | 39 | 190.424± .752 | 9.388± .531 | 4.930± .280 | 164–216 |
| 22 | Lot 10. Age 18 hours | 105 | 40 | 199.048± .380 | 11.844± .552 | 5.949± .278 | 168–228 |
| 23 | Lot 3. Age 24 hours | 300 | 41 | 168.532± .419 | 10.768± .629 | 6.389± .175 | 140–200 |
| 24 | Lot 3. Early fission, depth of constriction less than ¼ breadth | 42 | 44 | 167.620± .996 | 9.564± .704 | 5.706± .421 | 152–192 |
| 25 | Lot 1. Early fission, constriction 4μ or less | 131 | 13 | 175.696± .556 | 9.432± .393 | 5.368± .224 | 156–240 |

TABLE X.—*Continued.*

*Comparison with Random Samples.* (Each "Lot" consists of specimens
with those of Table VIII. are numbered the same as in Table VIII. The
headed "Table" gives the number of a table found in the appendix or

| Breadth. | | | | Mean Index, Ratio of Breadth to Length. Per Cent. | Coefficient of Correlation. |
|---|---|---|---|---|---|
| Mean in Microns. | Standard Deviation in Microns. | Coefficient of Variation. | Range of Variation in Microns. | | |
| 55.480±.297 | 5.040±.210 | 9.082±.382 | 44–72 | 63.136 | .6546±.0337 |
| 49.540±.215 | 4.296±.152 | 8.671±.309 | 40–68 | 53.592 | —.0938±.0496 |
| 50.220±.308 | 6.468±.218 | 12.877±.441 | 36–72 | 25.114 | .6064±.0302 |
| 48.852±.210 | 4.216±.149 | 8.633±.307 | 36–64 | 54.080 | —.3625±.0433 |
| 46.372±.332 | 3.804±.236 | 8.200±.524 | 36–56 | 44.037 | —.3138±.0792 |
| 46.020±.251 | 5.256±.177 | 11.421±.390 | 36–60 | 25.084 | .4282±.0389 |
| 60.168±.788 | 5.712±.556 | 9.495±.933 | 52–76 | 47.573 | —.0337±.1375 |
| 54.284±.364 | 3.788±.260 | 6.976±.478 | 48–64 | 37.921 | .1937±.0927 |
| 55.840±.636 | 4.724±.452 | 8.461±.813 | 48–64 | 37.296 | .2799±.1243 |
| 54.192±.600 | 5.752±.424 | 10.617±.790 | 40–68 | 33.558 | .5232±.0756 |
| 55.544±.308 | 5.416±.220 | 9.748±.397 | 40–76 | 38.038 | —.0844±.0566 |
| 64.880±.580 | 8.624±.412 | 13.292±.645 | 44–88 | 35.131 | .6469±.0392 |
| 46.768±.408 | 3.792±.288 | 8.108±.623 | 36–52 | 35.616 | —.2546±.1010 |
| 51.872±.680 | 7.980±.480 | 15.382±.946 | 36–76 | 40.028 | —.2476±.0798 |
| 50.832±.320 | 4.900±.228 | 9.640±.451 | 36–64 | 35.438 | .1319±.0644 |
| 51.568±.322 | 4.752±.236 | 9.212±.459 | 40–64 | 34.546 | .3201±.0628 |
| 60.168±.360 | 5.224±.256 | 8.679±.428 | 52–76 | 32.225 | .5557±.0478 |
| 55.916±.324 | 6.588±.229 | 11.785±.416 | 40–76 | 33.372 | .7132±.0242 |
| 47.364±.344 | 7.132±.244 | 15.057±.526 | 32–72 | 27.153 | .3945±.0408 |
| 62.796±.464 | 5.872±.328 | 9.350±.526 | 48–80 | 33.275 | .4868±.0602 |
| 63.156±.443 | 5.536±.313 | 8.763±.500 | 48–80 | 33.197 | .3474±.0704 |
| 56.496±.292 | 4.428±.108 | 7.837±.367 | 48–68 | 28.427 | .4304±.0536 |
| 40.320±.230 | 5.892±.162 | 14.615±.411 | 28–56 | 23.899 | .5496±.0272 |
| 65.716±.706 | 6.784±.499 | 10.322±.768 | 48–80 | 39.286 | .2215±.0999 |
| 55.480±.297 | 5.040±.210 | 9.082±.382 | 44–72 | 31.568 | .6546±.0337 |

TABLE X.—*Continued.*

| Row. | A. *Progeny of D* (*Caudatum Form*). | Number of Individuals. | Table. | Length. | | | |
|---|---|---|---|---|---|---|---|
| | | | | Mean in Microns. | Standard Deviation in Microns. | Coefficient of Variation. | Range of Variation in Microns. |
| 26 | Lot 1. Fission, all stages but earliest | 182 | 62 | 186.066± .710 | 14.208±.502 | 7.636±.271 | 160–224 |
| 27 | Lot 1. Random sample | 200 | 14 | 199.960± .740 | 15.528±.524 | 7.765±.263 | 148–240 |
| 28 | Lot 1. Largest specimens of random sample, all more than 196 long | 134 | — | 208.268± .566 | 9.720±.400 | | 196–240 |
| 29 | Lot 1. Combination of early fission with largest of random sample (sum of rows 25 and 28) | 264 | — | 192.108 | 18.904 | | |
| 30 | Lot 2. Early stages of fission | 40 | 44 | 165.200± .936 | 8.788±.664 | 5.320±.402 | 152–192 |
| 31 | Lot 2. All stages of fission | 62 | 42 | 171.548±1.188 | 13.848±.840 | 8.072±.492 | 144–212 |
| 32 | Lot 2. Random sample | 200 | 30 | 184.100± .776 | 16.264±.548 | 8.834±.300 | 140–216 |
| | B. *Progeny of c* (*aurelia form*). | | | | | | |
| 33 | Lot 4. Early fission, depth of constriction less than ¼ breadth | 66 | 47 | 103.737± .650 | 7.823±.379 | 7.541±.445 | 83.3–126.7 |
| 34 | Lot 4. Later stages of fission | 53 | 63 | 121.383±1.053 | 11.367±.743 | 9.365±.613 | 100–156.7 |
| 35 | Lot 4. Random sample | 225 | 49 | 114.163± .784 | 17.443±.555 | 15.279±.497 | 73.3–160 |
| 36 | Lot 5. Early fission | 38 | 48 | 113.333± .850 | 7.778±.603 | 6.862±.533 | 93.3–126.7 |
| 37 | Lot 5. Random sample | 100 | 50 | 114.033± .820 | 12.140±.580 | 10.643±.513 | 86.7–146.7 |
| 38 | Lots 4 and 5. All in early fission (sum of rows 33 and 36) | 104 | — | 107.243± .600 | 9.070±.423 | 8.459±.398 | 83.3–126.7 |

of separation of the two halves). The measurements of these 59 young specimens are given in Table XXIX., while the polygon of variation for length appears at *b*, Diagram 4. For control, Table XXX. gives the measurements of a random sample of the culture from which these young specimens were selected. The constants deduced from the measurements of the young and of the random sample are shown in Table X., rows 4 to 6.

The following are the important facts which result from the examination of the young, in comparison with the adults (rows 5 and 6, Table X.).

1. The mean length of the young (0 to 5 minutes old) is considerably more than half that of the culture as a whole, being 107.660 microns as compared with 184.100 microns. Of course, the culture

TABLE X.—*Continued.*

| Breadth. | | | | Mean Index, Ratio of Breadth to Length. Per Cent. | Coefficient of Correlation. |
|---|---|---|---|---|---|
| Mean in Microns. | Standard Deviation in Microns. | Coefficient of Variation. | Range of Variation in Microns. | | |
| 49.540±.215 | 4.296±.152 | 8.671±.309 | 40-68 | 26.796 | —.0938±.0496 |
| 50.220±.308 | 6.468±.218 | 12.877±.441 | 36–72 | 25.114 | .6064±.0302 |
| 52.360±.348 | 5.964±.246 | | 40-72 | | .4681±.0455 |
| 53.908 | 5.752 | | | | .0350±.0415 |
| 50.700±.364 | 3.432±.260 | 6.769±.513 | 48–80 | 30.765 | .1048±.1055 |
| 50.388±.308 | 3.584±.216 | 7.111±.433 | 40–60 | 29.583 | —.1136±.0840 |
| 46.020±.251 | 5.256±.177 | 11.421±.390 | 36–60 | 25.084 | .4282±.0389 |
| 34.850±.287 | 3.453±.203 | 9.911±.587 | 26.7–43.3 | 33.623 | .6502±.0479 |
| 34.590±.383 | 4.147±.273 | 11.989±.797 | 26.7–46.7 | 28.648 | .3100±.0837 |
| 34.207±.241 | 5.363±.171 | 15.683±.511 | 20–50 | 30.177 | .6757±.0244 |
| 45.263±.597 | 5.463±.423 | 12.071±.947 | 33.3–56.7 | 39.903 | .6744±.0597 |
| 47.300±.437 | 6.490±.310 | 13.720±.667 | 36.7–66.7 | 41.455 | .8152±.0226 |
| 38.653±.437 | 6.607±.310 | 17.089±.029 | 26.7–56.7 | | .7476±.0292 |

as a whole contains a large number of young specimens, so that the mean of the adults would be greater than that of the random sample.

2. The mean breadth of the young is almost exactly the same as that of the culture as a whole.

3. The relative variation in length is much greater for the young than for the culture as a whole, the coefficient being 13.729 for the former as compared with 8. 834 for the latter. Moreover, the coefficient of variation is almost three times as great as in the very youngest stages before separation (Table X., row 1), or in the first stages of fission (Table X., rows 25, 30, 33, 36).

This great variability of the young at this age indicates that they are growing rapidly in length; those five minutes old are considerably longer than those that have just separated, so that when all are taken together the variation is great in proportion to the mean length. While the statistical data are themselves open to other interpretations, observation of the changes in living individuals, as described earlier, shows that this explanation is the correct one.

The *absolute* variation of the young, as shown by the standard deviation, is less, as might be expected, than that of the culture as a whole, though the difference is not great.

4. The variation in breadth, both absolute and relative, is less in the young than in the culture as a whole. The fact that it is still considerable perhaps indicates that changes in breadth are taking place during growth. To this we shall return immediately.

5. The correlation between length and breadth is negative in the young, while in the culture as a whole it is positive. In the former the coefficient is —.3138; in the latter it is + .4282.

The fact that the correlation is negative in young specimens (greater length associated with less breadth) indicates that while the animals are growing in length they are becoming more slender. With an increase of 10 microns in length the decrease in breadth is .757 micron. If we group together the unseparated halves (124 in number) with the separated ones (59), we find that the negative correlation between length and breadth is still greater, becoming —.3625 (see row 4, Table X.).

6. The mean ratio of breadth to length ("mean index") is much greater in the young than in the random sample. In the former the breadth is 44.037 per cent. of the length; in the latter but 25.084 per cent. If we include the unseparated halves with those under five minutes old, the breadth is 54.080 per cent. of the length (row 4, Table X.), while in the unseparated halves alone it is 59.166 per cent., and in the earliest stages of the unseparated halves it is 61.530 per cent. (see Table VIII., rows 4 and 5). There is thus a steady reduction of the ratio of breadth to length; to this is due the negative correlation of the two, when those of different ages are thrown together.

(*d*) *Age 0 to 19 Minutes* (*Tables XXXI. and XXXII.*).—From another culture composed of descendants of the individual *D*, specimens were taken on June 14 and kept to several different ages. The various ages and measurements are given, with those of a random sample of the culture in lot 6, Table X.

The first set taken consisted of but 24 specimens, aged from 0 to 19 minutes. Though the number is small it is worth while to work out the constants for comparison with other stages in this same culture; it must be remembered that it is extremely difficult to get large numbers at any one time of individuals so young. The measurements are given in Table XXXI., while the constants are shown in row 7, Table X. For comparison with these a second lot of the same age, but containing 39 specimens, was taken from the same culture two weeks later. The measurements are given in Table XXXII.; the constants in row 13, Table X. The constants for the two sets taken together (63 specimens aged 0 to 19 minutes) are given in row 14, Table X.

Comparing these with the specimens but 0 to 5 minutes old, we find that the mean length has increased by 36 to 40 microns. The breadth is about the same in one of the lots (row 13, Table X.), but is much greater in the other (row 7). This difference is due to environmental effects. The coefficient of variability in length shows a decided decrease, indicating that growth is relatively more rapid during the first five minutes than later. The correlation between length and breadth is, as might be expected, negative in the sets 0 to 19 minutes old, as it was in the set still younger.

A number of specimens were killed at precisely known ages, and the measurements taken. Thus, from lot 7 (row 13, Table X.) a typical pair of young at the moment of separation measured 110 × 52 microns. At the age of one minute the two members of a pair measured each 124 × 52 microns; at two minutes another pair were each 120 × 52 microns. At three minutes one member of a pair measured 120 × 48 microns, the other 124 × 44. At five minutes the lengths of the two resulting from a certain fission were respectively 124 × 48 and 112 × 44 microns. Five specimens kept till they were precisely nineteen minutes old measured respectively 160 × 48 microns; 160 × 44; 152 × 36; 152 × 40; 156 × 44. The mean dimensions were thus 156 × 42.4 microns.

Outlines of individuals from 0 to 19 minutes old, showing the relative sizes, are given in Fig. 4. These may be compared with the adults of this race, *a* to *c*, Fig. 1.

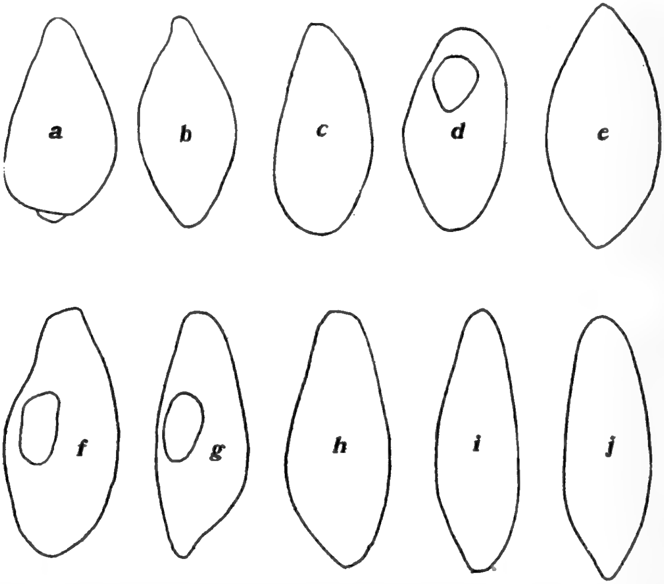

FIG. 4. Young *Paramecia*, descendants of *D* (*caudatum* form), from immediately after separation to the age of 19 minutes. *a* has just separated; *b*, *c* and *d* are two to three minutes old; *i* and *j* are 19 minutes old; the others are intermediate. These should be compared with the adults *a* to *c* of Fig. 1 (page 403), which are drawn to the same scale. All × 235.

(*e*) *Age 18 to 28 Minutes* (*Tables XXXIII. and XXXIV.*).—The first lot of this age (row 8, Table X.) contained 49 specimens (Table XXXIII.) and came on the same day from the same lot as the first lot of 24 of the preceding stage, so that the two are strictly comparable. The mean length has increased in the period of about thirteen minutes by nearly 16 microns, while the mean breadth has decreased 7 to 8 microns. The ratio of breadth to length has decreased almost 10 per cent. The correlation between length and breadth is in the present lot positive though small (.1937). If we should throw together the two lots (rows 7 and 8, Table X.), the correlation would, of course, be decidedly negative.

A second lot of 57 specimens aged 18 to 28 minutes was taken from the same culture about two weeks later. If we throw the two lots together (Table XXXIV.) we have 106 specimens at this age (row 15, Table X.); the mean length is 143.82 microns, the mean breadth 50.832 microns, while the mean ratio of length to breadth is 35.438 per cent.

The polygon for variation in length at this age is shown at *c*, Diagram 4, p. 440.

(*f*) *Age 35 to 45 Minutes* (*Table XXXV.*).—From the same lot 6 (Table X.) from which came the first sets aged 0 to 19 and 18 to 28 minutes, there were taken on the same day 25 specimens that were allowed to reach the age of 35 to 45 minutes (row 9, Table X.). Growth has now become much slower. These specimens average 17 minutes older than the last set, yet they have increased in length only about 6.5 microns. The breadth remains about the same; the slight increase shown in the figures is probably not significant, since it disappears at the next stage. The mean ratio of breadth to length continues to decrease, reaching now 37.296 per cent. The correlation between length and breadth is more strongly positive than before (.2799), indicating that these dimensions are not changing so decidedly in opposite ways.

The polygon for variation in length at this age is shown at *d*, Diagram 4.

(*g*) *Age 75 to 90 Minutes* (*Table XXXVI.*).—Forty-two specimens of this age were measured, taken on the same day from the same lot from which came the sets last described (lot 6, Table X.). The specimens average about twice the age of those in the last set, the absolute increase being 45 minutes, yet the growth in length has been only about 12 microns, which is about the same as the growth in the first five minutes after separation. The breadth still remains about the same; it is notably less than in the very earliest stages. The ratio of breadth to length continues to decrease, reaching now 33.558 per cent. Meanwhile the correlation between length and breadth has increased greatly, till now, at .5232, it is not much below that of the culture as a whole (.6469).

(*h*) *Age 0 to 90 Minutes.*—From a single culture of *D*, on a single day, we have thus measured 140 young specimens, varying in age from 0 to 90 minutes. The constants for variability and correlation of such a collection are of interest; they are therefore given in Table X., row 11. The variability, as measured by its coefficient, is less in both length and breadth than in the random sample, or in the collection of young specimens including only those under nineteen minutes in age. There is practically no correlation in the collection taken as a whole between length and breadth. This is because breadth at first decreases while length increases (giving negative correlation); later they increase together (giving positive correlation); the two tendencies about cancel each other in the collection as a whole.

### *Third Stage: Three to Five Hours Old (Tables XXXVII. and XXXVIII.).*

Three days later than the sets shown in lot 6, Table X., and under as nearly the same conditions as possible, I took from the same culture of progeny of *D* two sets of young, keeping the first set till the age was between 3 and 4 hours, the second set till the age was between 4.20 and 5 hours (see lot 9, Table X.). The culture was, however, in a different condition from that of lot 6; it contained a very large number of young and dividing specimens. A random sample of this culture, containing 195 specimens, is shown in Table VII. (page 412), while the constants for this sample are shown in row 19, Table X. The entire left portion of Table VII., up to the length of about 160 microns, or more, evidently consists of young individuals in various stages of growth. This decreases the main length (176.124 microns) and the correlation (.3945), while it greatly increases the variability in length (13.262, as against 6.821 for the random sample of the previous lot).

(*i*) *Age 3 to 4 Hours* (*Table XXXVII.*).—The effects of different environmental conditions are at once seen on comparing this set of 93 specimens (Table X., row 16) with the set 75 to 90 minutes old, from the previous culture (Table X., row 10). The specimens of the present lot, though 1½ to 2¾ hours older than the others, are shorter, the length (149.636 microns) being less by about 16 microns. The breadth is about the same as in the previous set; the correlation between the two is rather low (.3201).

(*j*) *Age 4.20 to 5 Hours* (*Table XXXVIII.*).—Ninety-five specimens kept for about an hour longer than those in the foregoing set showed a rapid growth in length and breadth. The length now reaches 186.736 microns, the breadth 60.168; both dimensions are considerably greater than the mean of the random sample. Thus, the animals at this age had reached about the average size of the infusoria in a collection of the same descent taken at random. Table VI. (page 412) shows a sample of this same culture taken twenty-four hours earlier, at a time when little division was occurring; the mean length is very nearly the same as that of the young of the present set. The correlation between length and breadth has considerably increased.

Certain peculiar facts are brought out by considering these two sets together (Table X., row 18). Here we have a collection of 188 young individuals taken at practically the same time from a small watch-glass culture. The variability and correlation depend in a high degree on the length of time we keep these. If they are all kept three to four hours (row 16) or 4.20 to 5 hours (row 17), the variability in length is about 5 to 6, in breadth about 9. But when we keep part of them for the shorter period, part for the longer, the variability rises to about 12.5 for length and 12 for breadth. Again, the correlation between length and breadth is but .3201 and .5557 in the two lots taken separately, but when we take them together the correlation is much greater, rising to .7132. These relations show the important part which may be played by growth in determining observed variability and correlation; their significance will be taken up again in our general sections on these topics.

### *Fourth Stage: 12 to 18 Hours Old* (*Table X., Lot 10*).

From the same culture of the progeny of *D* from which came the lots last described, but three days later were taken two lots of young, of 73 and 105 specimens, respectively, which were kept, the former to the age of 12 hours, the latter to the age of 18 hours.

(*k*) *Age 12 Hours* (*Table XXXIX., and rows 20 and 21, Table X.*).—There is a still further increase in both length and breadth, as compared with the specimens 4.20 to 5 hours old (see Table X., rows 20 and 21). Among the 73 specimens of this lot were two of about the same size which were much smaller than the others (see Table XXXIX.). There is little doubt, I believe, that these are the products of a second division; either one of the twelve-hour specimens had divided, or there was accidentally taken with them an older specimen which divided. In either case these two specimens do not belong in the twelve-hour lot, as they are much younger. On this account I have calculated the constants for this twelve-hour lot twice, once including these two small specimens (row 20, Table X.), the second time excluding them (row 21). The variability in length is much reduced—from 6.672 to 4.930—by the omission of these two. At the same time the correlation between length and breadth is likewise reduced from .4868 to .3474.

(1) *Age 18 Hours* (*Table XL., and row 22, Table X.*).—Growth in length continues, though very slowly; in six hours the increase has been less than during the first five minutes after separation. The animals at this age are decidedly longer than the mean for the culture as a whole, as judged from the random sample of Table VII. (page —), taken three days earlier. The mean breadth of the eighteen-hour specimens, while greater than that of the random sample, has decreased as compared with that of those only twelve hours old.

The variability of these two lots (12 and 18 hours old) of adult size is less than that of the random samples (for examples, rows 3, 6, 12, 19, Table X.).

### *Fifth Stage: 24 Hours Old* (*Table XLI., and row 23, Table X.*).

A final lot of 300 specimens was selected while dividing and these were kept till they were 24 hours old. These were progeny of *D*, but were taken from the culture somewhat more than a month later than those 0 to 18 hours old. To understand their measurements it is necessary to take into consideration the cultural conditions. These animals were living in an ordinary hay culture, which was getting old, so that they were not dividing rapidly; they were rather slender in form. Now a large number of these was placed in a fresh decoction of hay and left there for 24 hours. They increased in size and began to divide rapidly. Now 150 dividing specimens (producing, of course, 300 young) were taken out and *returned to the original culture fluid.* This was for the purpose of preventing a second division before the end of the period of twenty-four hours. As a result of this treatment they did not grow so rapidly as did the twelve- and eighteen-hour lots, and are smaller than these. The purpose in studying this group (as well as other groups) was mainly to determine the variability and the correlation between length and breadth. Both are less, as Table X. shows, than is usually the case in random samples.

The specimens 12, 18 and 24 hours old may be taken as types of adult *Paramecia* of this strain (progeny of *D*; *caudatum* form) before the changes leading to fission have begun.

Diagram 4 gives polygons of variation for the different ages, in descendants of *D,* as compared with a random sample; it shows clearly the part played in the observed variations by the presence of different stages of growth.

### *Sixth Stage: Preparing for Fission.*

As Table X. shows, the adults of the progeny of *D* (*caudatum* form) reach a mean length of 168.532 to 199.048 microns (rows 23 and 22) under the cultural conditions employed, while the mean breadth varies from 40.320 (row 23) to 62.796 microns (row 20). But the *maximum* length is (under the same conditions), of course, much greater than the mean. In the random samples we find individuals up to 224 microns in length and 88 in breadth (see, for example, Table LI.); and among those 18 hours old (Table XL.) we find a length of 228 microns.

Now, when we compare these large adults with the specimens actually beginning fission (which are supposedly the oldest of all), certain peculiar facts appear. *The specimens beginning fission are by no means the longest of the lot;* a given culture contains many specimens much longer than those showing the first signs of division. Thus, in the "Lot 1" of Table VIII., we find 131 specimens in the very earliest stages of fission (Table XIII., page 442). The mean length of these is 175.696 microns (row 25, Table X.), and the longest specimen is 204 microns long. But in the random sample of the specimens that are not dividing, from this same lot (taken at the same time) the mean length is 199.960 microns (row 27, Table X.), and certain individuals reach a length of 240 microns (Table XIV., page 443). Of the two hundred specimens of the random sample, 69, or more than one third, *are longer than the longest of the specimens beginning fission.* Only nine of the entire 200 falls below the mean length of the specimens beginning division.

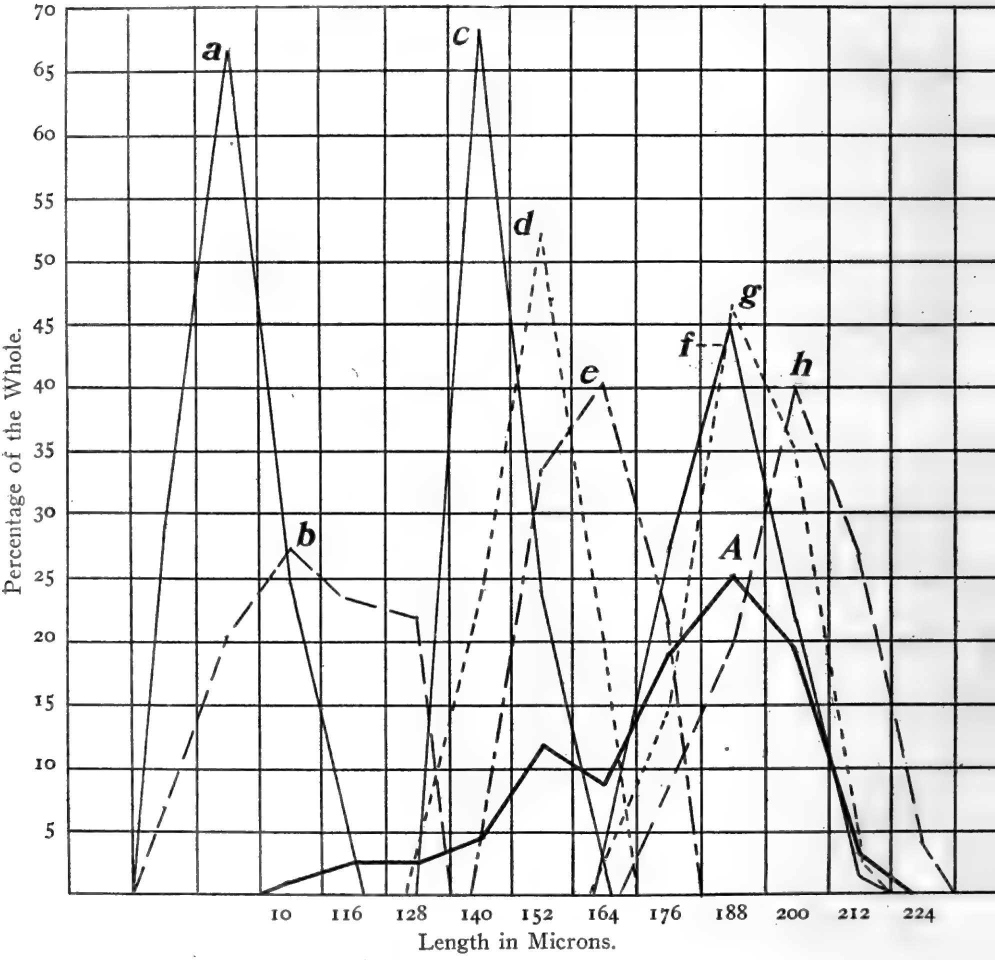

DIAGRAM 4. Polygons of variation in length for descendants of individual *D,* at various ages. *A* (heavy line), Random sample, 195 specimens (row 19, Table X.). *a,* youngest halves, constriction beginning (row 1, Table X.). *b,* age 0 to 5 minutes (row 5, Table X.). *c,* age 18 to 28 minutes (row 8, Table X.). *d,* age 35 to 45 minutes (row 9, Table X.). *e,* age 75 to 90 minutes (row 10, Table X.). *f,* age 4.20 to 5 hours (row 17, Table X.). *g,* age 12 hours (row 21, Table X.). *h,* age 18 hours (row 22, Table X.).

Since then the specimens beginning fission are not the longest of the culture, it is clear that *the length decreases before fission begins.* This is borne out by the form of the specimens beginning fission; though their mean length is less than that of the random sample, their mean breadth is greater (mean breadth 50.220 microns in the random sample, 55.480 in those beginning fission). While then the length decreases preparatory to fission, the breadth increases at the same time. How long before fission this change of dimensions begins I can see no way of determining. The period may perhaps be one or two hours.

Table XI.

*Correlation Table for Depth of Constriction and Total Length in 313 Dividing Specimens from a Single Culture of Descendants of D.*

All taken the same day.

Total Length of Body, in Microns.

| Depth of Constriction in Microns. | 156 | 160 | 164 | 168 | 172 | 176 | 180 | 184 | 188 | 192 | 196 | 200 | 204 | 208 | 212 | 216 | 220 | 224 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 1 | 8 | 12 | 17 | 22 | 15 | 31 | 8 | 5 | 6 | 4 | 1 | 1 | | | | | | 131 |
| 8 | | 1 | 2 | 7 | 8 | 5 | 7 | 5 | 2 | | | | | | | | | | 37 |
| 12 | | | 2 | 1 | 10 | 9 | 3 | 3 | | | | 1 | | | | 1 | | | 30 |
| 16 | | | | 2 | 3 | 5 | 4 | 4 | 4 | 2 | 3 | 2 | | | | | | | 29 |
| 20 | | | 1 | 1 | | 3 | 1 | 3 | 1 | 1 | 1 | | | | | | | | 12 |
| 24 | | 1 | | | | | | 3 | 4 | 5 | 2 | | 1 | | | | | | 16 |
| 28 | | | | | 1 | | 1 | 4 | 2 | 5 | 1 | 2 | 2 | 2 | 1 | 1 | | | 22 |
| 32 | | | | 1 | | 1 | | | | 3 | 1 | 2 | 4 | 3 | 1 | 1 | | | 17 |
| 36 | | | | | | | | | 2 | | 2 | 2 | 1 | | 1 | 1 | | 1 | 10 |
| 40 | | | | | | | | | | | 2 | | 1 | 1 | | 2 | 1 | 1 | 8 |
| 44 | | | | | | | | | | | | | | | | | 1 | | 1 |
| | 1 | 10 | 17 | 29 | 44 | 38 | 47 | 30 | 20 | 22 | 16 | 10 | 10 | 6 | 3 | 6 | 2 | 2 | 313 |

Length—Mean, 181.725 ± .512μ Depth of Constriction—Mean, 13.265μ
St. Dev., 13.446 ± .362μ St. Dev., 2.721μ
Coef. Var., 7.399 ± .201

Coef. of Cor. between Depth of Constriction and Length, .6882 ± .0201; Increase in Length for 1 unit of depth, .860μ; Coef. of Cor. if first row is omitted, .7818 ± .0194.

Thus, the longest individuals of the culture are the adults that have not begun the changes preparatory to fission. These decrease in length and increase in breadth before fission.

### TABLE XII.

*Correlation Table for Depth of Constriction and Breadth of Body, in 313 Dividing Specimens from a Single Culture of Descendants of D.*

(Same lot shown in Tables XI., XIII. and LXII.)

Breadth in Microns.

| Depth of Constriction in Microns. | 40 | 44 | 48 | 52 | 56 | 60 | 64 | 68 | 72 | |
|---|---|---|---|---|---|---|---|---|---|---|
| 4 | | 2 | 19 | 27 | 47 | 22 | 11 | 2 | 1 | 131 |
| 8 | | 1 | 13 | 18 | 3 | 2 | | | | 37 |
| 12 | | 3 | 13 | 9 | 3 | 1 | | 1 | | 30 |
| 16 | 1 | 2 | 15 | 4 | 4 | 3 | | | | 29 |
| 20 | 1 | 1 | 3 | 7 | | | | | | 12 |
| 24 | | 4 | 5 | 5 | 2 | | | | | 16 |
| 28 | | 7 | 9 | 3 | 3 | | | | | 22 |
| 32 | 1 | 6 | 7 | 1 | 2 | | | | | 17 |
| 36 | 2 | 2 | 4 | 2 | | | | | | 10 |
| 40 | | 4 | 1 | 2 | 1 | | | | | 8 |
| 44 | | | 1 | | | | | | | 1 |
| | 5 | 32 | 90 | 78 | 65 | 28 | 11 | 3 | 1 | 313 |

Breadth—Mean, 52.026 ± .209μ Depth of Constriction—Mean, 13.265μ
St. Dev., 5.473 ± .148μ St. Dev., 2.721μ
Coef. Var., 10.544 ± .287

Coef. of Cor. between Depth of Constriction and Breadth, —.5232 ± .0277; Decrease in Breadth with Increase of 10μ in Depth, 2.630μ.

Omitting uppermost row: Coef. of Cor., —.3316 ± .0445μ; Decrease in Breadth with Increase of 10μ in Depth, 1.252μ.

### TABLE XIII.

*Correlation Table for Length and Breadth of 131 Specimens of Lot 1 in the Earliest Stages of Fission.* (Descendants of D, Table X., row 25.)

Length in Microns.

| Breadth in Microns. | 156 | 160 | 164 | 168 | 172 | 176 | 180 | 184 | 188 | 192 | 196 | 200 | 204 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 44 | | 1 | | 1 | | | | | | | | | | 2 |
| 48 | 1 | 3 | 6 | 3 | 4 | 1 | | 1 | | | | | | 19 |
| 52 | | 1 | 2 | 8 | 6 | 2 | 6 | 1 | 1 | | | | | 27 |
| 56 | | 3 | 2 | 4 | 10 | 7 | 15 | 2 | 2 | 1 | 1 | | | 47 |
| 60 | | | 2 | 1 | 1 | 5 | 8 | 1 | 1 | 2 | 1 | | | 22 |
| 64 | | | | | 1 | | 2 | 3 | 1 | 2 | 2 | | | 11 |
| 68 | | | | | | | | | | 1 | | 1 | | 2 |
| 72 | | | | | | | | | | | | | 1 | 1 |
| | 1 | 8 | 12 | 17 | 22 | 15 | 31 | 8 | 5 | 6 | 4 | 1 | 1 | 131 |

Length—Mean, 175.696 ± .556μ Breadth—Mean, 55.480 ± .297μ
St. Dev., 9.432 ± .393μ St. Dev., 5.040 ± .210μ
Coef. Var., 5.368 ± .224 Coef. Var., 9.082 ± .382

Mean Index, 31.568 per cent.; Coef. Cor., .6546 ± .0337.

### *Seventh Stage: Fission.*

Some of the data bearing on the dimensions during fission have been incidentally taken up in the account of the young in the earliest stages, before the two halves have separated.

(*m*) *Beginning Fission.* Descendants of *D* (*caudatum* Form).—Four lots of dividing specimens descended from the individual *D* were studied. These lots were taken at different times; the first included 313 dividing specimens (Tables XI. and XII., and rows 25–29, Table X.); the second 62 (Tables XLII., XLIII. (appendix) and rows 30–32, Table X.); the third 77 (Table XLIV., and rows 23–24, Table X.); the fourth 37. The dimensions of random samples of the same lots are given in Table X.

The large lot containing 313 dividing specimens may be described as typical; the others show the same relations, except as hereafter noted.

Table XIV.

*Correlation Table for Random Sample of Specimens not Dividing, of Lot 1 (from which came the dividing specimens of Table XIII.).* (See Table X., row 27.)

Length in Microns.

| Breadth in Microns. | 148 | 152 | 156 | 160 | 164 | 168 | 172 | 176 | 180 | 184 | 188 | 192 | 196 | 200 | 204 | 208 | 212 | 216 | 220 | 224 | 228 | 232 | 236 | 240 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 36 | 1 | | | | | | | 1 | | 2 | | | | | | | | | | | | | | | 4 |
| 40 | | 1 | | | 1 | 2 | | | | 1 | 3 | 1 | | 2 | | 1 | | | | | | | | | 12 |
| 44 | 1 | | 2 | | | | | 1 | 3 | 5 | 4 | 10 | 5 | 4 | 4 | 2 | | 2 | 1 | | | | | | 44 |
| 48 | | | | | | 1 | | 1 | 1 | 1 | 5 | 3 | 7 | 4 | 2 | 4 | 3 | 3 | 2 | | 1 | | | | 38 |
| 52 | | | | | | | | | 2 | 2 | 2 | 5 | 6 | 6 | 7 | 7 | 3 | 4 | 2 | 1 | | | | | 47 |
| 56 | | | | | | | | | | | 2 | 2 | 1 | 11 | 2 | 3 | 3 | 1 | 4 | 3 | 1 | | | | 33 |
| 60 | | | | | | | | | | | | 1 | | | 2 | 1 | 2 | 4 | 3 | 1 | | | | | 14 |
| 64 | | | | | | | | | | | | | | 1 | | | | | 1 | 2 | 1 | | | 1 | 6 |
| 68 | | | | | | | | | | | | | | | | | | | | | | | | | 0 |
| 72 | | | | | | | | | | | | | | | | | | 1 | | | | | | 1 | 2 |
| | 2 | 1 | 2 | 0 | 1 | 3 | 0 | 3 | 6 | 11 | 16 | 22 | 19 | 28 | 17 | 18 | 11 | 15 | 13 | 7 | 3 | 0 | 0 | 2 | 200 |

Length—Mean, $199.960 \pm .740\mu$ Breadth—Mean, $50.220 \pm .308\mu$
St. Dev., $15.528 \pm .524\mu$ St. Dev., $6.468 \pm .218\mu$
Coef. Var., $7.765 \pm .263$ Coef. Var., $12.877 \pm .441$
Mean Index, 25.114 per cent.; Coef. Cor., $.6064 \pm .0302$.

In the dividing specimens the length of the body increases as the depth of the constriction between the two halves becomes greater; this is well shown in Fig. 2, page 416. In order to include only the earliest stages of fission we shall, of course, have to take the specimens in which constriction is beginning. Among the 313 dividing specimens of lot 1 (Table XI.) there were 131 in which the depth of the constriction below the body surface was less than one unit of the micrometer scale (less than 4 microns). These may be taken as representing the earliest stages of fission. The depth of the constriction is in these specimens less than one twelfth the breadth. Their measurements are given in Table XIII., while the constants deduced from the measurements are shown in row 25, Table X. These should be compared with the measurements and constants for the random sample of the specimens not dividing in this same culture (Table XIV., and row 27, Table X.).

Examination of these tables shows the following remarkable facts:

1. The mean length of the specimens beginning fission (175.696 microns) is much *less* than the mean length of the random sample (199.960 microns)—although the latter must contain many specimens that have not reached adult size.

2. The range of variation in length is much less in the specimens beginning fission than in the culture as a whole. In those beginning division the range is from 156 to 204 microns; in the random sample it is from 148 to 240 microns.

3. The longest specimens beginning fission are 36 microns shorter than the longest of the random sample. In the random sample, 34.5 per cent. of all the specimens are longer than the longest of those beginning fission, while 95.5 per cent. are longer than the mean length of the specimens beginning fission.

4. The variation in length is decidedly less in the specimens beginning fission than in the random sample. In the lot beginning fission the coefficient of variation is but 5.368, while in the random sample it is 7.636.

It may here be noticed that coefficient of variation in the specimens beginning fission is less than that for conjugating specimens, as studied by Pearl (1907). To this matter we shall return later.

5. In the specimens beginning fission the mean breadth (55.480 microns) is greater than the mean breadth of the random sample (50.220 microns).

6. The variation in breadth is much less in the specimens begin-

ning fission than in the others. In the former the coefficient is but 9.082, while in the latter it is 12.877.

7. The mean index, or ratio of breadth to length, is much greater in the specimens beginning fission; in these it is 31.568 per cent., as contrasted with 25.114 per cent. in the random sample.

8. The correlation between length and breadth is high in the specimens beginning fission; it is somewhat greater than in the random sample. In the former it is .6546; in the latter .6064.

Owing to the smaller numbers in the other lots of dividing specimens, I included in the group "beginning fission" all those in which the depth of the constriction below the body surface was less than one fourth the breadth of the animal. Thus, all specimens with constriction 12 microns deep, or less, were included. Of course, these groups contained specimens in decidedly more advanced stages of fission than in the large group we have been considering. The numbers of specimens in early stages of fission thus secured were respectively 40 (Table XLIII.) and 42 (Table XLIV.). The constants for these, in comparison with random samples or adults, are shown in Table X. (rows 24 and 30).

As the tables show, these manifest in most particulars the same relations which we have brought out above for the larger and more precise set containing 131 specimens. The differences between the dividing specimens and the other individuals (as shown by the random samples, etc.) are in the main somewhat less in amount than in our first example. This is because in the smaller lots specimens are included in which lengthening and narrowing had begun, causing the dimensions to approach those of the specimens not dividing.

The most striking difference between our large lot (Table X., row 25) and the smaller ones (Table X., rows 24 and 30) is in the correlation between length and breadth. While in the larger lot the correlation was high, in the smaller ones it is small or quite lacking. This is again due to the inclusion of more advanced stages in the smaller lots; as the length increases the breadth decreases, tending to destroy the correlation.

Descendants of *c* (*aurelia* Form).—Two lots of dividing specimens were examined from the descendants of the small individual *c*. The first contained 119 specimens (Table XLV.); the second 63 specimens (Table XLVI.).[5] Selecting from these, as representing the early stages of fission, all those in which the depth of constriction is less than one fourth the diameter of the body, we obtain from the larger lot 66 specimens (Table XLVII.); from the smaller lot 38 specimens (Table XLVIII.). The constants for these, in comparison with those for random samples, are given in Table X. (lots 4 and 5, rows 33 to 38). The measurements of the random samples are shown in Tables XLIX. and L.

These specimens of the *aurelia* form show the same relations that are found in the *caudatum* form, with one exception. In lot 5 (Table X., row 36) the mean breadth of the specimens beginning fission is *less* than that of the random sample, instead of greater as in all other cases. But this peculiarity is due to environmental conditions. In lot 5 the breadth was very great in proportion to the length, as is shown by the dimensions of the random sample (Table L., and row 37, Table X.). In this lot the breadth was 41.555 per cent. of the length, while in most cases it is near to 30 per cent. This was due to the recent transference of the animals to a nutritive solution; they became very plump. Evidently, when preparing to divide the body tends to return to a constant form; in this case, therefore, it becomes narrower instead of broader.

In the specimens of the *aurelia* form, as in the *caudatum* form, all dimensions are less variable in the specimens beginning fission. This difference in variability, as compared with the random samples, is very great in some cases. Thus, while the coefficients of variation in length for the random samples of lots 4 and 5 are 15.279 and 10.643, for those of the same lots beginning fission they are but 7.541 and 6.862, respectively. Had we included in the lots beginning fission only specimens in which the depth of constriction was still less, the coefficients of variation would have been still smaller.

The constants for all specimens of *c* that are beginning fission, taken together, are shown in row 38, Table X. The standard deviations and coefficients of variation are, of course, greater than for

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[5] In making these measurements of descendants of *c*, a higher power of the microscope was used, so that the single unit of measurement was 3⅓ microns. This caused the tables (in the appendix) to take a somewhat different appearance from those of the descendants of *D*.

each of the two component lots taken separately, since the two lots differed as a result of different environmental conditions.

(*n*) *Later Stages of Fission.*—As the constriction deepens the animal as a whole becomes more elongated, while the breadth decreases slightly. These relations are shown both for the descendants of *D* (*caudatum* form) and the descendants of *c* (*aurelia* form) in Table X. (rows 25 and 26; 30 and 31; 33 and 34). In the large lot 1 of dividing descendants of *D,* comprising 313 specimens (Table XI.) the correlation between length of body and depth of constriction below the surface is .6882. The length increases 8.6 microns with every increase of 10 microns in the depth of constriction. The correlation between breadth and depth of constriction (Table XII.) is —.5232, the breadth decreasing 2.63 microns for each 10 microns increase in depth of constriction. If we include only the specimens in which lengthening has decidedly begun (thus omitting the earliest stages, in the uppermost rows of Tables XI. and XII.), then the correlation between length and depth of constriction is .7818; between breadth and depth of constriction, —.3316. With an increase of 10 microns in depth of constriction the length now increases 11.195 microns, while the breadth decreases 1.252 microns. In this same culture while the mean length of the 131 specimens beginning fission is 175.696 microns, that of the seven specimens having a connecting portion but 4 microns wide is 212.572 microns. Thus, the increase in length before separation takes place is 36.876 microns, or about 21 per cent. of the length at the time fission begins. The breadth has decreased from 55.480 microns at the beginning of fission to 43.428 microns in the seven specimens with the narrowest connections—a decrease of about 21 per cent. The ratio of breadth to length decreases from 31.568 per cent. at the beginning of fission to 20.430 per cent. just before separation.

Corresponding relations are shown in other lots of dividing specimens; some of the data are given in Table X.

### 2. SUMMARY ON GROWTH IN PARAMECIUM WITH A GROWTH CURVE.

We have thus followed the growth from the time when the individual is but half a constricting specimen to the period when it is again ready to separate into two new individuals. We are ready, therefore, to outline the main features of the growth of *Paramecium,* and to construct curves which shall give an idea of the processes involved. In spite of an incredible amount of work devoted to collecting the data, certain of the less important features of the growth curves must remain obscure, but the main facts are clear.

The main outlines of the changes due to growth are as follows: From the time the constriction appears in the mother until a few minutes after separation takes place, the length increases rapidly, while the breadth decreases a little. A few minutes after separation the processes become less rapid. The breadth soon reaches its minimum, then begins to increase like the length, though more slowly. Growth in length continues for at least eighteen hours; the time undoubtedly varies with the conditions. The breadth continues to increase for some time, but it undergoes marked fluctuations, due to environmental conditions. In lot 10 (Table X.) it decreased between the ages of 12 and 18 hours; this is probably an environmental effect, not one due to the normal growth processes.

As the time for fission approaches the animals are considerably more than twice as long as the original halves from which they developed. Now as fission comes on they shorten and thicken, all tending to approach a uniform length and thickness. There is thus much less variation in the dimensions at the beginning of fission than in specimens taken at random. Now the constriction appears and the animal begins to narrow and extend in the way already described, finally separating into two parts.

If from our data we construct curves showing these changes, we get such results as are shown in Diagram 5.

*Method of Constructing the Curves.*—The horizontal scale represents the time in hours, while the vertical scale represents the measurements of the animals in microns. The upper curve shows the length, the lower one breadth, as measured from the base line. Fission is assumed to take place once in twenty-four hours, which is an approximation to a rate commonly occurring. The time between the appearance of the constriction and the actual separation of the two halves is taken as one half hour.

The relative distances of the two curves from the base line shows the relative dimensions of length and breadth. The vertical rise of

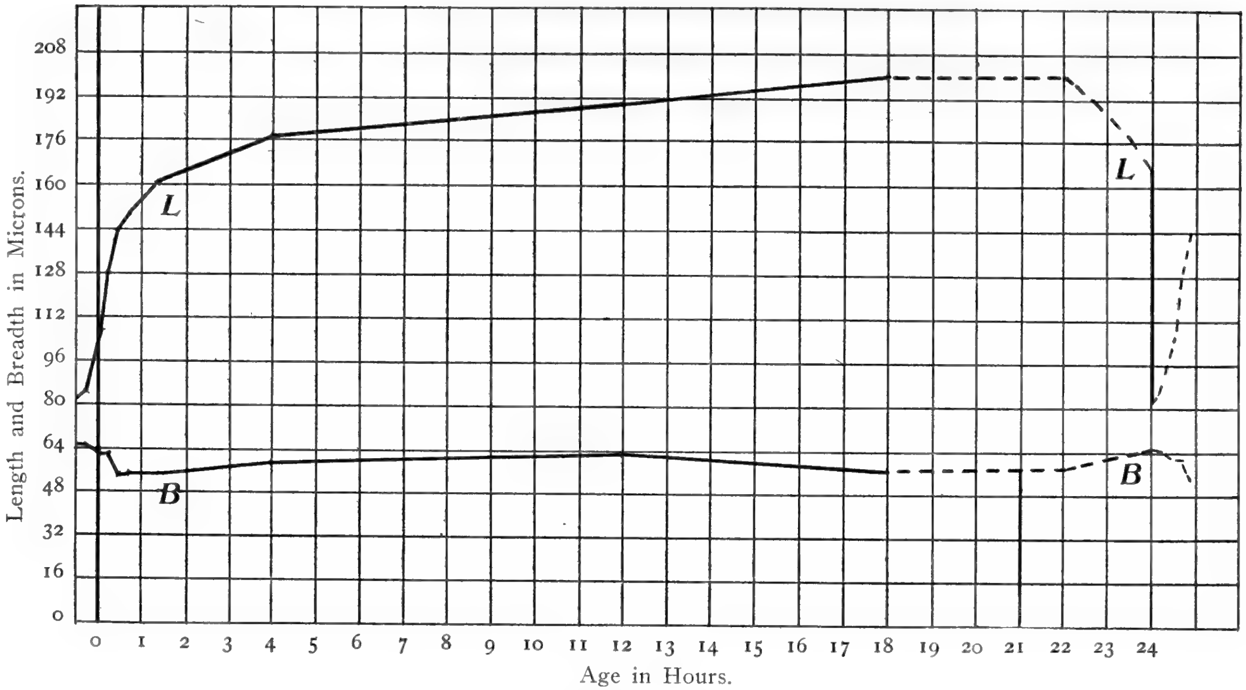

DIAGRAM 5. Curves of growth, for length and breadth in *Paramecium* plotted directly from Table XV., page 451. The upper line marked *L* is the curve of length; the lower line (*B*) that for breadth. The horizontal scale represents the time in hours; the vertical scale gives the measurements in microns. The relative distances of the two curves from the base line *o* shows the proportions of length and breadth at the different ages. The vertical rise of the curve shows the proportion of growth to the original length. The distance from the base line to the curve is 357 times the actual dimensions at the given ages. Fission occurs at *o* and at 24 hours. The curves are not smoothed. The broken parts of the curves are not constructed from precise data.

the curve of length shows the actual proportion of growth to the original length. The distance from the base to the curves is 357 times the actual dimension at the given time.

In order to show changes due to growth alone all the data for such a curve should be measurements from a single uniform culture on a single day; otherwise environmental differences complicate the matter, as we shall see more clearly in the next division of this paper. Now, it is impracticable to obtain from a single culture on a single day measurements of all the required stages. We are compelled therefore to make certain corrections in some of the measurements, to compensate so far as we can for environmental differences. As Table X. shows, the mean dimensions of random samples differ much in (for examples) lots 1 (row 3) and 6 (row 12). It will not do, therefore, to compare *directly* the young of these two lots. Since we have from lot 6 the greatest number of different stages, it is best to make the measurements from this the basis for the curve, correcting others, so far as possible, to compare with this. In lot 2 the mean length (Table X., row 6) is almost exactly the same as for lot 6, so that we may use the measurements of lot 2 without correction, so far as length is concerned. On this account we shall employ lot 2 for the earliest stages, in place of lot 1, though the latter is based on a larger number of specimens.

Since the mean breadth of the sample of lot 6 is 64.880 microns, while that of lot 2 is but 46.020 microns, it is necessary to correct the breadth for lot 2. At first thought it would seem that the proper method of making this correction would be by multiplying the breadths of the different sets of lot 2 by the ratio 64.880/46.020. This would be the proper method of procedure if we were dealing with the same stages of growth in the two lots; the specimens of lot 2 would be made plump, like those of lot 6. But the stage with which we are dealing is that of the beginning of fission. Now, we have already seen that when the specimens not dividing are plump, the breadth does not increase at the approach of fission nearly so much as when the specimens not dividing are thin. Indeed, if the specimens are very plump, there is an actual decrease, instead of an increase, at the approach of fission. Our problem is: What would be the breadth of specimens beginning fission, in which the length is 82.600, and the animals are very plump, as in lot 6? This problem can best be solved by asking what is the ratio of breadth to length in specimens beginning fission, in a very plump culture? In lot 3 (row 7, Table VIII.) we have such a plump culture, and we find that the ratio of breadth to length is, in the earliest stage of fission, 78.563 per cent. We therefore take this as the ratio of breadth to length for the earliest stage of lot 2, from which the corrected breadth is found to be 64.893. If this decreases at the same relative rate as actually occurred in lot 2, then the breadth 15 minutes after the beginning of constriction would be 64.493 microns.

We are compelled to use, further, lots 9 and 10 (Table X.). In lot 9 both length and breadth require correction to make them comparable with the measurements of lot 6. The correction is made by multiplying the dimensions by the ratio between the length of the random samples of the two lots. In lot 9 we use only the average of the two sets, as given in row 18, Table X.

In lot 10, since we unfortunately have no random sample, we are unable to make a correction.

Owing to the very great difference in the environmental conditions of lot 3 (rows 23 and 24, Table X.) we are unable to use the 24-hour-old specimens of that lot, although we need measurements at that age. The older portions of the curve (beyond 18 hours, at the right) cannot be plotted from exact data, and there are certain features of much importance for which it appears that the collection of such data would be almost impossible. As we have shown, before fission the animals shorten and thicken. How long before fission this begins it is not possible to say; in making the curve the period is arbitrarily taken as two hours.

When we make the corrections above described, we have the following mean dimensions at different ages, as data for the construction of our curve. The *ages* given are the *average* ages for the lots considered; thus the age for row 8, Table X. (18 to 28 minutes) is taken as 23 minutes.

TABLE XV.

*Dimensions in Microns of Paramecia (Descendants of D) at Different Ages, Corrected (so far as possible) to Correspond with Those of Lot 6, Table X. Data used in making the Curves of Growth.*

| Age. | Lot. | Mean Length in Microns. | Mean Breadth in Microns. |
|---|---|---|---|
| Beginning constriction | Row 4, Table VIII. | 82.600 | 64.893 |
| Fifteen minutes after beginning constriction | " 5, " VIII. | 85.774 | 64.493 |
| 2½ minutes after separation | " 5, " X. | 107.660 | 59.355 |
| 9½ minutes | " 7, " X. | 128.000 | 60.168 |
| 23 minutes | " 8, " X. | 143.348 | 54.284 |
| 40 minutes | " 9, " X. | 149.920 | 55.840 |
| 82½ minutes | " 10, " X. | 161.524 | 54.192 |
| 4 hours | " 18, " X. | 176.560 | 58.922 |
| 12 hours | " 20, " X. | 188.988 | 62.796 |
| 18 hours | " 22, " X. | 199.048 | 56.496 |
| Beginning constriction | " 30, " X. | 165.200 | 64.893 |

When we lay off on the vertical scale the distances corresponding to the lengths and breadths at the different periods, as given in the above table, and connect these points, we obtain the curves given in Diagram 5.

*Characteristics of the Curves.*—As the curves show, the length increases with great rapidity for about twenty minutes after fission; continues less rapidly for about an hour, and still less rapidly for four or five hours. Now the increase continues, though very slowly, till a maximum is reached at a length considerably greater than twice the original length; later the length decreases in preparation for fission; this decrease continues till the length is just twice the original length. Now the constriction appears, so that the animal may be looked on as two; the length, therefore, drops in a straight line to the original length found at the beginning of the curve. The breadth decreases from the beginning till about an hour after fission; then slowly increases; it shows in the course of the twenty-four hours many fluctuations which are doubtless mainly due to differences in the environment—especially to differences in the amount of food taken. In preparation for fission the breadth increases at the same time that the length decreases.

The curve of length is much the more interesting of the two, since it is the one which represents mainly the actual growth. It is of great interest to find that this curve of growth in a single cell is of essentially the same form and character as those which have been obtained for the growth of many higher organisms, composed of many cells. A number of such curves are brought together in the recent interesting paper of Robertson (1908). Inspection shows at once that the curve of growth in *Parmecium* closely resembles that for growth of the rat, as worked out by Donaldson (1906); for growth of man, and for growth in various other organisms.

The curve of growth, as is well known, is a logarithmic curve in the cases where it has been worked out mathematically. While the growth in *Paramecium* has merely been plotted empirically, it is evident that it is essentially a similar logarithmic curve; this could doubtless be worked out from the data given.

The fact that the curve of growth is essentially the same in the unicellular organism as in the animal composed of millions of cells is in some respects surprising. In the brain of the rat, or in its body, the curve of growth is the resultant of the growth of many different groups of cells, some groups growing at one period, some at another; yet the resultant curves are of the same character as when there is growth in but a single cell.

The temporal relations shown in the curves are likewise of much interest. As our diagram shows, that portion of the curve showing the greatest curvature requires in *Paramecium* about four hours from the beginning. In the rat the corresponding part of the curve takes several months, while in man it requires several years. It seems extraordinary that a process following the same laws should in some cases be measured by hours, in other cases by months, in others by years.

### 3. Effects of Growth on the Observed Variation.

A random sample of an ordinary culture of *Paramecium* contains specimens falling in all parts of the growth curves represented in Diagram 5. If we measure the various members of such a sample, as was done by Pearl (1907), we shall then find many variations in size, which variations consist to a considerable extent of different growth stages. Not all the observed variations are due to this factor, but its importance is very considerable. This will best be appreciated by running through the columns headed "coefficients of variation" in Table X. If we take samples including specimens falling in the early parts of the growth curve, when the absolute size is small but the changes with growth are very marked, then the coefficients of variation in length are high; thus in rows 4 and 5 they are 15.494 and 13.729, respectively, while in the random sample of the same culture the coefficient is but 8.834 (row 6). On the other hand, if we take specimens restricted to a very small portion of the curve, the coefficient of variation becomes very low; thus in a lot whose age falls between 18 and 28 minutes the variation is but 4.521 (row 8); at the age of 4.20 to 5 hours is 5.043 (row 17), though the variation for a random sample of this same culture is 13.262 (row 19). The effects of growth on variation are shown to the eye in Diagram 4, p. 440.

*Variation at Fission.*—The effects of growth on the observed variation are likewise seen when we compare random samples with individuals that are at a definite stage in the life history. Thus, if we take specimens at the beginning of fission, when the constriction first appears, we find the coefficient of variation very low, as compared with those of random samples of the same cultures. This is readily seen in the following tabulation of the coefficients of variation for the four cultures of Table X. in which the specimens beginning fission were studied (see next page).

*Variation in Conjugants.*—Again, the same thing appears when we compare conjugating individuals with random samples of the same cultures. Conjugation does not occur till a certain stage of growth has been reached, and the conjugants do not include specimens undergoing the changes preparatory to fission. The conjugants would then fall in those portions of the growth curve that are nearly straight; that is, there would be in these little variation due to growth.

TABLE XVI.

*Coefficients of Variation.*

| Lot. | Length. | | Breadth. | |
|---|---|---|---|---|
| | Beginning Fission. | Random Sample. | Beginning Fission. | Random Sample. |
| 1 | 5.368 | 7.765 | 9.082 | 12.877 |
| 2 | 5.320 | 8.834 | 6.769 | 11.421 |
| 4 | 7.541 | 15.279 | 9.911 | 15.683 |
| 5 | 6.862 | 10.643 | 12.071 | 13.720 |

Pearl (1907) has already shown that the observed variability of conjugants is less than that of random samples of the same culture. I have made extensive studies of conjugants and find the same thing. Details regarding the relation of conjugation to variation and heredity are to be taken up in a later communication; here I give merely the coefficients of variation for certain cases, as compared with those of random samples.

TABLE XVII.

*Coefficients of Variation for Conjugants, as compared with those for random samples of non-conjugants of the same culture.*

| Lot. | Length. | | Breadth. | |
|---|---|---|---|---|
| | Conjugants. | Non-Conjugants. | Conjugants. | Non-Conjugants. |
| *A*, Pearl. | 6.668 | 8.185 | 9.398 | 11.112 |
| *C*, " | 7.439 | 9.123 | 7.910 | 10.894 |
| *a*, Jennings. | 7.39[illegible] | 11.578 | 12.409 | 19.176 |
| *b*, " | 7.678 | 11.026 | 15.766 | 18.142 |

On comparing the coefficients of variation in conjugants, as given in Table XVII., with those for specimens beginning fission (Table XVI.), and those for specimens at definite ages (Table X.), it is found that in the conjugants the variation is not so small as it is in specimens at definite growth stages. This shows clearly that nothing is required to explain the low variation of conjugants, save the fact that a certain number of growth stages (the earlier and later ones) are lacking in these. There is no evidence of an unusually low degree of congenital variation in the conjugants, for the non-conjugating specimens beginning fission show a still lower variability (Table XVI.).

It appears highly probable that if we could examine a large number of individuals, derived from the same parent, cultivated under identically the same conditions, and all in precisely the same stage of growth, we should find coefficients of variation considerably smaller than the smallest we have found, which is 4.521 (row 8, Table X.). Indeed, if we could further exclude all inaccuracies of measurement, it is quite possible that the coefficient of variation would approach closely to zero, if it did not reach it completely. This would, of course, mean that the variations observed among the progeny of a single individual are not congenital, but are all due to growth and environmental action. Further evidence of this will come out later in this paper.

### 4. Effects of Growth on the Observed Correlation Between Length and Breadth.

As Diagram 5 shows, the curves of length and breadth diverge at the beginning, then run for a considerable distance nearly parallel, then finally approach each other. That is, at first the breadth decreases while the length increases; later they increase together; and still later the breadth increases while the length decreases. If a collection of specimens includes individuals in various different stages of growth (as is usually the case), then these various relations of breadth to length will deeply affect the amount of correlation observed between the two dimensions.

Thus, if we take a collection composed of various ages under one hour, when the length is increasing while the breadth is decreasing, then on the whole greater length will be associated with less breadth, so that the correlation between them will tend to be negative. This is the explanation of the negative correlation shown in Table X., rows 2, 4, 5, 7, 11, 13, 14. Next follows a period (from about the end of the first hour to the fourth) in which the inclusion of individuals of different ages tends to cause a certain degree of positive correlation, since the two dimensions are increasing together. Then comes a long period in which both dimensions remain nearly the same—the length increasing slowly, while the breadth fluctuates. Different growth stages during this period have little marked effect on the coefficient of correlation between length and breadth; they tend to prevent its reaching 1.000, but this it would not reach for other reasons.

Now, for a certain period before fission (taken as two hours, in our curves), the length decreases while the breadth increases. Greater breadth will then be associated with less length, tending to produce again a negative correlation. If we make a collection of individuals representing various stages in this process, we should, therefore, expect to find the correlation much less than in collections taken (1) either before these processes have begun, or (2) after they are ended. We can realize this, in the main, by taking from a large random sample all the largest specimens (which are, of course, the older ones) and combining these into a single correlation table with specimens from the same culture that are beginning fission (the *oldest* specimens of the culture). I performed this operation for lot 1 of Table X. This collection contains 131 specimens beginning fission (row 25, Table X.), and 134 specimens (not dividing) that are 196 microns, or more, in length (row 28, Table X.); throwing these together, we have a collection of 264 of the oldest specimens in the culture (row 29, Table X.). For the 131 specimens beginning fission the coefficient of correlation is + .6546; for the 134 large specimens it is + .4681. When the two are taken together the correlation disappears. The computation gives us a coefficient of + .0350, but this is less than its probable error (.0415), so that the figures have no significance; no correlation appears.

The effects of the inclusion of various growth stages on the observed correlation shows itself in many other ways, which will become evident to anyone who carefully examines the data of Table X., in connection with our curves of growth (Diagram 5), and the relations brought out in the foregoing paragraphs. Note, for example, the coefficients of correlation for lot 9 (rows 16–18, Table X.). For the specimens 3 to 4 hours old the coefficient is but .3201, and for those 4.20 to 5 hours old it is .5557. When we throw these two lots together, so as to include a much greater proportion of the growth curve, the correlation rises to .7132. In this larger collection the short specimens are much the narrower, the large specimens much broader—giving high positive correlation. Slight changes in one dimension may not be accompanied by notable changes in the other, while *great* changes in one are always accompanied by changes in the other. This is a relation which we shall meet again.

While thus growth has a very great effect on the correlation to be computed from the measurements of a collection of *Paramecia,* it is important to bear in mind the fact that it is by no means the only factor concerned in correlation. This becomes evident as soon as we take a collection in which the specimens are all in nearly the same stage of growth; the coefficient of correlation is then high. This is perhaps best realized by considering specimens in the beginning of fission. As we have before noticed, in the collection of 131 specimens beginning fission, from lot 1, great pains were taken to include only a single stage in the process. This collection gives a high positive correlation of .6546. This correlation can be due only to the fact that in specimens at a single growth stage the length and breadth tend to bear a certain proportion to each other. The effects of this are clearly seen in many other collections of Table X. Thus, in rows 8, 9 and 15 the specimens all fall in the period when length is increasing while breadth is decreasing; yet there is in each case a small positive correlation. This is due to the fact that the period of growth over which each collection extended was small, so that the negative correlation due to growth was more than counterbalanced by the inherent proportionality of length to breadth. A collection including only specimens that were all in the same stage of growth would undoubtedly (other things begin equal) show a high correlation between length and breadth, no matter what point on the growth curves they represented. This signifies, of course, that in any given stage of growth the relation of length to breadth tends to be the same in all specimens—although in *different* stages of growth this is often not the case. Other factors which modify the correlation will be considered in the later sections of this paper; a summary of all these factors will be presented in a special section.

With this we conclude our study of growth in *Paramecium;*

being prepared to understand the part played by this in the observed variations and correlations, we may pass to other factors affecting these.

## IV. THE EFFECTS OF ENVIRONMENTAL CONDITIONS ON DIMENSIONS, VARIATION AND CORRELATION.

The data for the study of growth, just concluded, show incidentally that environmental conditions affect profoundly the dimensions, variation and correlation in *Paramecium*. As we have seen, samples taken from the same culture on two successive days are not strictly comparable for determining matters relating to growth, because of the environmental changes from day to day, inducing marked changes in the organisms. Thus, in a given culture we found that the mean length at the age of 1¼ to 1½ hours was 161.524 microns; three days later specimens more than twice as old, from the same culture, were smaller, measuring but 149.636 microns. We wish now to investigate the causes of such differences.

We shall not attempt at present a systematic investigation of the effects of different chemical and physical agents on size, form and variation, though this is a matter which much needs study. Our present object is rather to examine the effects of altered nutritional conditions and of the commoner "favorable" and "unfavorable" conditions. We shall study the variations from the standpoint of interest in the organism rather than in the agents inducing them, the purpose being to form a conception of the changes which may be looked for in *Paramecium* as a result of common alterations, mainly nutritional, in its cultural conditions. One of the results of this study will be to show that we cannot assign a definite effect to each agent taken in any absolute way. What effect a given agent will have depends on the previous condition of the organisms on which it acts. The same agent produces at one time an increase in size, at another a decrease; at one time it increases the variability; at another it decreases it. A given agent may either increase the positive correlation between length and breadth, or it may decrease it or convert it into a negative correlation. In succeeding days the same agent may produce these diverse effects on the same set of *Paramecia*.

Yet, of course, these results are not produced haphazard; what we wish to study are the laws they follow.

The effects of the environment were studied mainly on the same animals that served for the study of growth. Two strains were used; one consisted of descendants of the individual *D*, of the *caudatum* form, the other of descendants of *c* (*aurelia* form). The results show the extent of the variations producible through environmental action in the progeny of single individuals multiplying by fission. No conjugation occurred in the *D* strain during the time it was under experimentation. On a given date, therefore, the age of the individuals, as measured in generations of the "cycle," was about the same.

Table XVIII. gives a summary of the statistical results in the experiments on the effects of the environment; it will be referred to frequently in the following account (see next page).

### 1. PROGENY OF *D* (*caudatum* FORM).

The individual *D* was isolated April 12, 1907; it measured, as nearly as could be determined when alive, about 250 microns. It was placed in culture fluid made of boiled hay and the progeny were kept in such cultures for months. Characteristic progeny of *D* are shown in Fig. 1, *a* to *d*.

The experiments with the descendants of *D* may be divided into three series.

### *First Series.*

*Old Large Culture.*—On June 11 a sample of 100 of the descendants of *D* was killed, from a hay culture that had stood several weeks and was flourishing, though multiplication was not occurring actively. This culture was in a vessel about nine inches across. The measurements of this sample are given in Table V. (page 406), while the constants are found in row 1, Table XVIII.

*Effects of Fresh Hay Infusion.*—Three days after these measurements were taken, a number of individuals of this culture were removed and placed in a fresh hay infusion, in a watch-glass; in this they were allowed to remain 24 hours. The increased food in the fresh infusion caused them to increase much in breadth (from 49.000 microns to 64.880 microns), and at the same time to begin to

## TABLE XVIII.

*Effects of Environmental Conditions on Dimensions and Constants of Varia-*
same culture at the same time (except in rows 12, 15 and 20). The
appendix or elsewhere, in which fuller data are given for the lot in

| Row. | A. *Progeny of D.* *First Series.* | Number of Individuals. | Table. | Length. | | | |
|---|---|---|---|---|---|---|---|
| | | | | Mean in Microns. | Standard Deviation in Microns. | Coefficient of Variation. | Range of Variation in Microns. |
| 1 | Random sample of *D*, June 11, 1907 | 100 | 5 | 188.360± .980 | 14.532± .692 | 7.715±.370 | 128–228 |
| 2 | Same after 24 hours in fresh hay infusion, June 15 | 100 | 51 | 184.680± .848 | 12.596± .600 | 6.821±.327 | 156–224 |
| 3 | Two days after last; culture fluid not renewed, June 17 | 135 | 6 | 185.008± .836 | 14.420± .592 | 7.794±.324 | 148–212 |
| 4 | Same, after 24 hours in fresh hay infusion. Rapid multiplication, June 18 | 195 | 7 | 176.124±1.128 | 23.360± .797 | 13.262±.461 | 104–220 |
| 5 | Same, one week later; bacteria multiplied injuriously, June 25 | 178 | 52 | 201.888±1.147 | 22.680± .811 | 11.233±.407 | 140–256 |
| 6 | Starvation, same as row 2, but left 11 days in small quantity of fluid, June 25. | 100 | 53 | 149.360± .736 | 10.896± .520 | 7.296±.350 | 128–188 |
| | *Second Series.* | | | | | | |
| 7 | 24 hours in fresh hay infusion; rapid multiplication, July 17 | 200 | 30 | 1 .100 .776 | 16.264± .548 | 8.834±.300 | 140–216 |
| 8 | Same as last, but starved a week, July 24 | 150 | 19 | 146.108± .563 | 10.228± .398 | 7.003±.274 | 120–176 |
| 9 | Same as last, but 24 hours in fresh hay infusion, July 25 | 350 | 20 | 163.932± .754 | 20.928± .533 | 12.767±.331 | 120–220 |
| 10 | Same as last, but kept 1 week without change of fluid, July 31 | 150 | 21 | 174.400± .819 | 14.876± .579 | 8.530±.335 | 132–212 |
| 11 | Same as last, but kept 48 hours in fresh hay infusion, Aug. 3 | 150 | 22 | 191.360± .943 | 17.116± .666 | 8.945±.351 | 136–240 |
| 12 | Rows 8, 10 and 11 combined | 450 | — | 180.624± .748 | 23.537± .529 | 13.795±.316 | 120–240 |
| | *Third Series.* | | | | | | |
| 13 | Slender, old culture, in large jar, September 15 | 100 | 54 | 202.280±1.031 | 15.284± .729 | 7.556±.362 | 160–232 |
| 14 | Same as last, after 48 hours in fresh hay infusion, September 15 | 100 | 55 | 175.320±1.060 | 15.708± .749 | 8.959±.431 | 124–216 |
| 15 | Rows 13 and 14, combined | 200 | — | 188.800± .980 | 20.540±1.092 | 10.879±.371 | 124–232 |
| | B. *Progeny of c.* | | | | | | |
| 16 | Random sample of *c*, June 11, 1907 | 100 | 4 | 130.120± .628 | 9.284± .443 | 7.134±.342 | 104–156 |
| 17 | Random sample of *c*, August 9 | 100 | 56 | 123.666± .813 | 12.040± .573 | 9.736±.469 | 100–160 |

TABLE XVIII.—*Continued.*

*tion in Paramecium.* Each row consists of specimens taken from the column headed "Table" gives the number of a table found in the question.

| Breadth. | | | | Mean Index, or Ratio of Breadth to Length. Per Cent. | Coefficient of Correlation. |
|---|---|---|---|---|---|
| Mean in Microns. | Standard Deviation in Microns. | Coefficient of Variation. | Range of Variation in Microns. | | |
| 49.000±.548 | 8.144±.388 | 16.618± .814 | 28–76 | 26.029 | .4188±.0556 |
| 64.880±.580 | 8.624±.412 | 13.292± .645 | 44–88 | 35.131 | .6469±.0392 |
| 43.556±.392 | 6.748±.276 | 15.490± .651 | 32–60 | 23.517 | .5955±.0375 |
| 47.364±.344 | 7.132±.244 | 15.057± .526 | 32–72 | 27.153 | .3945±.0408 |
| 56.112±.395 | 7.808±.279 | 13.913± .507 | 36–80 | 27.850 | .6771±.0274 |
| 38.080±.356 | 5.288±.252 | 13.881± .675 | 28–52 | 25.515 | .4481±.0539 |
| 46.020±.251 | 5.256±.177 | 11.421± .390 | 36–60 | 25.084 | .4282±.0389 |
| 31.180±.212 | 3.881±.151 | 12.473± .493 | 20–40 | 21.337 | .3906±.0467 |
| 46.684±.488 | 13.484±.344 | 28.879± .793 | 20–80 | 28.236 | .8463±.0102 |
| 44.800±.429 | 7.796±.304 | 17.397± .698 | 32–68 | 25.657 | .5704±.0372 |
| 54.880±.431 | 7.824±.305 | 14.255± .566 | 36–84 | 28.639 | .7364±.0252 |
| 43.600±.377 | 11.852±.266 | 27.184± .654 | 20–84 | | |
| 49.600±.298 | 4.412±.210 | 8.896± .428 | 40–60 | 24.593 | .4085±.0562 |
| 63.160±.472 | 7.000±.334 | 11.083± .535 | 44–80 | 36.123 | .5376±.0480 |
| 56.380±.427 | 8.956±.302 | 15.884± .549 | 40–80 | 30.350 | —.2613±.0414 |
| 36.280±.260 | 3.880±.184 | 10.700± .516 | 28–44 | 27.913 | .5208±.0492 |
| 33.600±.400 | 5.917±.283 | 17.608± .865 | 23.3–50 | 27.136 | .6258±.0410 |

TABLE XVIII.—*Continued.*

| Row. | B. Progeny of *c*. Continued. | Number of Individuals. | Table. | Length | | | |
|---|---|---|---|---|---|---|---|
| | | | | Mean in Microns. | Standard Deviation in Microns. | Coefficient of Variation. | Range of Variation in Microns. |
| 18 | Same as last, but 24 hours after addition of boiled grass, August 10 | 225 | 49 | 114.163± .784 | 17.443± .555 | 15.279±.497 | 73.3–160 |
| 19 | Same as row 17, but 24 hours in fresh hay infusion, August 12 | 100 | 50 | 114.033± .820 | 12.140± .580 | 10.646±.513 | 86.7–146.7 |
| 20 | Rows 17 and 19, together; same animals, half in old fluid, half in new | 200 | — | 118.850± .622 | 13.037± .440 | 10.698±.374 | 86.7–160 |
| 21 | Conjugating culture, large vessel, September 25 | 200 | 57 | 158.800± .877 | 18.384± .620 | 11.578±.396 | 124–200 |
| 22 | Same culture, 5 days after, food getting scarce | 100 | 58 | 129.640± .867 | 12.848± .613 | 9.911±.477 | 100–152 |
| 23 | Large, old culture, January 23, 1908; | 100 | 59 | 144.880±1.097 | 16.264± .776 | 11.224±.542 | 100–176 |
| 24 | Same, two days later, January 25, 1908 | 50 | — | 130.640±1.227 | 12.863± .868 | 9.846±.670 | 104–156 |
| 25 | Another old culture, January 23, 1908 | 100 | — | 137.200± .842 | 12.488± .596 | 9.102±.438 | 104–162 |
| 26 | Same as row 23, but starved 3 weeks, February 14 | 37 | — | 102.594±1.161 | 10.467± .821 | 10.202±.808 | 76–128 |
| 27 | Same as row 23, but cultivated in small watch glass, January 30–February 15, 1908 | 100 | 60 | 100.320± .528 | 7.828± .373 | 7.804±.374 | 76–120 |

multiply. The measurements of a sample of 100 of these are given in Table LI. (appendix), while the constants are found in row 2, Table XVIII. The increased breadth, with little change in the length, of course, results in an increase of the mean index or ratio of breadth to length; while in row 1 this was but 26.029 per cent., in the present lot it is 35.131 per cent. It is worthy of notice that with the increase in ratio of breadth to length there is an increase in the correlation between length and breadth from .4188 to .6469.

*Scarcity of Food.*—The watch-glass culture just described (row 2, Table XVIII.) was now allowed to stand for three days (till June 17) without renewing the culture fluid. The animals had multiplied greatly, so that food became scarce; as a result they became thin. The measurements are given in Table VI. (page 412) and the constants in row 3, Table XVIII. While the length remained about the same, the mean thickness of the body decreased from 64.880 to 43.556 microns. The mean ratio of breadth to length fell from 35.131 per

TABLE XVIII.—*Continued.*

| Breadth. | | | | Mean Index or Ratio of Breadth to Length. Per Cent. | Coefficient of Correlation. |
|---|---|---|---|---|---|
| Mean in Microns. | Standard Deviation in Microns. | Coefficient of Variation. | Range of Variation in Microns. | | |
| 34.207±.241 | 5.363±.171 | 15.683± .511 | 20–50 | 30.177 | .6757±.0244 |
| 47 300±.437 | 6.490±.310 | 13.720± .667 | 36.7–66.7 | 41.455 | .8152±.0226 |
| 40.450±.441 | 9.247±.312 | 22.857± .810 | 23.3–66.7 | | .1758±.0462 |
| 38.560±.353 | 7.396±.249 | 19.176± .670 | 16–60 | 24.244 | .7135±.0234 |
| 35.440±.400 | 5.928±.283 | 16.730± .820 | 20–48 | 27.262 | .7576±.0287 |
| 54.160±.765 | 11.346±.541 | 20.948±1.042 | 32–84 | 37.106 | .8500±.0187 |
| 37.760±.639 | 6.697±.452 | 17.736±1.233 | 28–52 | 28.975 | .4141±.0790 |
| 37.960±.413 | 6.128±.292 | 16.142± .790 | 24–56 | 27.625 | .6691±.0373 |
| 23.892±.644 | 5.804±.455 | 24.291±2.014 | 16–40 | 23.067 | .8018±.0396 |
| 26.480±.266 | 3.944±.188 | 14.895± .753 | 16–36 | 26.321 | .7671±.0278 |

cent. to 23.517 per cent., and at the same time correlation between the two fell from .6469 to .5955.

Thus, within a week we find enormous fluctuations in breadth, due to changes in the amount of food, while the length remains about the same. The breadth is much more affected by nutritional changes than is the length.

*Rapid Multiplication.*—To the watch-glass culture just described (row 3) new hay infusion was added. Twenty-four hours later (June 18) multiplication was occurring actively; stages of fission and all the stages of growth were numerous. Measurements of 195 specimens, taken at random at this time (Table VII., page 412, and row 4, Table XVIII.) show a very great increase in the range and amount of the variability in length, while there is little change in the breadth. This is, of course, due to the fact that the culture contains many young; these differ much from the adults in length, but little in breadth. The mean length decreases from 185.008 to 176.124

microns, and the variability in length almost doubles, increasing from 7.794 to 13.262. Owing to the inclusion of many young individuals, in which the length is increasing while the breadth is stationary or decreasing, the correlation between length and breadth decreases to .3945. Inspection of Tables VI. and VII. (page 412) shows at a glance the great effect of nutrition and division on the range and distribution of variations in size and form.

*Injurious Bacteria.*—A remarkable effect of what may be called "bad" conditions is shown in this series of experiments. The same watch-glass culture shown in row 3, Table XVIII., was allowed to stand for a week, till June 25. Bacteria of a certain character multiplied greatly, and seemed to get the upper hand of the *Paramecia.* The latter became opaque and abnormal in appearance, and some of them died, disintegrating into shapeless masses. It was now observed that many of the specimens still living were very large, and that variation in size was extreme. The distribution of the variations is shown in Table LII.; the constants in row 5, Table XVIII. Though no multiplication is occurring, so that no young are present, the range of variation is from 140 to 256 microns, while in row 3, from which this lot is derived, the range is only from 148 to 212 microns. The mean length has increased to 201.888 microns, one of the greatest mean lengths ever observed in progeny of *D*. The maximum size for descendants of *D* was likewise reached in this culture; in no other case were specimens 256 microns long observed.

*Starvation.*—In striking contrast with the effects of much nutrition (row 4, Table XVIII.) and of injurious bacteria (row 5) are the results of starvation (Table LIII., and row 6, Table XVIII.). The starving culture consisted of individuals from the same culture as row 1, placed in fresh hay infusion June 14. The constants before they were placed in the hay infusion are given in row 1, Table XVIII., while the immediate effects of the infusion are shown in row 2 of the same table. The same animals were left in this fluid for eleven days, till June 25. They had evidently begun to starve; they were small and thin and almost half of them had died. The dimensions are given in Table LIII., and the constants in row 6, Table XVIII. The length had fallen from 184.680 to 149.360 microns; the breadth from 64.880 to 38.080 microns. The breadth decreases with lack of food proportionately more than does the length, so that the ratio of length to breadth has fallen from 35.131 per cent. to 25.515 per cent. It is to be noticed, however, that this greater proportionate decrease of breadth takes place in the first days after the withdrawal of abundant food, since after the animals had been only three days without new food the ratio of breadth to length fell to 23.517 per cent. (row 3, Table XVIII.); it did not decrease farther after starvation began.

A comparative inspection of Tables VII. (page 412) and LIII. (appendix) shows to the eye the very great effects of nutrition on size and variation.

### *Second Series.*

After the series of experiments described above, the progeny of *D* were kept in large culture jars of hay and water for about three weeks. Then followed an exceedingly instructive series of experiments on the effects of environmental conditions, the results of which are shown in Tables XIX.–XXII. and in the large Table XVIII., rows 7 to 12. Mere inspection of the correlation tables shows the effects in such a striking way that I have placed the main tables together in the text, instead of relegating them to the appendix.

*Fresh Hay Infusion.*—On July 16, 1907, specimens from the large cultures were placed in a watch-glass of hay infusion and allowed to remain twenty-four hours. This induced rapid multiplication; while this was occurring a random sample of 200 specimens was measured, with the results shown in Table XXX. (appendix), and in row 7, Table XVIII.

*Starvation.*—Next these were allowed to starve for a week; then 150 specimens were measured (Table XIX., and row 8, Table XVIII.). The results may be compared with our other starving culture of Table LIII., and row 6, Table XVIII. It will be noticed that for both length and breadth the amount of variation is not great; that the absolute dimensions are small; that the ratio of breadth to length (21.337 per cent.) is the least we have even seen, and that the correlation between length and breadth is very low (.3906).

*Effects of Abundant Food on a Starving Culture.*—Now this starving culture (Table XIX.) was placed for twenty-four hours in

### Table XIX.

*Correlation Table for Length and Breadth of a Starving Culture of Descendants of D.* (Row 8, Table XVIII.)

Length in Microns.

| Breadth in Microns. | 120 | 124 | 128 | 132 | 136 | 140 | 144 | 148 | 152 | 156 | 160 | 164 | 168 | 172 | 176 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20 | | | | | | 1 | | | | | | | | | | 1 |
| 24 | 1 | 1 | 1 | | 1 | 2 | 2 | | 1 | 1 | | | | | | 10 |
| 28 | 1 | | 6 | 2 | 5 | 12 | 10 | 3 | 9 | 4 | 2 | | | | | 54 |
| 32 | | 1 | | 4 | 3 | 8 | 1 | 8 | 11 | 9 | | 2 | | 1 | | 48 |
| 36 | | | | | 2 | 3 | 3 | 7 | 1 | 8 | 3 | 1 | 1 | | 1 | 30 |
| 40 | | | 1 | | | | | 3 | | 1 | 1 | 1 | | | | 7 |
| | 2 | 2 | 8 | 6 | 11 | 26 | 16 | 21 | 22 | 23 | 6 | 4 | 1 | 1 | 1 | 150 |

| | | | |
|---|---|---|---|
| Length—Mean, | 146.108 ± .563μ | Breadth—Mean, | 31.180 ± .212μ |
| St. Dev., | 10.228 ± .398μ | St. Dev., | 3.881 ± .151μ |
| Coef. Var., | 7.003 ± .274 | Coef. Var., | 12.473 ± .493 |

Mean Index or Ratio of Breadth to Length, 21.337 per cent.; Coef. Cor., .3906 ± .0467.

### Table XX.

*Correlation Table for Length and Breadth of Descendants of D when a Starving Culture (Table XIX.) is placed for 24 Hours in Fresh Hay Infusion.* (Row 9, Table XVIII.)

Length in Microns.

| Breadth in Microns. | 120 | 124 | 128 | 132 | 136 | 140 | 144 | 148 | 152 | 156 | 160 | 164 | 168 | 172 | 176 | 180 | 184 | 188 | 192 | 196 | 200 | 204 | 208 | 212 | 216 | 220 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20 | | 1 | | | 1 | | | | | | | | | | | | | | | | | | | | | | 2 |
| 24 | 3 | 1 | 1 | 1 | 5 | 4 | 1 | 2 | | | | | | | | | | | | | | | | | | | 18 |
| 28 | 1 | 1 | 2 | 3 | 3 | 11 | 5 | 4 | 1 | 2 | 1 | | | | | | | | | | | | | | | | 34 |
| 32 | | | 1 | 1 | 6 | 3 | 6 | 4 | 3 | 2 | | 1 | | | | | | | | | | | | | | | 27 |
| 36 | | | 1 | 1 | 3 | 3 | 1 | 3 | 4 | 5 | | 1 | | | | | | | | | | | | | | | 22 |
| 40 | | | 1 | | 2 | | 2 | 3 | 4 | 3 | 3 | 3 | 2 | 2 | 2 | | | | | | | | | | | | 27 |
| 44 | | | | 1 | | 1 | 2 | 1 | 4 | 2 | 5 | 6 | 3 | 1 | | | 1 | | | | | | | | | | 27 |
| 48 | | | | | 1 | | 2 | | 2 | 5 | 5 | 9 | 4 | 2 | 2 | 3 | 1 | | 1 | 1 | | | | | | | 38 |
| 52 | | | | | | | 1 | 1 | 2 | 2 | 7 | 7 | 4 | 3 | 1 | 1 | 4 | 2 | 3 | | | | | | | | 38 |
| 56 | | | | | | | | | | 1 | 3 | 2 | 1 | 3 | 10 | 6 | 3 | 2 | 6 | 1 | 1 | | | | | | 39 |
| 60 | | | | | | | | | 1 | | 1 | | 1 | 2 | 4 | 5 | 6 | 3 | 2 | 3 | 2 | | 2 | | | | 32 |
| 64 | | | | | | | | | | | | | | 1 | 1 | 8 | 3 | 4 | 2 | 4 | | | | | | 1 | 24 |
| 68 | | | | | | | | | | | | | | | | | 1 | | 3 | 1 | 6 | | 1 | | 1 | | 13 |
| 72 | | | | | | | | | | | | | | | 1 | 1 | | 1 | 1 | | | | | 1 | | | 5 |
| 76 | | | | | | | | | | | | | | | | 1 | | | 1 | | | 1 | | | | | 3 |
| 80 | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | 1 |
| | 4 | 3 | 6 | 7 | 21 | 22 | 20 | 18 | 21 | 22 | 25 | 29 | 15 | 14 | 21 | 25 | 19 | 12 | 19 | 10 | 9 | 1 | 3 | 2 | 1 | 1 | 350 |

| | | | |
|---|---|---|---|
| Length—Mean, | 163.932 ± .754μ | Breadth—Mean, | 46.684 ± .488μ |
| St. Dev., | 20.928 ± .533μ | St. Dev., | 13.484 ± .344μ |
| Coef. Var., | 12.767 ± .331 | Coef. Var., | 28.879 ± .793 |

Mean Index, 28.236 per cent.; Coef. Cor., .8463 ± .0102.

## Table XXI.

*Correlation Table for Length and Breadth of Descendants of D, after Remaining One Week in Hay Infusion, Unchanged.* (Row 10, Table XVIII.)

Length in Microns.

| Breadth in Microns. | 132 | 136 | 140 | 144 | 148 | 152 | 156 | 160 | 164 | 168 | 172 | 176 | 180 | 184 | 188 | 192 | 196 | 200 | 204 | 208 | 212 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 32 | | | | | 1 | | 1 | 3 | 2 | | 1 | 1 | | | | | | | | | | 9 |
| 36 | 1 | | 2 | | | 3 | 2 | 4 | 3 | 3 | 1 | 2 | 1 | | | | | | | | | 22 |
| 40 | | | | | | 1 | 4 | 2 | 3 | 3 | 2 | 10 | 2 | 2 | 1 | | 1 | | | | | 31 |
| 44 | | | | | | 2 | 1 | 1 | 2 | 7 | 5 | 5 | | 1 | 2 | 1 | | | | | | 27 |
| 48 | | | | | 1 | | | | | | 3 | 2 | 3 | 4 | 3 | 1 | 2 | 4 | | | | 23 |
| 52 | | | | | 1 | | | 1 | | 2 | | 4 | 2 | 1 | 2 | 2 | 1 | 1 | 2 | | 1 | 20 |
| 56 | | | | | | | | | 1 | | | 1 | 2 | | | 1 | 3 | | | 1 | | 9 |
| 60 | | | | | | | | | | 1 | 1 | | 1 | 2 | | 1 | | | | | | 6 |
| 64 | | | | | | | | | | | | | | | | | | | | | | 0 |
| 68 | | | | | | | | | | | | 1 | | | | | | 1 | 1 | | | 3 |
| | 1 | 0 | 2 | 0 | 3 | 6 | 8 | 11 | 11 | 16 | 13 | 26 | 11 | 10 | 8 | 6 | 7 | 6 | 3 | 1 | 1 | 150 |

Length—Mean, 174.400 ± .819μ  Breadth—Mean, 44.800 ± .429μ
St. Dev., 14.876 ± .579μ  St. Dev., 7.796 ± .304μ
Coef. Var., 8.530 ± .335  Coef. Var., 17.397 ± .698

Mean Index or Ratio of Breadth to Length, 25.657 per cent.; Coef. Cor., .5704 ± .0372.

## Table XXII.

*Correlation Table for Length and Breadth, after the Culture shown in Table XXI. has remained 48 hours in Fresh Hay Infusion.*
(Row 11, Table XVIII.)

Length in Microns.

| Breadth in Microns. | 136 | 140 | 144 | 148 | 152 | 156 | 160 | 164 | 168 | 172 | 176 | 180 | 184 | 188 | 192 | 196 | 200 | 204 | 208 | 212 | 216 | 220 | 224 | 228 | 232 | 236 | 240 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 36 | 1 | | | | 2 | 1 | | | | | | | | | | | | | | | | | | | | | | 4 |
| 40 | | | | 1 | | | | | 1 | 1 | | | | | | | | | | | | | | | | | | 3 |
| 44 | | | | | | | 1 | 1 | | 1 | 1 | 3 | 1 | | | | | | | | | | | | | | | 8 |
| 48 | | | 1 | | | | | 1 | 4 | 2 | 3 | 2 | 7 | 3 | 1 | 1 | | 1 | | | | | | | | | | 26 |
| 52 | | | | | | | | 1 | | | 3 | 3 | 2 | 5 | 8 | 3 | 1 | 1 | | 2 | | | | | | | | 29 |
| 56 | | | | | | | | | | 1 | | 2 | 2 | 4 | 1 | 8 | 1 | | 2 | 6 | 1 | | | | 1 | | | 29 |
| 60 | | | | | | | | | | | 1 | | 1 | 1 | 4 | 3 | 4 | 3 | 3 | 2 | 1 | 1 | | | | | | 24 |
| 64 | | | | | | | | | | | | 1 | 2 | 1 | 1 | 3 | 3 | 1 | 3 | 1 | 1 | | 1 | | | | | 18 |
| 68 | | | | | | | | | | | | | | | | 1 | | | 1 | 1 | | 1 | | | | | | 4 |
| 72 | | | | | | | | | | | | | | | | | | | 1 | 1 | 1 | 1 | | | | | | 4 |
| 76 | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0 |
| 80 | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0 |
| 84 | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 1 |
| | 1 | 0 | 1 | 1 | 2 | 1 | 1 | 3 | 5 | 5 | 8 | 11 | 15 | 14 | 15 | 19 | 9 | 6 | 10 | 13 | 4 | 3 | 1 | 0 | 1 | 0 | 1 | 150 |

Length—Mean, 191.360 ± .943μ  Breadth—Mean, 54.880 ± .431μ
St. Dev., 17.116 ± .666μ  St. Dev., 7.824 ± .305μ
Coef. Var., 8.945 ± .351  Coef. Var., 14.255 ± .566

Mean Index, 28.639 per cent.; Coef Cor., 7364 ± .0252.

a fresh hay infusion. At once the culture "spread out" greatly, in a way that will appear on comparing Table XIX., for the starving culture, with Table XX., for those twenty-four hours in nutritive fluid. Many of the animals began to grow at once after they were placed in the nutritive fluid, so that the maximum length increased from 176 to 220 microns, the maximum breadth from 40 to 80 microns (see rows 8 and 9, Table XVIII.). Others had not yet begun to increase when the sample of Table XX. was taken, so that

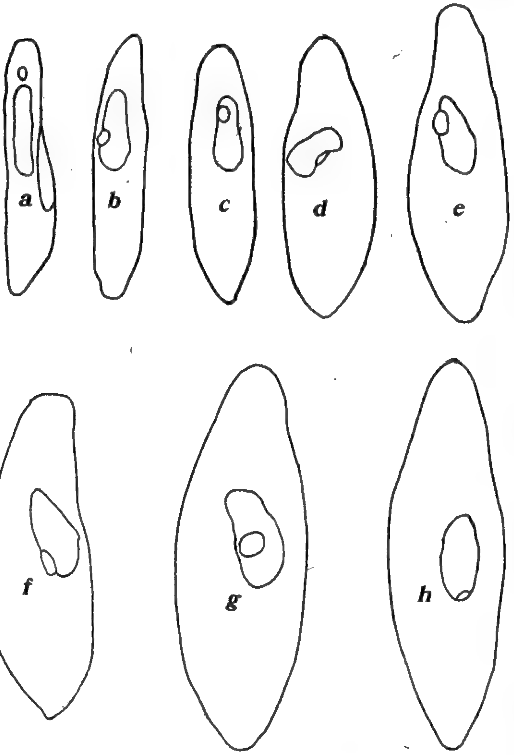

Fig. 5. Characteristic forms and sizes from a culture of descendants of D (*caudatum* form), that had been starved for a week (Table XIX.), then was left twenty-four hours in fresh hay infusion (Table XX.). *a* and *b*, Starved specimens. *c, d, e, f*, transitional forms, becoming large and plump in the abundant food; *g*, characteristic large, plump form. *a* to *g* from Table XX. *h*, characteristic form a week later (Table XXI.); animals becoming thinner again, but retaining the increased length. All × 235.

the minimum size remained as before; and between these extremes all intermediate gradations were found. Fig. 5 shows characteristic forms and sizes from this culture, *a* and *b* showing the starving condition, while *c* to *f* show various stages in the transition to the largest size, one of which is shown at *g*.

As a result of these changes, the variability has increased enormously. The coefficient of variation in length has increased in twenty-four hours from 7.003 to 12.767; that for breadth has more than doubled, increasing from 12.473 to 28.879. The mean size has likewise increased greatly, while the ratio of breadth to length has changed from 21.337 per cent. to 28.236 per cent. Perhaps the most striking change is in the correlation between length and breadth. In the starving culture this is but .3906; twenty-four hours later it has become, in the growing culture, .8463—one of the highest coefficients of correlation that I have ever found in *Paramecium*. It is evident that breadth and length are increasing proportionately, on the whole, so that the inclusion of different degrees of increase in size in Table XX. gives a high coefficient of correlation. Furthermore, the fact that fission had not begun in this lot permits the correlation to remain high; if there were many young included, the correlation would, of course, be lowered. With every increase of 10 microns in length the breadth increases 5.452 microns.

*Fluid Unchanged for a Week.*—Now the same culture was kept for a week in the same fluid. The animals had reached more nearly a condition of equilibrium; the variability, and with it the correlation, had greatly decreased, while the mean length had increased (Table XXI., and row 10, Table XVIII.). It is noticeable here, as in many other cases, that the coefficient of correlation decreases when the ratio of breadth to length decreases.

*Forty-eight Hours in New Culture Fluid.*—The addition of new hay infusion to the culture just described caused in forty-eight hours a considerable increase in mean length and breadth, while the variation did not change greatly (Table XXII., and row 11, Table XVIII.). Again, as the ratio of breadth to length increases, the correlation between the two likewise increases.

*Résumé.*—Polygons showing the changes in the animals of this series, from the starving condition of Table XIX. to the well-fed condition of Table XXII. are given in Diagram 6; these, taken in connection with Fig. 5 and with Tables XIX. to XXII. give a good idea of the changes in dimensions and variation that may be produced in a short time by changes in the conditions of nutrition. Evidently Table XX., taken twenty-four hours after the starving specimens were placed in the fresh hay infusion, is a transitional

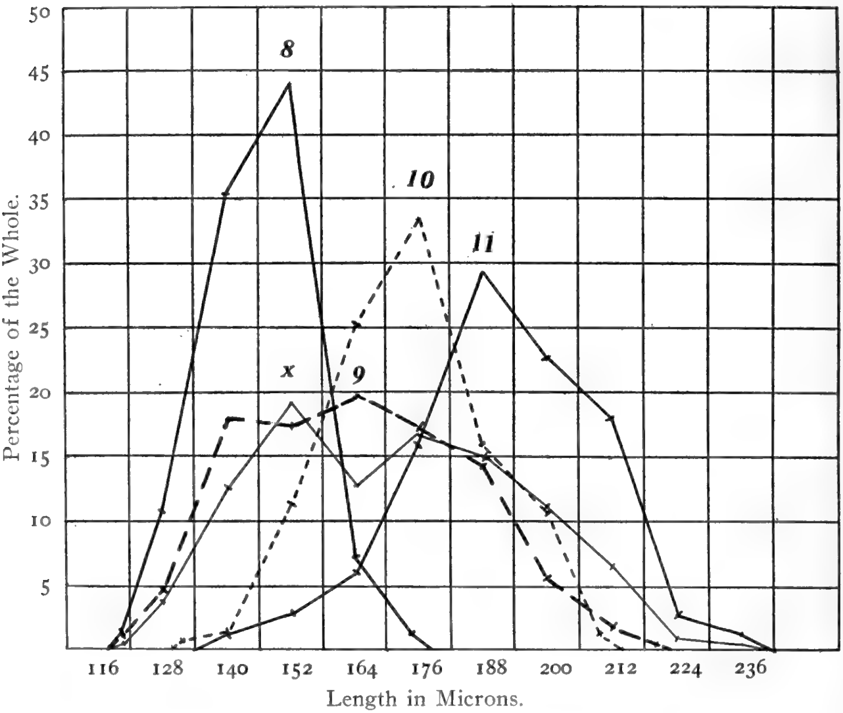

Diagram 6. Polygons of variation in length for a culture of descendants of the individual *D* when subjected successively to varied conditions of nutrition. The numbers above the highest points of the polygons correspond to rows of Table XVIII., in which are given the constants for the different polygons. *8,* culture starved a week. *9* (heavy broken line), same as 8, but after 24 hours in fresh hay infusion. *10,* same after one week in the same fluid, unchanged. *11,* same after 48 hours in fresh hay infusion. *x,* polygon for combination of 8, 10 and 11, showing its resemblance to the polygon for 9 alone.

The correlation tables for these polygons are numbers XIX. to XXII., pages 466, 467.

condition, including representatives of the small, starving condition, the well grown condition, and intermediate states; it is a sort of a résumé of the variations due to nutrition. If we add together the tables given by the starving culture (earlier than Table XX.) and the two well-fed cultures (later than Table XX.), we get a collection of 450 individuals, in which the variation in length and breadth is about the same as for Table XX. (see row 12, Table XVIII.). For Table XX. the coefficients of variation for length and breadth are 12.767 and 28.879; the corresponding coefficients for the three lots combined are 13.795 and 27.184.

Although the animals are all descended from the same parent and have lived under the same conditions save for the ten days during which these experiments lasted, we find that in the period just mentioned the polygons of distribution of variations in length have so changed that the one for the end of the ten day period (11, Diagram 6) hardly more than overlaps at one end that for the beginning of the period (8, Diagram 6).

Addition of fresh hay infusion causes in these cases an increase in length, in breadth, in variation, and in the correlation between length and breadth. But whether these results shall follow depends upon the previous condition of the animals. This is illustrated by the fact that there is one exception to the statement just made; the variability in breadth decreased in place of increasing in the transition from Table XXI. to Table XXII. The effect of the previous condition is better seen in the experiments of the third series, to be described next.

### *Third Series.*

A culture of the descendants of *D* was rather ill-fed, though not starving; the animals were long and slender (Fig. 6, *a* and *b*). Half of these were allowed to remain in the old fluid, while half were placed in fresh hay infusion. After forty-eight hours, a random sample of each set was measured. The measurements of the set in the old fluid are given in Table LIV., the constants in row 13, Table XVIII. The results of keeping the animals forty-eight hours in the fresh infusion are shown in Table LV., and in row 14, Table XVIII. The animals grew plump and multiplied; the mean breadth increased from 49.600 microns to 63.160 microns (characteristic form shown at *c*, Fig. 6). But *the mean length decreased* from 202.280 to 175.320 microns. This is probably due to rapid multiplication; the animals now divide before they reach the length which they had at first. As a result of the increase in breadth and decrease in length, of course, the mean ratio of breadth to length increased greatly, from 24.593 per cent. to 36.123 per cent. With the increase of this ratio, the correlation likewise increased, as is usually the case. The variation increased, both in breadth and in length.

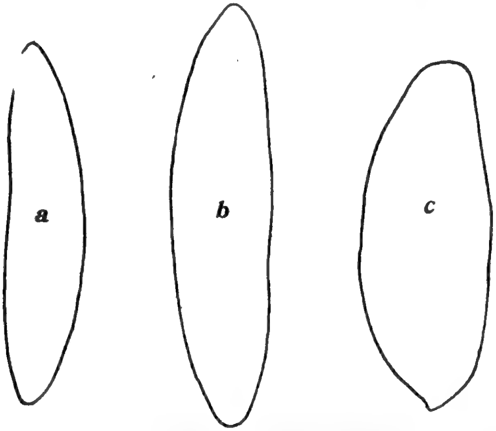

FIG. 6. *a* and *b*, characteristic slender specimens from row 13, Table XVIII. *c*, characteristic short plump specimen from row 14, Table XVIII.; produced by allowing those of row 13 to remain 24 hours in fresh hay infusion. Descendants of *D* (*caudatum* form). All × 235.

These are the results if we consider separately the two samples, taken forty-eight hours apart. But if we throw them together, looking at them merely as a sample of the descendants of *D*, taken at intervals, we get a surprising effect on the correlation between length and breath. The marked positive correlation in the two samples taken separately *disappears and is replaced by a negative correlation.* In the first sample the correlation is + .4085; in the second it is + .5376; in the two together it is — .2613. (The constants for the two together are given in row 15, Table XVIII.) The negative correlation is, of course, due to the fact that the nutritive fluid causes the breadth to increase and the length to decrease, so that, on the whole, when the two samples are taken together, greater breadth is associated with less length.

### 2. Progeny of *c* (*aurelia* Form).

With the smaller *Paramecia,* progeny of the small individual *c,* a similar series of experiments was undertaken. The individual *c* came from the same wild culture as *D;* its length, as nearly as could be determined in life, was 120 microns. It was isolated April 8, 1907. Fig. 3 shows some examples of the descendants of *c,* drawn to the same scale as the figures of the descendants of *D.*

*Random Sample.*—On June 11 one hundred of the progeny of *c* gave the measurements shown in Table IV., page 405, the constants being given in row 16, Table XVIII.

*Effect of Adding Boiled Hay.*—On August 9 a fairly flourishing culture of the descendants of *c* was examined, with the results shown in Table LVI., and in row 17, Table XVIII. To this culture a quantity of boiled grass was added; this caused rapid multiplication. Twenty-four hours later a sample of 225 specimens was measured, with the results shown in Table XLIX., and row 18, Table XVIII. The added nutrition has caused the mean length to decrease, while the mean breadth remains nearly the same. This is due to the fact that the main effect of the nutrition was to cause rapid multiplication rather than growth in size. The coefficient of variation in length increased greatly, from 9.736 to 15.279, while the variation in breadth remained about the same, though with a slight *decrease.* This peculiar result is mainly due to the fact that the culture after the addition of the grass (row 18) contains many young specimens, which differ from the adults greatly in length, but little in breadth. As usual, we find that an increase in the ratio of breadth to length is accompanied by an increase in the correlation between the two.

*Effect of Fresh Hay Infusion.*—The next day (August 11) another lot from the culture shown in Table LVI. (row 17, Table XVIII.) was placed in a fresh hay infusion and left twenty-four hours. This nutritive fluid caused the animals to become very plump, while at the same time a moderate amount of fission was induced. The results are shown in Table L., and in row 19, Table

XVIII. As there appears, the mean breadth increased from 33.600 to 47.300 microns. The length, on the other hand, decreased from 123.666 to 114.033 microns. The mean ratio of breadth to length thus increased very greatly, from 27.136 per cent. to 41.455 per cent. The latter is the largest mean index I have ever observed in *Paramecia* not selected with relation to the age of the individuals; it is exceeded only by the mean index of the young halves during fission (see Table X.). With the increase in the mean ratio of breadth to length, there is as usual an increase in the correlation between the two dimensions; this reaches the unusually high value of .8152. The nutritive fluid left the variation in length about the same, but considerably decreased the variation in breadth. This is undoubtedly due to the fact that before the hay infusion was introduced some of the specimens were well fed, some poorly fed, as the chances of the daily life determined; while after the infusion was introduced *all* were well fed, so that there was less variation in breadth than before. Characteristic forms after the infusion was introduced are shown in Fig. 3, *a* to *c* (page 423).

The facts in these cases are nearly parallel with those observed in the third series of experiments on the progeny of *D* (Table XVIII., rows 13–15). If we combine the two samples of *c* (row 20, Table XVIII.), as we did those of *D*, the effect is, as in the case of *D*, to decrease greatly the correlation between length and breadth But in the present case the very high positive correlation of the two samples taken separately is not entirely overcome by combining them, though the correlation falls to .1758. The actual numerical coefficient just given is the resultant of a number of conflicting factors. In the two samples taken separately greater length is associated on the whole with greater breadth, giving high positive correlation, which in passing from Table LVI. to Table L. an increase in breadth is associated with a decrease in length, tending to diminish the correlation. The facts show clearly that the observed statistical correlation does not involve any necessary and constant relation of the one dimension to the other; both dimensions depend on various factors, which sometimes act in the same way on both, sometimes differently.

Combining the two samples of *c* (as in row 20, Table XVIII.), gives, of course, increased variation, illustrating, like most of our results, the fact that a definite coefficient of variation cannot be considered characteristic of a given species or race. The observed variation depends on many factors.

*Conjugating Culture.*—The progeny of *c* I divided into two sets, both of which were kept in larger culture vessels and maintained by adding boiled hay at intervals. September 25 one of these cultures was found to be undergoing an epidemic of conjugation (though, of course, all were progeny of a single individual). The details regarding the relation of conjugation to the phenomena we are studying are to be taken up in a later communication, but I will give here the essential facts regarding dimensions and constants of variation, in order that our picture of the changes undergone by the *c* line may be as complete as possible. A random sample of the non-conjugants of this conjugating culture gave the results shown in row 21, Table XVIII., and in Table LVII. The mean length (158.800 microns) was considerably greater than has been observed in any other culture of *c*. Whether this fact has any relation to the occurrence of conjugation, or whether it is merely a matter of the environmental conditions must remain for the present a question.

*Scarcity of Food After Conjugation.*—This conjugating culture was allowed to stand five days. All conjugation ceased and the food began to get scarce. Now a sample gave the results shown in row 22, Table XVIII., and in Table LVIII. The length had decreased from 158.800 to 129.640 microns. Breadth likewise decreased, though not in so great a proportion as length, so that the ratio of breadth to length increased. As is usual when this ratio increases, the coefficient of correlation likewise increased.

*Variation in Different Divisions of the Same Pure Line on the Same Date.*—After the observations just described, the two cultures composed of the progeny of *c* were maintained for several months. On January 23, 1908, samples from each were measured, giving the results shown in rows 23 and 25, Table XVIII. As is evident, the two differed considerably. The details do not demand attention, save that in one of these old cultures (row 23, and Table LIX.) the coefficient of correlation between length and breadth was the highest I have ever observed in *Paramecium,* reaching .8500. Both these cultures were flourishing and well fed.

*Effects of Lack of Food.*—From the culture shown in row 23, Table XVIII., a large number of specimens were removed and placed in a small watch-glass, which was allowed to stand for two days. The food decreased rapidly and the animals became smaller, giving the results shown in row 24, Table XVIII. The mean length had decreased 10.174 per cent.; the mean breadth 33.024 per cent. These were now allowed to stand for three weeks more in the watch-glass, without adding food. At the end of this time they were in the extremes of starvation, and only 37 specimens remained of the many hundreds originally present. These 37 gave the results shown in row 26, Table XVIII. As compared with the original condition of row 23, the mean length had decreased 30.638 per cent., the mean breadth 55.886 per cent. A peculiar fact is that this starving culture shows a very high coefficient of correlation between length and breadth (.8018), while in our other starving cultures this has not been the case (see rows 6 and 8, Table XVIII.).

From the culture of large specimens shown in row 23 another lot was removed January 30 and kept in a small watch-glass, new hay infusion being added at intervals. In spite of this addition of new food material, and the fact that they continued to flourish and multiply, these decreased in length even more than in the starving culture, the mean being 100.320. This is the smallest mean length observed in any lot of the *c* line. The data for this lot are given in row 27, Table XVIII., and in Table LX.

### 3. Summary on the Effects of Environment.

The facts given above show that the nature of the environment affects greatly the dimensions, proportions and variations of *Paramecium,* and that these effects are produced with great ease and rapidity by such changes as are common in any culture of these infusoria. Some of the more important effects may be summarized as follows:

*Effect on Length.*—Under the influence of varied nutritional conditions the *length* varies extremely. In the line descended from the individual *D* the mean length varied under different conditions from 146.108 to 202.280 microns—the difference being 38.445 per cent. of the smallest mean length. In the *c* line the variation in mean length under the influence of the environment was from 100.320 to 158.800 microns, or 58.293 per cent. of the lowest mean. The *extreme* lengths in each line, of course, differed still more; in the *D* line the extreme variation in length was from 104 to 256 microns, or 146.153 per cent. of the least length; in the *c* line it was from 73.3 to 200 microns, or 172.851 per cent. of the minimal length.

*Effect on Breadth.*—The breadth (the thickness of the body) varies under different environmental conditions more readily and in a higher degree than does the length. In the *D* line the mean breadth varied in different cultures from 31.180 to 64.880 microns, or by 108.08 per cent. of the lowest mean; the *extreme* variation in breadth, under different conditions, was from 20 to 88 microns, or 340 per cent. of the minimal breadth. In the *c* line the mean breadth varied under different conditions from 23.892 to 54.160 microns, or by 126.69 per cent. of the lowest mean; the *extreme* variation in breadth was from 16 to 84 microns, or 425 per cent. of the minimal breadth. The greater variability of the breadth, as compared with the length is seen in the coefficients of variation of the single cultures. The largest coefficient of variation for length is 15.279, while for breadth it is 28.879.

*Relation of Length to Nutrition.*—In general, increased nutrition increases the length. But the result is not always the same, because increased nutrition has two main effects: to increase directly the size of the adults, and to bring about multiplication. The latter effect, of course, decreases the mean length of the individuals of a culture, since it induces the presence of many specimens that are young, and therefore small. Increase in mean length due to added nutrition is seen in Table XVIII., rows 8 to 9, 10 to 11. *Decrease* in mean length, due to added nutrition is seen in the same table on comparing rows 1 and 2; 3 and 4; 13 and 14; 17 and 18. This decrease is due to the fact that in the nutritive fluid the animals divide before they reach the length of those in the poor fluid.

Decrease of length, due to decrease of nutrition, is seen in Table XVIII., by comparing rows 2 and 6; 7 and 8; 21 and 22; 23 and 24; 23 and 26.

*Relation of Breadth to Nutrition.*—The relation of breadth to nutrition is simpler than that of length; in all cases increase of nutrition increases the breadth; decrease of nutrition decreases it. The response of breadth to changes in nutrition is immediate and very marked. Within twenty-four hours increased nutrition caused in the *D* line an increase of 49.724 per cent. in breadth (rows 8 and 9, Table XVIII.); in the *c* line it caused in twenty-four hours an increase of 40.778 per cent. (rows 17 and 19, Table XVIII.).

But the decrease of breadth with decrease of nutrition does not vary directly with the time; when plump individuals are left without food, they decrease much more rapidly at first than later. Thus, in the series shown in Table XVIII., rows 2, 3 and 6, the breadth decreased in the first forty-eight hours 21.324 microns, or 32.867 per cent.; in nine days more of lack of food the breadth decreased only 5.476 microns, or 8.440 per cent. more.

*Proportion of Breadth to Length.*—Since changes in nutritional and other conditions act more readily and more strongly on breadth than on length, and since the same agent may increase the breadth while decreasing the length, the proportion of breadth to length varies greatly under different conditions. The mean index, or ratio of breadth to length, varies in different cultures of the *D* line from 21.337 per cent. to 36.123 per cent.; in the *c* line from 23.067 per cent. to 41.455 per cent. Since the breadth is more dependent on nutritive conditions than is the length, we find the lowest ratio of breadth to length in the starving cultures (rows 8, 26, Table XVIII.); the highest ratio in well-fed cultures (rows 2, 14, 19, Table XVIII.). An increase of nutrition causes uniformly an increase of the ratio of breadth to length; a decrease of nutrition has almost uniformly the reverse effect. A single exception to the relation last mentioned is seen in the change from row 21 to row 22, Table XVIII.; here other causes, connected with conjugation, were probably at work. Whenever the mean breadth increases, the mean ratio of breadth to length likewise increases. (The only exception is the case just mentioned, where conjugation was involved.) It must be understood that this does not mean that in all cases the mean ratio of breadth to length varies directly with the mean breadth; if we compare rows 6 and 7, Table XVIII., for example, we find that this is not the case. But whenever, as a matter of experimental procedure, the mean breadth was caused to increase, the mean ratio of breadth to length likewise increased. This is due to the two facts mentioned in the first sentence of this paragraph.

*Effect of Environment on Variation.*—The amount of observed variation, as measured by the coefficient of variation, depends largely on environmental conditions; this is true both for length and for breadth. In the *D* line the coefficient of variation for length varies in different cultures from 6.821 to 13.262;[6] for breadth it varies from 8.896 to 28.879. In the *c* line the coefficient varies for length from 7.134 to 15.279; for breadth from 10.700 to 24.291.

The effects on the coefficient of variation of changes in nutrition vary much in different cases; increased nutrition sometimes increases the coefficient, sometimes decreases it, sometimes produces first one effect, then the other. There are evident physiological reasons for the different effects. In a starving culture the first effect of rich nutrition is to cause many of the individuals to increase in size, while those individuals in which the effects of starvation had gone far do not at first take food and change. Hence there is a great increase in the coefficients of variation; in changing from row 8 to row 9 (Table XVIII.) both coefficients approximately doubled in twenty-four hours. Later, though the animals were kept in the same fluid, the coefficients decreased again—all of the specimens having reached more nearly a condition of equilibrium. If the animals are fairly well fed before the additional nutrition is met, an early effect is to cause rapid multiplication; the consequent presence of both young and old individuals in the culture increases the coefficients of variation, and particularly that for length. An example of this is seen in the change from row 3 to row 4, Table XVIII. A little later, when the multiplication has ceased, the coefficients of variation become small again. The coefficients of variation are likely to be small in starving cultures, owing to the fact that there is little multiplication and the adults have reached a condition of relative equilibrium. By taking into consideration the immediate and the remote effects of a given agent on growth and multiplication, its effects on the coefficients of variation usually become intelligible.

[6] Of course the cultures contain specimens in all stages of growth; as we have previously seen, the coefficient of variation becomes much less when the animals are selected with reference to age.

It is not necessary to emphasize the fact that since different environmental conditions produce different dimensions, the coefficients of observed variation will be much increased by throwing together specimens from different environments, or those taken at different times from the same culture. Examples of this are seen in rows 12, 15 and 20, Table XVIII.

The question may be asked, How can we account for the large coefficients of variation in given lots, taken all from the *same* environment (as in the various "rows" of Table XVIII.)? Surely, it may be said, the age differences among the individuals are not sufficient to account for coefficients of 12, 13, 20, etc., such as we actually find. This is undoubtedly true, and it becomes still more striking when we consider cases like Table XLI. (appendix), where the individuals are all of practically the same age, and all come at one time from the same small watch-glass of hay infusion, yet we find the coefficients of variation to be respectively 6.389 and 14.615. The considerable variation is to be understood only by realizing that even a small mass of fluid constitutes a relatively large and varied environment for *Paramecium*. A watch-glass of hay infusion is a microcosm to this animal. Bacteria gather on the surface, while they may not be found on the bottom or through the middle. The bacterial zoöglœa may become thicker at one edge than at the other, owing to the accidents of the original distribution of the seed bacteria or of the infusoria. Some of the *Paramecia* thus get more food than the others, perhaps at a critical period of growth; they thus get a start, which enables them perhaps to obtain more food than the others, even under uniform conditions. Some of the individuals get crowded away from the bacterial zoöglœa, and remain against a rough spot on the glass instead, where they get no food. In short, even in a few drops of water the conditions are *not* uniform throughout; some of the animals are well nourished, others poorly nourished, and the results show in the variations of their measurements.

The question whether some of the variations in such cases are not congenital and hereditary will be taken up later; we shall find little evidence that this is the case.

It is clear that no particular coefficient of variation can be considered characteristic of a particular race, except as the conditions are very precisely defined. If all conditions of environment and growth were made absolutely the same, there is reason to believe (as we shall see farther) that for a given line (descended from a single individual) the coefficient of variation would be very close to zero. Its actually observed value in a given lot then depends almost entirely on environmental and growth differences.

*Effect of Environment on Correlation.*—The observed correlation between length and breadth varies greatly under different environmental conditions. In the *D* line the coefficient which measures correlation varies in different cultures from .3906 to .8463; in the *c* line from .4141 to .8500 (see Table XVIII.). Such differences are easily and quickly produced by environmental changes; thus the two extremes just mentioned for the *D* race were found in samples of the same lot of *Paramecia* taken twenty-four hours apart—one before, the other after, the addition of a nutritive fluid.

The correlation between length and breadth expresses the accuracy with which length and breadth vary proportionately. The actual proportion of one to the other, in a given lot, is, of course, of no consequence; length and breadth might be the same, or one might be 50 per cent. or 1 per cent. of the other; the correlation would still be complete (1.000) provided this same proportion were maintained throughout the particular lot examined. Any factor which causes the proportion of breadth to length to vary in a given lot, of course causes the correlation to fall below 1.000. If in a given lot many different ratios of breadth to length are represented, the correlation is, of course, lowered. In such a lot, any factor which tends to make the proportion of breadth to length more constant, of course, increases the correlation.

Examining the various factors which have the effects just mentioned, we find that the observed correlation depends upon many things.

(*a*) In considering the effects of growth (page 455), we saw that the proportion of breadth to length differs in different stages. Some of the effects of the environment on correlation are due to its effect on multiplication and growth.

(*b*) Certain environmental agents (as increased nutrition) increase the breadth while decreasing the length. Now, if this happens at the same time and in the same proportion in all the individuals, then at any given moment the coefficient of correlation will, of course, not be altered by it. But if for any reason the changes occur more quickly or strongly in certain individuals than in others (as is usually the case), then, of course, the coefficient of correlation will be decreased. Or, if we throw together individuals taken at different stages of the process, the correlation becomes greatly decreased; it may even become negative. For examples, see rows 15 and 20, Table XVIII.

(*c*) Even if a given agent causes a change in the same direction (*e. g.*, an increase) in both length and breadth, the inclusion of different stages in the process may reduce the correlation (if it is already high). This will occur (1) if the two dimensions are not changed proportionately to each other, and (2) if the change in a given dimension varies at different stages of the process. Both these conditions, as we have seen, are fulfilled in the changes in dimensions induced by the environment. Under almost any environmental change breadth is altered more than the length. Furthermore, when nutrition is decreased, breadth decreases more rapidly at first than later. The inclusion of different stages of the process in a collection therefore results in the inclusion of various different proportions of breadth to length—lowering the correlation.

(*d*) If the correlation is already low, indicating the presence of many different ratios of length to breadth, then varied changes in these ratios may compensate some of the existing differences, causing an increase in the correlation. Whether this shall or shall not occur depends upon the condition of affairs before the changes are made, and on the nature of the changes themselves. A special case of this comes up in the next.

(*e*) When a culture containing thin, poorly fed individuals is given added nutriment, the correlation between length and breadth increases (compare, in Table XVIII., rows 1 and 2; 8 and 9; 10 and 11; 13 and 14; 17 and 18; 17 and 19, etc.). This is because, when fresh nutriment is added, the thinnest, poorest-fed individuals naturally take more food than do the individuals that are already plump and well-fed; they therefore increase most in breadth. As a result, existing differences in breadth are compensated; all the animals take on that relative proportion of breadth to length that belongs to well-fed specimens.

Thus, we find almost throughout that an increase in the ratio of breadth to length is accompanied by an increase in the coefficient of correlation; a decrease in the ratio of breadth to length by a decrease in the coefficient of correlation. Examining these two constants, in the last two columns of Table XVIII., we find this relation to hold in every case of experimental procedure save one. (In the change from row 3 to row 4 it does not hold; this is due to another factor, to be taken up later.) If without regard to experimental procedure, we merely compare the mean index (or ratio of breadth to length) with the coefficient of correlation, we find the relation a little less general, though still marked; a large mean index is usually accompanied by a high coefficient of correlation.

Since, as we have previously seen, greater breadth is usually accompanied by a higher mean index, it follows that greater breadth is likewise usually accompanied by a higher correlation between breadth and length. This is, on the whole, evident on inspection of Table XVIII., though since other factors are involved, the relation is not without exception. But in general, broader specimens tend to show a more constant proportion of breadth to length than do thin ones.

(*f*) In poorly-fed cultures, as we have just seen, the breadth is apt to be variable in proportion to the length (giving low correlation) because some of the individuals get more food than others. But if all are reduced to an actually starving condition, then this source of variation is removed, and we may again get high correlation between breadth and length. This condition appears to be realized in row 26 of Table XVIII. Here a large culture had been reduced by starvation to a population of but 37, and these give the very high correlation of .8018 ± .0396.

(*g*) When a given agent causes rapid multiplication, so that the sample taken includes many different stages of growth, with their different proportions of breadth to length, the correlation becomes low. This is the reason for the marked decrease in correlation in changing from row 3 to row 4 in Table XVIII.

All together, it is clear that no particular coefficient of correlation can be taken as characteristic of a particular race of *Paramecia;* certainly not without very precise definition of the conditions. It appears probable that if all conditions of environment, growth, food taken, etc., could be made absolutely the same for individuals derived from the same ancestor, the coefficient of correlation would be close to 1.000.[6a] By varying these conditions any degree of positive correlation, down to zero, and many degrees of negative correlation can be attained.

## V. INHERITANCE OF SIZE.

Having examined the effects of growth and of environment on size and form, we are now prepared to investigate how far these are determined by internal factors, handed on from parent to progeny. Without such a preliminary study of growth and environmental action it would be impossible to investigate successfully the heredity of size and form.

We have already seen that not all differences in size are due to growth and environment; in the first culture examined (Table I., page 398) there were at least two sets of individuals of characteristic different sizes, and these differences in size are lasting. Progeny of the two typical individuals *D* and *c*, from these two sets, still retain their characteristic relative sizes after more than a year of culture under all sorts of conditions.

The differences between these two sets are about the same as those which have been described as distinguishing two species, *D* corresponding to the accounts of *Paramecium caudatum, c* to *Paramecium aurelia.* The next problem is to determine whether there are still other races of *Paramecium,* distinguishable on the basis of differences in size, independently of the environment. Can we by selecting individuals of differing sizes isolate races of corresponding sizes? Can we find races of all sorts of sizes intermediate between the largest and smallest adult representatives of such a heterogeneous culture as is shown in Table I.?

The clear grouping of the culture of Table I. into two sets seems to indicate that we have present simply two races or species. My

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[6a] Of course if all variation disappeared, as would perhaps be the case, then the concept of correlation would have no further application.

first experiments consisted of attempts to break the two lines derived respectively from *D* and *c* into other races of different sizes by selection and breeding of individuals of different sizes. This led incidentally, as we have seen, to the study of the effects of growth and environment on size; it was found that the observable differences between different members of either race were due to these factors, so that selection of such members did not lead to the establishment of races of different sizes. The results of a large amount of time-consuming work along this line, done before the investigation of growth and environmental action, were throughout negative.[7]

As a result of this work, I was disposed toward the belief that the characteristic sizes of *D* and *c* represent conditions of stability, which have properly been distinguished as two species, and that races of other sizes were not to be found or produced.

But the work thus far has, of course, been based on "pure lines," in the sense in which that expression is used by Johannsen (1903, 1906). The lines *D* and *c* are each derived from a single individual, reproducing asexually, so that no admixture from outside has entered them during the experiments. Now, while it appears difficult or impossible to produce other races *within* these pure lines, there remains, of course, the possibility that still other lines exist in nature. Can we find in a "wild" culture, by proper selection of differing individuals, still other races of differing size? This was the question next investigated.

## 1. SELECTION FOR DIFFERENT RACES IN A WILD CULTURE.

### (*a*) *Races Isolated from Cultures Not Conjugating.*

Attempts to separate out other races than those represented by *D* ("*caudatum* form") and *c* ("*aurelia* form") were first made with a wild culture which I called *OI*. This culture developed in decaying vegetation from a marsh. It contained two well marked sets of individuals: (1) very large individuals, corresponding in many respects to the *D* line, but with a mean length on January 3, 1908, of 238.280 microns; these we will designate *E*; (2) smaller

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[7] To the experiments on selection within a pure line we return in a later section.

individuals corresponding in many respects to the *c* line, with a mean size on November 14, 1907, of 140.133 microns. These two sets occurred mixed, but each reached its maximum development at the dates mentioned. Isolated samples of the two sets retained their characteristic differences in size, just as happened in the case of *D* and *c*.

But the interesting condition showed itself in the smaller set. Among these were individuals of such different sizes, that in spite of our knowledge of the great differences produced by growth and environment, it seemed worth while to try to isolate and breed them. In a random sample of 60 specimens the length varied from 96 to 176 microns—the smaller sizes being grouped about 120 microns, the larger about 160 microns.

Accordingly, on November 9, 1907, I separated two lots, one containing ten of the smaller specimens, the other ten of the larger ones. These were placed in watch-glasses with equal quantities of the same culture fluid, and kept under identical conditions, where they were allowed to multiply. One week later (November 16) thirty specimens measured from each showed mean dimensions of 125.600 × 36.200 microns for the progeny of the larger ten, 96.400 × 30.00 microns for the progeny of the smaller ten. On November 27, a random sample of 100 from each gave for the progeny of the larger ten, dimensions of 134.320 × 36.280 microns; for the smaller set, 92.240 × 26.920 microns. Thirty-seven days later (January 2, 1908) the two lots still showed their characteristic differences, though cultivated under identical conditions. The mean dimensions of the two sets (from random samples of 100) were now 134.360 × 33.440 microns (for the larger), and 104.208 × 26.583 microns (for the smaller).

Thus, we have clearly two sets, with differences in size persisting from generation to generation (in spite of fluctuations in each due to environmental changes), and both falling, in a general way, in the dimensions previously found for the line *c*. It is evident, therefore, that *D* and *c* did not represent the only existing different lines.

Since the two sets under experimentation had come each from ten individuals which may be of heterogeneous origin, I isolated from each, as soon as it was evident that they were retaining their differences, a single characteristic individual. This was done on November 13. The specimen from the larget set I called *g*; it measured approximately 130 to 140 microns in length. The specimen from the smaller set I called *i*; its length was about 90 to 95 microns. These two individuals were kept under the same conditions and allowed to multiply.

The small specimen *i* multiplied more rapidly than the large one *g*. On November 16 there were but seven progeny of *g*, while *i* had produced a large number. Two typical specimens of *g* were killed and gave measurements of 160 × 48 microns and 164 × 56 microns. Five typical specimens of *i* ranged in size from 92 × 36 to 128 × 44 microns, with a mean of 103.2 × 39.2.

Evidently, therefore, the progeny of *g* and *i* tend to retain the differences in size characteristic of the parents. The two lines were kept for a long time, under the same conditions; at intervals random samples were measured. The measurements at different dates, with the number of specimens on which they are based are given in Table XXIII., p. 488. (The small numbers of specimens employed on certain dates are due to the fact that only a small number existed at that time.)

The great fluctuations in the dimensions of each line will of course surprise no one who has examined that part of this paper which deals with the effects of the environment. These fluctuations are due mainly to differences in nutritional conditions. At intervals it was necessary to add new culture fluid; the dimensions in both lines thereupon rose at once; they then gradually declined till new fluid was added. Details on this matter are not necessary for our present purpose.

The important fact is, that in spite of all fluctuations, the lines *g* and *i* retained throughout the three months in which they were under observation their characteristic relative sizes. Multiplication was probably at the rate of about one fission a day, so that the table represents 90 to 100 generations. We have here two lasting races comparable to the two races from our first culture, which we called *D* and *c*. It is clear that neither *g* nor *i* is identical with *D*, since the latter is much larger; whether either is the same as *c* we shall inquire later.

### TABLE XXIII.

*Comparative Sizes in Microns of g and i and their Progeny at Different Dates, when Cultivated under the Same Conditions.*

| Date. | *g* and Its Progeny | | | *i* and Its Progeny. | | |
|---|---|---|---|---|---|---|
| | No. of Specimens. | Mean Length. | Mean Breadth. | No. of Specimens. | Mean Length. | Mean Breadth. |
| 1907 | | | | | | |
| Nov. 13 | 1 | 130–140 | 35–40? | 1 | 90–95 | 30–40? |
| " 16 | 2 | 162.000 | 52.000 | 5 | 103.200 | 39.200 |
| " 18 | 7 | 140.000 | 40.000 | 12 | 103.666 | 35.666 |
| " 23 | 30 | 129.333 | 34.933 | 30 | 88.268 | 30.268 |
| " 26 | 100 | 137.120 | 38.720 | 100 | 99.560 | 28.200 |
| Dec. 7 | 61 | 120.590 | 41.110 | 96 | 98.709 | 34.208 |
| " 16 | 17 | 127.059 | 38.588 | 23 | 98.608 | 29.739 |
| " 30 | 40 | 112.600 | 31.300 | 64 | 86.756 | 22.062 |
| 1908 | | | | | | |
| Jan. 2 | 100 | 146.640 | 40.600 | 100 | 106.680 | 26.400 |
| Feb. 5 | 57 | 116.912 | 36.070 | 43 | 93.583 | 27.500 |

It will be recalled that in the original culture from which came *g* and *i*, there was a still larger set which we called *E*. Ten of these were selected and cultivated under the same conditions as *g* and *i*. They retained throughout their much larger size (numerical results are given later), so that from this culture we have isolated three lines or races which retain their differences in size under the same external conditions.

At this period, then (January 1, 1908), I had in the laboratory a number of lines or races which had been studied with care. These formed two sets, so far as our knowledge of them up to this point is concerned. The two lines, *D* and *c*, from culture *I*, were clearly distinct even under identical conditions. The three lines, *g*, *i* and *E*, from the second wild culture *OI*, are likewise clearly distinct from each other. But the relation of *g*, *i* and *E* to *D* and *c* is uncertain; we may have on hand five distinct lines, or only four, or three.

To determine whether any of these five lines are identical, it is necessary to cultivate all five under the same conditions. A certain number must be selected from each; these must be brought into the same culture fluid and allowed to multiply in the same environment.

It is extraordinary what difficulties are presented in carrying out this apparently simple plan. The different lines have become adapted to certain diverse nutritive conditions; if now they are brought at once into the same culture fluid, some of them die. In the present case, *g* and *i* had been living in comparatively fresh hay infusion, *D* and *c* in different old hay cultures, *E* in a culture of decaying pond weeds. When all were brought into fresh hay infusion, *E* died at once, *c* after a day or two; *D* multiplied slowly, then died in the course of a week or so, while *g* and *i* throve and multiplied.

It was therefore necessary to bring the different lines gradually into the new fluid, by mixing some of it with the fluid in which they lived, increasing the proportion of new fluid at intervals. This was found to be a very delicate undertaking. Certain of the lines would thrive for a time, under this procedure, then would begin to degenerate; in this way much time was lost. Finally, however, the different sets were induced to thrive in the same hay infusion.

*Procedure Necessary for Making the Conditions Identical for Different Lines.*—The procedure followed, in order to be certain that the cultural conditions were the same for all, was as follows: From each race ten typical individuals were selected. These were mixed with gradually increasing amounts of hay infusion, in the way just set forth—while at the same time of course they multiplied in number. After they had all gotten accustomed to the infusion, it was necessary to take measures to assure the identity of the solutions in which the different sets were living. For this it is not sufficient merely to transport the individuals to definite quantities of the same nutritive solution. For up to this point each set has been living in a solution which has received an admixture of the original culture for that set. Now, *these different original cultures contained different kinds of bacteria.* On transferring the infusoria to the hay infusion, they of course carried some of their own bacteria. By repeated changes the number of bacteria introduced could be much reduced. Nevertheless different kinds were brought in in different cases, so that we still have the different lines in cultures of diverse bacteria. From this fact naturally diverse chemical properties may develop in the different cultures, though the basic nutritive solution is the same. These diverse chemical properties would of course modify the organisms, making it impossible to compare them with regard to inherited size. To make the conditions of existence the same, *it is not sufficient to attend merely to the basic fluid; the bacteria in the fluid must also be the same.* This is a principle of wide practical importance in all experimental work with such infusoria. It is not a mere theoretical requirement; death frequently results from the introduction of a certain kind of bacteria into a certain culture, while another culture of identically the same fluid flourishes, because the bacterial infection is different.

This requirement was met in the following way: After the different sets had become acclimatized to the same hay infusion, ten of each were removed with a fine capillary pipette, and washed twice in fresh hay infusion. The second washing of the different sets was done *in the same mass of fluid,*—a small watch-glass full. The different sets might of course each carry with them a few of the bacteria characteristic of their original culture. After all had been washed in the same mass of fluid, this fluid would of course be infected with bacteria from all the different sets. Now, after the washing was finished, a definite quantity of this fluid in which all had been washed *was added to the final culture fluid for each lot.*

Thus each lot of ten is in the same quantity of the same nutritive fluid, and infected with the same bacteria as all the others. All are kept in watch-glasses of the same form and size, close together in the same moist chamber. Any characteristic differences in the resulting progeny must then be due to conditions within the animal, and not to differences in the environment. If we reach the same result, not merely in one experiment, but in a series conducted in this manner, we can be sure of our results.

Cultures of the five lines, *D, c, g, i* and *E,* prepared in the way just described, were set in progress January 19, 1908. In order to determine with certainty how much effect possible environmental differences might have on the results (as well as for certain other purposes), two lots each of *D, g* and *i* were used. If the two lots of *g,* for example, show differences as great as those between *g* and *c,* then, of course, we have no ground for considering *g* and *c* inherently different; the environmental differences account for all. These lots were allowed to multiply till February 5. Then a sample of each was killed and measured. Now a new lot of ten of each set was prepared by the methods given above, and the animals were again allowed to multiply till February 15, when samples were again measured.

It will be recalled that *E* is a lot derived from ten specimens of possibly diverse ancestry, from the culture *OI,* with an original mean length of 238.280 microns; that the line *D* has shown in repeated determinations a highest mean length of 202.280 microns (Table XVIII.); that *c, g* and *i* are smaller lines, derived from single individuals; *g* is known to be larger than *i,* but the relation of *c* to these is unknown.

The results of these breeding experiments are given in the following Table XXIV.

The experimental results given in this table show certain things clearly.

1. The method of culture is adequate for bringing out the inherent differences in different lines without confusion due to environmental effects. This is shown by the fact that when two cultures are made from certain single lines, these show themselves after breeding for many generations to be nearly identical, while the different lines give diverse results. In only one case (*D* on February 15) is there a notable difference btween the two samples of a single line, but this is much less than the difference between that line and any other.

### Table XXIV.

*Mean Dimensions in Microns of the Five Lines E, D, c. g and i, when Cultivated under the same Conditions, January 19 to February 5 and February 5 to February 15.*

| Date. | Dimensions of *E*. | | Dimensions of *D*. | | Dimensions of *c*. | |
|---|---|---|---|---|---|---|
| | Number Measured. | | Number Measured. | | Number Measured. | |
| Feb. 5 | 43 | 169.395×52.930 | 57<br>19 | (1) 169.754×46.877<br>(2) 169.895×43.579 | 60 | 99.667×26.333 |
| Feb. 15 | 100 | 200.320×52.400 | 100<br>100 | (1) 180.240×46.880<br>(2) 173.240×49.760 | 100 | 100.320×26.480 |
| Feb. 27 | 100 | 172.040×55.520 | 100 | 175.360×47.160 | | |

| Date. | Dimensions of *g*. | | Dimensions of *i*. | |
|---|---|---|---|---|
| | Number Measured. | | Number Measured. | |
| Feb. 5 | 50<br>57 | (1) 114.720×33.920<br>(2) 116.912×36.070 | 50<br>48 | (1) 92.000×26.960<br>(2) 93.583×27.500 |
| Feb. 15 | 100 | 125.240×35.440 | 100 | 95.440×30.040 |

2. At least four distinct lines are present, *D, c, g* and *i*; these maintain their relative different sizes throughout the experiments, which lasted about twenty-five generations.

3. The lines *E* and *D* are nearly or quite the same. On February 5 they show nearly the same measurements, but on February 15 there was a marked difference. To test the meaning of this these two were cultivated twelve days more; then on February 27 they gave again nearly the same measurements. It will doubtless be safest to consider them the same.

We have now, therefore, four different lines or races of *Paramecium,* characterized by persisting relative differences in size. One of these (*D* and *E*) belongs, from its size, to the "*caudatum* group"; the other three are much smaller and fall in the "*aurelia* group." Of these, *g* is the largest, *i* the smallest, while *c* is intermediate. Under a similar change in the environment these all change in a corresponding way, as is shown by the fact that on February 15 all were somewhat larger than on February 5. It may be noted that the differences in size among these four lines were very evident to the eye on inspection with the low power of the microscope, and that the difference was clearly present at all periods between the dates when the measurements were made. The measurements merely make precise what is evident to the eye without them.

Before attempting to determine whether still other lines can be isolated, and particularly whether it is possible to fill the wide gap between the *caudatum* group and the *aurelia* group, another question must be investigated—a question which strikes at the foundation of our conclusions up to this point. This is the question of the relation of these lines of diverse size to conjugation and the life cycle.

### (*b*) *Are the Lines of Different Size Merely Different Stages in the Life Cycle?*

Calkins (1906) and others have set forth the fact that *Paramecium* and other infusoria show different dimensions in different stages of the life cycle—the cycle which begins with conjugation, extends over many generations of reproduction by fission, and ends with another conjugation. The question arises, therefore, whether our lines of diverse dimensions are not merely different stages in the life cycle; whether they would not, if brought to the *same* stage of the cycle, show the same dimensions. This possibility must be investigated before we proceed farther.

The details of the relation of conjugation and the life cycle to variation, inheritance, etc., are to be dealt with in a separate paper of this series. But since the question which stands at the head of this section is an absolutely fundamental one for the proper interpretation of the results of the present paper, it must be dealt with here.

To answer this question, it is evidently necessary to proceed as follows: Cultures showing epidemics of conjugation must be examined for conjugating pairs of diverse sizes. If such are found, the individuals must be isolated and allowed to multiply, in order to determine whether the progeny retain the diverse sizes characteristic of the parents. If from a conjugating culture we can obtain diverse lines standing all in the same relation to conjugation and the life cycle, then evidently our diverse lines represent something more than different stages in the life cycle. The problem also can be attacked in certain other ways, which will be described.

The relation of diverse sizes to conjugation and the life cycle was studied with special thoroughness in the case of a culture in which there was an epidemic of conjugation January 29, 1908. This culture was found in decaying vegetation from a small pond near Baltimore; I called it culture *M*. Table LXI. (appendix) shows a random sample of this culture, including both conjugants and non-conjugants; of the 238 specimens in the table, 38 were conjugants, 200 non-conjugants.

From this culture *M* a large number of pairs were isolated, for various purposes, and allowed to multiply. Without going here into the details of the experiments, on February 21 I had from this culture eight sets or lines, each descended from a single equal pair or a single ex-conjugant; these lines were designated in my notes *L2, G1, A1, A2, I, C2, F1* and *F2*. (The designations are the same as those given to the original pair or individual from which the lines came.) In addition to these eight "pure lines," I had two cultures derived each from eight pairs of conjugants of approximately the same size; these were called *K1* and *K2*. A final culture was derived from ten small, nearly equal, non-conjugants from the same culture; it was designated *H*.

It is, of course, unfortunate that it is not possible to measure accurately the original living individuals from which the different lines are derived, but this will not alter in any way the results on the problem in which we are at present interested. The essential question is whether the lines derived from the different pairs or individuals are identical or diverse in size.

These various cultures were kept, so far as possible, in the same nutritive fluid and under the same conditions. Marked differences in size were apparent on examining the different sets with low power of the microscope. On February 21 fifty individuals of each of these eleven different sets were brought, with all the precautions mentioned on page 489, into the same culture fluid, while at the same time fifty specimens each of *D* and *g* of our earlier pure lines (see page 491) were brought into the same fluid. These were all allowed to multiply till February 26, when a random sample of 100 or more of each was killed and measured. Later, on March 7, twenty individuals were taken anew from each of these thirteen lots, brought again with elaborate precautions into the same culture fluid, kept under the same conditions and allowed to multiply, part till March 13, part till March 19, when other samples were killed and measured. From our previous extensive experience with *i* and *g* (Table XXIII., page 488) and with five lines of Tables XXIV. (page 491), we can be assured that two sets of measurements taken at such intervals will give us reliable data as to the existence of any considerable lasting differences among the different lines. The results of the measurements of the thirteen different sets are given in classified form in Table XXV.

TABLE XXV.

*Mean Dimensions in Microns, of the Thirteen Sets Described in the Text, after Cultivation under the Same Conditions, February 21 to February 26, and March 7 to March 13 (or March 19).* (The conditions before; and in intervening periods were essentially the same, but elaborate precautions were taken for the periods specified). All are from the conjugating culture *M*, of January 29, save the last two sets.

| Line. | Number Measured. | February 26. | Number Measured. | March 13. | Number Measured. | March 19. |
|---|---|---|---|---|---|---|
| (1) Descendants of Pairs. | | | | | | |
| *L* 2 | 100 | 206.360 × 60.840 | 100 | 220.560 × 59.960 | | |
| *G* 1 | 100 | 201.400 × 52.400 | 100 | 210.960 × 52.200 | | |
| *A* 1 | 100 | 193.560 × 51.840 | 100 | 203.640 × 52.560 | | |
| *A* 2 | 100 | 184.640 × 50.760 | 100 | 187.878 × 44.490 | | |
| *I* | 100 | 132.880 × 41.960 | | | 100 | 138.880 × 43.120 |
| *C* 2 | 100 | 128.880 × 40.400 | | | 100 | 119.200 × 37.280 |
| (2) Descendants of Single Ex-conjugants. | | | | | | |
| *F* 1 | 100 | 193.000 × 50.840 | 56 | 209.643 × 56.643 | | |
| *F* 2 | 100 | 182.200 × 51.040 | 100 | 199.960 × 50.120 | | |
| (3) Descended each from 8 Equal Pairs. | | | | | | |
| *K* 1 | 100 | 133.680 × 39.400 | | | | |
| *K* 2 | 100 | 125.920 × 37.040 | | | 100 | 125.000 × 42.520 |
| (4) Descended from 10 Small Non-conjugants. | | | | | | |
| *H* | 100 | 131.400 × 42.000 | | | 100 | 128.840 × 41.360 |
| (5) Older Lines, not from Culture *M*. | | | | | | |
| *D* | 111 | 176.901 × 50.018 | 120 | 187.033 × 49.100 | | |
| *g* | 100 | 124.440 × 35.920 | | | | 140.800 × 39.640 |

Examination of this table shows that lines derived from different conjugating pairs or different ex-conjugants do differ from each other at the same periods in the life cycle, even though living under identical conditions. The differences are fully as marked as those found among diverse lines derived from individuals not conjugating and taken without reference to the period in the life cycle in which they happen to be.

Besides this general result on our main problem, the following important facts are brought out by the table:

1. The six lines derived from the six different pairs (first six of the table) are clearly distinct. They show parallel differences in both sets of tests; the order of dimensions from largest to smallest is the same in both the first and the second measurements, though these are separated by at least fifteen generations.

2. The two lines, *F1* and *F2,* derived from single ex-conjugants, are likewise distinct from each other. So far as the measurements go, *F1* may possibly be the same as *A1, F2* as *A2.*

3. Certain different sets are likewise found in the other lots of the table.

4. The different sets fall into two very distinct groups, whose dimensions are separated by a wide interval. To the large group belong *L2, G1, A1, A2, F1, F2* and *D.* To the small group belong the others. The greatest mean length of any set of the smaller group (140.800 microns) differs widely from the least mean length of any set of the larger group (176.901 microns). These two groups correspond in general to what we have heretofore called the "*aurelia* form" and the "*caudatum* form."

As there was no danger of confusing any lot of the larger group with any lot of the smaller one, the second measurements of the two groups were not made for the same day; the lots of the larger group were killed March 13, while those of the smaller group were not killed till March 19, as the table shows. This was done on acount of the great labor involved in selecting, with capillary pipette, killing properly, and preserving, so many different sets on the same day. This difference of treatment of course does not alter the comparability of the different sets within a given group, which is all that we require.

5. How shall we decide which of the thirteen different sets form distinct lines? For this it will be best to take into consideration mainly the length, since we know from our earlier studies that little significance is to be attached to difference in breadth, owing to the extreme changes in that dimension with slight differences in food.

If any two sets differ in length in the same way at both measurements (taken many generations apart) and if the differences between them are each time decidedly greater than the sum of the probable errors of the measurements of the two, then we can be assured that we are dealing with really differentiated sets. Now, examination of the extensive series of measurements in Tables X. and XVIII. shows that the probable error of the mean length never reaches two microns, even when the number of specimens is much smaller than in our present measurements, and when conditions are of the most varied character. It is practically certain that the probable error of the mean length would not amount to one micron in any of the comparatively homogeneous sets with which we are here dealing. If, then, we require a difference of four microns between the mean lengths of the two sets, this difference to have the same sign (+ or —) at both measurements, we shall be within safe limits. Applying this test, we find four lines clearly distinct in the larger or "*caudatum*" group, while in the smaller or "*aurelia*" group we can be certain of but two distinct lines (represented best perhaps by *I* and *C2*). We have previously found three distinct lines in the *aurelia* group (*c*, *g* and *i*, Table XXIV.), so that all together we now have at least seven different lines of *Paramecium*, showing constant relative differences in length. It is probable that very exact tests would show the distinctness of some other lines of Table XXV.

The striking difference between adults of different races, under varied conditions, is shown in Fig. 7. Here we have two adults, one belonging to our smallest race (*i*); the other to one of the large races.

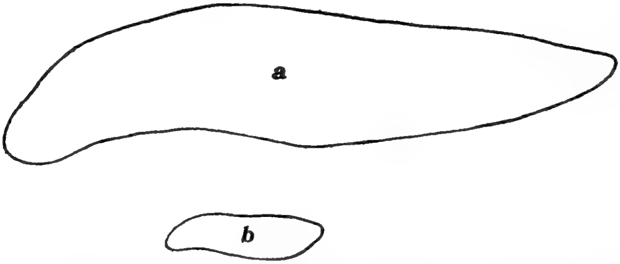

FIG. 7. Extreme adult sizes from different pure lines of *Paramecium*. *a*, large individual from a large line. *b*, small individual from the small line *i* of Table XXIII., page 488. Both magnified 235 diameters.

It is clear, then, that the question placed at the head of the present section is to be answered in the negative. The diverse lines of different size are *not* merely different stages in the life cycle.

### (*c*) *Other Evidences of Permanent Differentiation in Size, Independent of the Life Cycle.*

The proof just given, that lines beginning with conjugants are differentiated in size even in the same portion of the life cycle and under the same conditions, is conclusive. But it may be worth while to give briefly certain other evidences of the same thing.

1. First we have the fact that in a given culture the conjugants themselves differ in size; this has already been shown by Pearl (1907). In a certain Culture IV., I found conjugants varying in dimensions from 148 × 44 to 260 × 60 microns. I have found (not in the same culture) conjugants with length as low as 100 microns. It is clear, therefore, that not all individuals are of the same size at conjugation. There is no reason to expect them to be so, therefore, at other definite periods in the life cycle; as we have seen, they are not. Selection of small pairs gives small progeny; of large pairs, large progeny.

2. In certain of my pure lines whose history was followed for a long time and whose dimensions were taken at intervals, conjugation occurred at times, but the dimensions at such times were not very different from the dimensions at other periods in the life history. Thus, in the earlier sections of this paper we have dealt with two pure lines, *D* and *c;* the former showed usually a mean length of about 180 microns, the latter a mean length of about 130 microns (see Table XVIII.). At a certain time an epidemic of conjugation arose in *c*. The mean dimensions were indeed higher than usual at that time, the mean length of the conjugants rising to 158.496 microns. But this does not by any means bring it up to the ordinary mean of *D,* and immediately after conjugation (in five days) the mean length of *c* fell back to 129.640 microns. Again, in the small race *g,* of Table XXIII., conjugation occurred in a number of cases; a typical pair measured but 110 microns in length. In other lines I have found for the conjugants means as high as 199.024 and as low

as 116.856, and these were correlated with corresponding measurements throughout the series.

These facts, of course, do not show that the size may not change at the time of conjugation or before or after. What they do show is that any differences thus produced do not account for the permanent differentiations we have found among different lines. We may distinguish (1) differences in size due to growth; (2) those due to nutrition and other environmental conditions; (3) those due to different stages in the life cycle (as a rule not marked in comparison with the others); (4) inherent, hereditary differences in size, persisting when all other conditions are made the same.

### (*d*) *Lines Intermediate Between the Two Main Groups. The Question of Species in Paramecium.*

As we have already noted, the seven differentiated lines which we have thus far distinguished fall into two main groups, separated by a wide interval. In Table XXV. we find one group with mean lengths varying from 119.200 to 140.800 microns, while in the other group the mean lengths vary from 176.901 to 220.560 microns. Between the two there is thus a gap of 36.101 microns in which none are found. Is this gap constant and characteristic, so that our two large groups are permanently differentiated? If so, we should have some real basis for the common distinction into two species, *Paramecium caudatum* (larger) and *Paramecium aurelia* (smaller). The fact that we find in nature such cultures as that shown in Table I. (page 398), in which the individuals are distinctly separated into the two groups, seems to raise a presumption that the groups are natural ones, not due to accidents of selection.

For a long time I found no pure lines that were intermediate between these groups. It is possible that this was partly due to a tendency to choose for breeding the largest and smallest specimens, rather than intermediate ones, since my purpose at first was to determine whether there were any permanent differentiations at all; for this, marked differences were desirable.

In the course of work on certain problems connected with conjugation, I came in possession of a pure line, *Nf2*, descended from a single ex-conjugant. This, when cultivated in the usual hay infusion, gave, under various different conditions, the following mean lengths in microns (each mean is based on measurements of 100 individuals): 148.197, 151.920, 158.760, 153.320, 160.852, 156.482.

It is evident that these means fall in the gap separating the "*caudatum*" group from the "*aurelia*" group. I therefore decided to cultivate these under identical conditions with a typical representative of each of the two main groups. For this purpose I chose *D* and *c*, the two lines longest cultivated, which I had used for the study of growth, environmental action, etc. (Tables X., XVIII., etc.). Twenty-five specimens, each of the three lines, *D*, *c* and *Nf2*, were brought on May 1, with the precautions described on page 489, into the same quantity of the same hay infusion and allowed to multiply till May 5. On that date a random sample of each was killed. Though the samples were large, extrinsic conditions prevented my measuring more than the numbers mentioned below; larger numbers would not have altered the results by more than one or two microns in any case. The mean dimensions of these three lines, cultivated under identical conditions, were

*D* (31 specimens), 202.710 × 51.871 microns.
*Nf2* (33 specimens), 168.970 × 48.970 microns.
*c* (43 specimens), 126.605 × 44.930 microns.

Thus, the dimensions of *Nf2* lie almost precisely half way between those of *D* and *c* (the dimensions exactly half way between would be 164.658 × 48.401). We have, therefore, in *Nf2* an eighth pure line, intermediate between the "*caudatum*" and "*aurelia*" groups formed by the other seven. These two groups are then not separated by an unbridged gap.

The other character which had been held to separate *Paramecium caudatum* from *Paramecium aurelia* was the presence of but a single micronucleus in the former, while the latter had two. Calkins (1906) showed that in the same pure line we sometimes have two micronuclei, sometimes but one, so that this is not sufficient ground for distinguishing two species. Though the present study has shown that differences in size among different lines are more permanent than the data available to Calkins had seemed to indicate, this does not give any better basis for distinguishing two species, since we have been able to isolate, not merely two permanently differentiated lines, but eight. Of course, it would require merely more extensive and intensive work to isolate others; doubtless the number to be isolated would depend only on the accuracy of the methods used.

To my great regret, I was unable to take the steps necessary to determine the number of micronuclei in the various pure lines with which I worked. The animals multiply so rapidly that with several lines in progress it is quite impossible even to keep up with the data for size alone; probably half my experiments were lost on this account, after much work had been spent on them. It was then out of the question to carry on at the same time the staining processes necessary to determine with certainty the number of micronuclei. For work of the kind presented in this paper, a syndicate of investigators is needed for keeping track of the various important aspects of the matter. In the case of two of my lines the number of micronuclei was determined; *D* (larger) had one; *c* (smaller) had two.

I may be permitted to add to the precise data thus far given a personal impression or surmise. Though, as I have shown, intermediate lines occur, I believe it will be found that most *Paramecia* can be placed in one of the two groups that we have called "*caudatum*" and "*aurelia*." In other words, if my impression is correct, most lines will have a mean length either below 145 microns or above 170 microns; rarely will lines be found whose mean falls between these values. Such at least has been my experience in a large amount of work. Furthermore, I am inclined to believe that those belonging to the smaller group (mean length below 145 microns) will be found to have as a rule two micronuclei; those belonging to the large group but one micronucleus. This matter is worthy of special examination.

### (*e*) *Do the Diverse Lines Differ in Other Respects Besides Dimensions?*

In the investigations above set forth the dimensions, and especially length, were made the basis of study, simply because they were the characters most readily examined. Most other characteristics are not easily handled in so minute and relatively undifferentiated an animal as *Paramecium*. But there is, of course, no reason to suppose that the relations we have brought out are limited to length alone. Probably other differentiated pure lines could be distinguished on the basis of other characteristics.

The only other characteristic on which our data might give results is that of *form,* as distinguished from size. Are some races broader, some narrower, in proportion to the length?

We may first examine this question with reference to the two main groups into which most of our lines fall. Is there any general difference in the proportion of breadth to length when we compare the larger races ("*caudatum* group") with the smaller ones ("*aurelia* group")? The experiments whose results are summarized in Table XXV., page 494, give us data for a number of different lines of both groups, cultivated under the same conditions. We may, therefore, determine the proportion of breadth to length in these. The more accurate way of doing this would be by means of the formula given on page 399. This, however, would involve much computation not made for other purposes; and we may reach very nearly the same results by simply dividing the mean breadth by the mean length. If the differences between the different races are not sufficient to show clearly under this treatment, they are doubtful and inconsequential. The following table gives the ratio of mean breadth to mean length in the different lines represented in Table XXV.; the lines are arranged according to relative size, so as to exhibit any differences between the large and small groups.

The table shows that the ratio of breadth to length is almost uniformly greater in the small or *aurelia* group than in the larger. The lowest ratios of the *aurelia* group are, indeed, a little below the highest of the *caudatum* group, but the difference between the groups as a whole is unmistakable. The first column of the table is the most satisfactory in this respect, since both sets were killed at the same time. In the second column the difference between the ratios for the two groups is still more decided, but environmental differences may play some part in this case. The average ratio for the *caudatum* group is, from the first column 27.473 per cent.; from the second 25.679 per cent. For the *aurelia* group the averages are: first column 30.441 per cent.; second column 31.319 per cent. The

TABLE XXVI.

*Ratio of Mean Breadth to Mean Length in the Lines and Races of Table XXV., page 494, Cultivated under Identical Conditions.*

| 1. Caudatum Group. | February 26.<br>Per Cent. | March 13.<br>Per Cent. |
|---|---|---|
| L2 | 29.482 | 27.185 |
| G1 | 26.018 | 24.744 |
| A1 | 26.782 | 25.810 |
| F1 | 26.342 | 27.019 |
| A2 | 27.491 | 23.680 |
| F2 | 27.921 | 25.065 |
| D | 28.275 | 26.252 |
| **2. Aurelia Group.** | **February 26.<br>Per Cent.** | **March 19.<br>Per Cent.** |
| K1 | 29.473 | |
| I | 31.577 | 31.048 |
| H | 31.967 | 32.102 |
| C2 | 31.347 | 31.275 |
| K2 | 29.416 | 34.016 |
| g | 28.865 | 28.153 |

general average for the *caudatum* group is 26.576 per cent.; for the *aurelia* group 30.840 per cent.

In Table XXIV., page 491, we have data for certain other members of the two groups when cultivated under similar conditions. If we determine the ratio of mean breadth to mean length for this table, the results are not so clear as in the cases we have just considered. They are given in Table XXVII.

TABLE XXVII.

*Ratio of Mean Breadth to Mean Length for the Races of Table XXIV., page 491.*

| 1. Caudatum Group. | February 5.<br>Per Cent. | February 15.<br>Per Cent. | February 27.<br>Per Cent. |
|---|---|---|---|
| E | 31.245 | 26.158 | 26.458 |
| D | 27.615<br>25.651 | 26.010<br>28.723 | 26.893 |
| Average | 28.170 | 26.964 | 26.675 |
| **2. Aurelia Group.** | | | |
| c | 26.482 | 26.396 | |
| g | 29.568<br>30.853 | 28.298 | |
| i | 29.303<br>29.386 | 31.852 | |
| Average | 29.118 | 28.849 | |

In this table the averages for the *aurelia* group are again higher throughout than for the *caudatum* group. But the highest ratio is given by one of the *caudatum* group, and the line *c* of the *aurelia* group gives in both cases a low ratio. But taking the averages, in connection with those of Table XXVI., it is clear that the smaller races are as a rule slightly broader in proportion to the length than are the larger races.

Turning now to the question whether there are differences in the proportion of breadth to length in different races of the same group, we have full data only for the lines *g* and *i*, as given in Table XXIII., page 488. Beginning with the data for November 23 (since before that date the number of individuals is small), we can make determinations for seven different dates of the ratio of mean breadth to mean length, the two sets being on each date as nearly as possible under identical conditions.

TABLE XXVIII.

*Ratio of Mean Breadth to Mean Length for g and i* (Table XXIII.).

| | November 23. Per Cent. | November 26. Per Cent. | December 7. Per Cent. | December 16. Per Cent. | December 30. Per Cent. | January 2. Per Cent. | February 5. Per Cent. |
|---|---|---|---|---|---|---|---|
| *g* | 27.011 | 28.238 | 34.091 | 30.370 | 27.797 | 27.686 | 30.853 |
| *i* | 34.291 | 28.325 | 34.655 | 30.159 | 25.430 | 24.747 | 29.386 |

Thus, in the first three determinations the ratio was greatest in the line *i*; in the last four it was greatest in the line *g*. Evidently there is no constant difference in proportions between these two lines.

For other lines our data are not sufficient to test this matter. Our only positive result on this point then is that the smaller races are as a rule proportionately broader than the larger ones.

## 2. RESULTS OF SELECTION WITHIN PURE LINES.

We have seen that an ordinary "wild" culture of *Paramecium* contains many lines or races, which are differentiated in size. By selection it is possible to isolate these diverse lines; so that in this way we can obtain cultures in which the mean size is large or small, or intermediate, as we prefer. In this case selection, of course, acts by isolating lines that already exist, and allowing them to propagate unmixed.

How do these diverse lines arise? Can we obtain them by selection within the limits of a single line? If from among the progeny of a single individual we select the larger and the smaller specimens, will we obtain two diverse lines, one showing a greater mean size than the other?

As we have already seen, our first attempts to do this failed. But these first experiments were made before our study of growth and environmental effects, so that the basis of selection was wrong. The smaller specimens selected were as a rule the younger ones; they grew to full size, then, of course, produced progeny of the same size as other adults.

After the thorough study of growth, it appeared possible that a more adequate method of selection might be found. The proportions of the young differ from those of the adult (as our account has shown), so that after long practice one comes to recognize the young specimens with some accuracy. It appeared worth while, therefore, to attempt to select larger and smaller adults for further propagation.

### (*a*) *Differences Due to Environmental Action Not Inherited.*

It is, of course, easy to obtain within a pure line adults of different size, by subjecting them to different environments. An analysis of our section on the effects of the environment shows that as a rule these are not inherited. Thus, if we examine Table XVIII. (page 460), we find that the same set that gave on July 17 a mean length of 184.100 microns (row 7) gave one week later, under different conditions, a mean of 146.108 microns; one day later 163.932 microns; one week later 174.400 microns; two days later 191.360 microns. The breadth changed even more, and the extremes of size in a given culture showed corresponding changes. There was no difficulty in changing the dimensions back and forth in the most varied ways. The entire Table XVIII. is an illustration of the general lack of continued inheritance of environmental effects.

Many experiments directed precisely on this point gave the same results. When, for example, the small specimens of row 8 (Table XVIII.) were cultivated under the same conditions as large specimens from row 9, the resulting cultures were soon indistinguishable.

Thus, it is clear that such environmental action as is summarized in Table XVIII. is not as a rule inherited. But I wish to point out and emphasize certain facts regarding the experiments on the action of the environment. (1) In all the experiments thus far tried, the differential action of the diverse environments lasted but a short time. (2) The experiments were directed toward determining whether the differences produced were *permanently* inherited. Critical investigations have not yet been made to determine whether the environmental effects may not persist for one or a few generations after transference to the new fluid; nor whether long continued action of a certain environment may not produce more lasting results than brief action.

To these points I hope to devote special and extended investigations. The purpose in the present paper is to show on this matter the main general result; this unquestionably is that environmental action is not as a rule inherited in any lasting way.

### (*b*) *Selection from Among Differing Individuals in the Same Environment.*

Besides the differences among individuals under different environments, we likewise find differences among individuals of the same pure line in the same culture, as a glance at the tables of the appendix will show. What will be the effect of selecting for breeding larger and smaller specimens from such a culture, avoiding, so far as possible, different stages of growth?

In order to make the selections properly, certain things must be considered. (1) It is well to bring the culture into as stable a condition as possible—a condition where there is little or no multiplication—in order that we may not be confused by different stages in growth. (2) It must be remembered that, so long as conjugation does not occur, the same results that selection would produce are brought about in the ordinary course of events, save that the large and small specimens remain mixed. That is, if there is congenital variation, producing large and small individuals, this must occur in the same way whether the different sizes are isolated or not. The progeny of every individual forms a "pure line," quite unmixed with any other, so long as no conjugation occurs. If, then, by variation a large individual *a* and a small one *b* are produced, and these differences are inherited, then later we shall find a mixture of two strains instead of a single strain. We should then expect the progeny of a single individual to show more and more variation as the strain became older; it would break into several or many strains, which would, however, remain intermingled.

Therefore, the best method of procedure will be to take an old strain, which, derived from a single individual, has for a long time been multiplying freely without conjugation. From this the largest and the smallest individuals should be separated and allowed to propagate under identical conditions. If hereditary variations in size have occurred, we should in this way reach the same result as by actual selection and isolation through many generations. Physiological isolation has been as complete as would be experimental isolation.

A race fulfilling these conditions we have in the pure line derived from the individual *D*, on which most of the work described in the first parts of this paper was done. On January 19, 1908, large cultures of *D* had been multiplying without conjugation since April 12, 1907, a period of about nine months. During this time about 250 generations must have been produced; these had remained physiologically isolated. The superfluous individuals had been removed by periodic "catastrophic" destruction; the greater part of the culture was thrown out, and a remnant saved, without selection, for a new culture.

On January 19, 1908, I took from the large stock culture of *D* (1) the ten largest individuals that I could find; (2) the ten smallest individuals I could find. They were separated in two watch-glasses and kept under identical conditions. The difference between the two sets was very marked; the smaller lot were certainly not more than two-thirds the length of the larger, and they were very slender, while the large ones were both long and broad. It was clear that both sets were adults.

It was found that the smaller lot multiplied much less rapidly than the large lot, and some of the small ones died. By January 30 there were but twenty of the small lot, while a very large number had arisen from the large lot. On this date the culture fluid was changed and but fifty of the larger lot retained. The small lot continued to multiply very slowly. It is clear that the small specimens are weak, sickly ones, and the physiological difference persists at least for some generations (a matter for further study).

On February 5 about half of each lot was killed and measured. This gave 57 specimens from the larger lot, 19 from the smaller. The mean dimensions were, for the larger lot, 169.754 × 46.877 microns; for the smaller lot, 169.895 × 43.579 microns.

Thus the two were practically identical; one could not expect a closer approximation in two identical lots kept separate for seventeen days. The slight difference in breadth is only what we might expect when we consider the extreme sensitiveness of that dimension to faint environmental differences. The most striking differences that we can find as a result of physiological isolation for 250 generations have equalized themselves in a short time, when we got both sets to multiplying freely under the same conditions.

It seems hardly worth while to continue this series, since the two sets have now become equalized. However, they were continued for some time, and samples of 100 each were measured on February 15 and February 27. In these two measurements we find certain differences between the two sets, but these are in opposite directions in the two cases. The means are as follows:

| | February 15. | February 27. |
|---|---|---|
| Large D | 180.240 × 46.880 | 175.360 × 47.100 |
| Small D | 173.240 × 49.760 | 193.680 × 52.320 |

Evidently slight environmental differences between the two cultures had crept in. It is clear that the two sets show no constant differences, such, for example, as we find between the two lines, *g* and *i*, in Table XXIII., page 488.

Another set of experiments dealt with the two differentiated lines, *g* and *i*. The line *g* consists of individuals that are constantly larger than those of the line *i*, when the two are under the same conditions (see Table XXIII., p. 488). The experiments consisted in an attempt to separate these races still farther by propagating continually from the largest specimens of *g* and from the smallest specimens of *i*. Thus, if selection is effective, *g* must become larger, *i* smaller. The *length* was the dimension mainly attended to in these selections.

On November 23, 1907, the mean size for *g* was 129.333 × 34.933

microns; for *i* it was 88.268 × 30.268. On this date I placed in separate watch-glasses the ten largest specimens of *g* and the ten smallest specimens of *i*, keeping them under the same conditions.

On November 29 I again selected from the progeny of these the ten largest *g* and the ten smallest *i*, destroying the others.

On December 7 the same selection was repeated; the remainder of each lot was killed and measured. The mean measurements were

*g*, 120.590 × 41.115 microns.
*i*, 98.709 × 34.208 microns.

Thus, in spite of the fact that for at least fourteen generations we have selected for propagation the largest of *g* and the smallest of *i*, *g has become smaller and i has become larger!* The results of selection, if there are any, quite disappear in comparison with the effects of slight environmental differences.

In spite of this discouraging result, the experiment was continued. On December 16 I selected the five largest *g* and the five smallest *i* and again measured the rest of each. The results were

*g*, 127.059 × 38.588 microns.
*i*, 98.608 × 29.739 microns.

Thus, *i* retains the same length, while *g* has increased, but has not regained the length it had at the beginning of the experiment.

On December 25 the five largest *g* and the five smallest *i* were again selected for propagation.

On December 30, thirty-seven days after the beginning of the experiment, I again measured all but the five largest of *g* and the five smallest of *i*. The results are

*g*, 112.600 × 30.300 microns.
*i*, 86.756 × 22.062 microns.

Thus, *i* has decreased as compared with its original length, while *g*, which was selected for increase of size, has decreased a great deal more! The decrease in length of *i* is less than two microns; the decrease in *g* is more than sixteen microns! And this is the result of five selections, taking for *g* the largest, for *i* the smallest, specimens produced in the course of at least thirty generations![8]

[8] The number of specimens on which the measurements are based will be found in Table XXIII., page 488, which includes, for another purpose, the measurements from these experiments.

Evidently, selection is having no effect that can be detected. The fluctuations in the two sets are precisely what would be expected from unavoidable changes in conditions of nutrition; they show no relation to selection.

Later another experiment in selection was tried with these same races, *g* and *i*. On January 19 I selected from a large culture that had been multiplying freely for a month (1) the ten largest specimens of *g* that I could find; (2) the ten smallest specimens of *g*; (3) the ten largest specimens of *i*; (4) the ten smallest specimens of *i*.

These were allowed to multiply under identical conditions till February 5. Then a sample of fifty of each was measured. The results are as follows:

Large *g*, 114.720 × 33.920 microns.[9]
Small *g*, 116.912 × 36.070 microns.
Large *i*, 92.000 × 26.960 microns.
Small *i*, 93.583 × 27.500 microns.

The difference between the two sets of each is slight and without significance, but such as is found is in favor of the progeny of the *smaller* specimens in each case.

Evidently, we are not making a start with any effect of selection, and it is useless to continue the experiment.

Many other attempts were made to break a pure line by selection into several strains; on this point an immense amount of work was directed. But in most cases the difference between the two sets became equalized almost at once, so that the experiments were not carried farther. As soon as two unequal sets become quite equalized, there is little opportunity for further selection. In the experiments described above, though their futility seemed evident from the first results, the work was continued for many generations, in order that failure might not be due to lack of perseverance.

One other set of experiments deserves to be described, because in these the basis for selection was changed. Among the progeny of a certain individual *Nf2* conjugation occurred. The conjugants varied in size. This offered an opportunity to make a selection

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[9] These measurements are found, for another purpose, in Table XXIV., page 491.

based on specimens that were evidently adults; possible confusion due to growth differences could be avoided.

On March 31 I killed and measured all but the largest and smallest pairs of conjugants; the length was found to vary from 124 to 148 microns. The smallest and largest pairs were reserved for propagating; the former, of course, measured not more than 124 microns, the latter not less than 148 microns. These were allowed to multiply separately, but under the same conditions, till April 10.

On April 10 I measured a random sample of 100 specimens of the progeny of each of these pairs. The results are as follows:

Larger pair, 151.920 × 43.840 microns.
Smaller pair, 158.760 × 38.120 microns.

Thus, the difference in size, whatever its cause, does not correspond to the difference between the ancestors; selection for size has had no evident effect.

Another experiment on the progeny of *Nf2* consisted in comparing the descendants of a single small conjugant with those of several large non-conjugants. Details of this and similar experiments will be reserved for our paper on the relation of conjugation to variation and heredity. But since it has a certain bearing on our present problem, the results may be given here.

At the same time with the cultures last described (on March 31), I isolated ten of the largest non-conjugant progeny of the same individual *Nf2*. A sample of thirty-four of these had given a mean length of 147.412 microns, so that this may be taken as the mean length of these ten specimens. With the progeny of these was compared the progeny of the smaller pair mentioned in the preceding experiment. As we have seen, this pair measured not more than 124 microns in length. The greatest pains were taken to cultivate the two sets under identical conditions. On April 20 I killed a sample of 108 of each. The mean measurements were as follows:

Progeny of small pair (124 microns) — 160.852 × 42.036 microns.
Progeny of ten large (147 microns) — 156.482 × 43.815 microns.

Thus, again, there is no correspondence between the differences in size of the parents and those of the progeny. The determining factor in the size is the fact that both sets belong to the same pure line; the variation of the parents from the type of the pure line has no effect. The difference in the figures above is either purely statistical in character or means a faint variation in the culture fluid.

### (*c*) *Summary on Selection within Pure Lines.*

Thus, we come uniformly to the result in all our experiments, that selection has no effect within a pure line; the size is determined by the line to which the animals belong, and individual variations among the parents have no effect on the progeny.

But for our results with different lines, it might be maintained that the reason why we get no constant differences between the progeny of different individuals of the same line is because the effects of environment are so much greater than the effects of selection that the latter are covered up and obscured. But as soon as we are dealing with lines that are really different (though by but a small amount) we have no such difficulty; the different lines retain their relative sizes in spite of environmental action. This is clearly shown in Tables XXIII. and XXV., pages 488 and 494.

The significance of these results will be dealt with in the next section.

## VI. SUMMARY AND DISCUSSION.

### 1. Résumé of the Investigations.

The present paper is an experimental study of the factors involved in variation and inheritance of size in the infusorian *Paramecium,* in the period when reproduction is taking place by fission, without conjugation.

1. The first question proposed is whether the differences in size among different individuals of a culture are inherited. The preliminary study showed that in a typical culture there were two permanently differentiated groups of large and small individuals, respectively, corresponding to what had been described as the two species, *Paramecium caudatum* and *Paramecium aurelia.* But when a culture was produced from a single individual of either of these groups, forming thus a "pure line," it was found that though the different individuals of the single pure line differed much in size,

these differences were not inherited. Large and small specimens of a single pure line produced progeny of the same mean size.

2. The next question then was: What are the causes and the nature of the variations in size among the different individuals of a culture of *Paramecium?* Even in a pure line the individuals differ greatly. The "polygon of variation" of a given culture was looked upon as a mass of problems for analysis. What determines the position which any given individual holds in such a polygon, or in a correlation table? And why do different lots of *Paramecia* differ in mean dimensions; in the amount of variability; in proportions, and in the correlation between length and breadth?

The analysis of the factors in variation led to a detailed study of (1) growth, (2) the effect of the environment; (3) inherited differences in size. To these three matters the three main divisions of the paper are devoted. To one or the other of these three categories most of the variations in size were found to belong. A fourth category, consisting of variations connected with conjugation, is reserved for consideration in a later paper.

3. A large share of the differences in size to be observed in a given culture are differences in growth. In study of variation in protozoa it is as necessary to take growth into consideration as it is in the study of higher animals; the part played by it is fully as great in the protozoa as elsewhere. The paper gives a detailed study of growth, based on the measurements of 1,500 specimens of various known ages, in comparison with large numbers of "random samples." In this way a curve of growth was plotted (Diagram 5, page 449); this curve resembles essentially the curves of growth of higher animals, as the rat, or man. In different parts of this curve of growth individuals show different lengths, different breadths, and, of course, different proportions of breadth to length. A flourishing culture contains individuals in all stages of growth; so that this affects largely the mean dimensions, the observed variations, and the correlations between length and breadth. The precise effects of growth on each of these matters are dealt with in detail in the paper; they will be summarized in later paragraphs. A summarized account of growth and its effects is found in the body of the paper, pages 447 to 458; the constants for dimensions and variation in dif-

ferent stages of growth are brought together in Table X., page 428.

4. Environmental conditions were found to play a very large part in determining dimensions, variations and correlation in *Paramecium.* Conditions of nutrition were found to be particularly effective. By changes in nutrition the mean length of a given culture could be changed in a week from 146 microns to 191 microns; the breadth from 31 to 54 microns; in twenty-four hours the coefficient of variability for length was thus changed from 7.003 to 12.767, for breadth from 12.473 to 28.879; the coefficient of correlation from .3906 to .8463. Changes of the most varied sort could be produced and reversed with the greatest ease in short periods; many examples of this are summarized in Table XVIII., page 460. Within a given culture at a given time many of the differences between individuals are due to slight environmental differences in different regions. The breadth is more sensitive to environmental changes than the length; to such an extent is this true that it is difficult to use the breadth dimensions for accurate study of any other factors. A summary on the effects of the environment on dimensions, proportions, variation and correlation is found on pages 476 to 484.

5. After the study of growth and environmental action, an investigation was made of the internal factors in dimensions and variation; of the inheritance of size. Are all the observed differences between the individuals of a culture mere matters of growth and environment? Or may we find different races or lines that retain their relative sizes even in the same stage of growth and in the same environment?

A thorough experimental study showed that a given "wild" culture usually contains many different lines or races, which maintain their relative sizes throughout all sorts of changing conditions. Eight of these differing pure lines were isolated and propagated; these varied in mean length from a little less than 100 to a little more than 200 microns (see Tables XXIII. and XXV.). Other lines could unquestionably be distinguished by sufficiently accurate experimentation.

These different lines fall usually into two main groups, one group having a mean length greater than 170 microns, the other having a mean length below 140 microns. These two groups correspond to the distinction that has been made between two species, the larger ones representing the supposed species *caudatum*, the smaller ones *aurelia*. But a line or race was found with mean length lying midway between these groups, at about 150 to 160 microns.

The smaller or *aurelia* lines were found to be, under the same conditions, as a rule a little broader in proportion to the length than the larger or *caudatum* lines. But the difference is slight and the two sets overlap extensively in this matter; slight differences in environment quite obscure the difference in proportions.

The differences among the different lines were found not to be due to different periods of the life cycle. By beginning with conjugating pairs of different sizes, distinct pure lines were as readily isolated as by beginning anywhere else in the cycle.

6. After becoming thoroughly familiar with differences due to growth, to environment, and to divergent ancestry, a further attempt was made to change by selection the characteristics of pure lines, or to break such lines into strains of differing size. In spite of much work directed on this point, it was found that selection within a pure line was quite without effect. Large individuals of the line produce progeny of the same mean size as do the small individuals. To this matter we return in later paragraphs.

## 2. Determining Factors for Dimensions, Variations and Correlations.

Based on the analysis of the factors in variation above set forth, a summary can be given of the various determining causes of the different dimensions, the proportions, the amount of variation and the correlations observed in samples of different cultures of *Paramecium*. We may take as an example such a sample as is shown in Table LXI. (appendix) from a "wild" culture.

1. The various different *lengths* depend upon the following factors:

(*a*) The collection embraces a number of different races or lines, having different lengths even when all conditions are the same. We have seen that different lengths varying from less than 100 to more than 200 microns may be included as a result of this fact. The *mean* length may not represent any of these races (this is the case in Table I.).

(*b*) The collection includes various growth stages of each of the lines represented. The youngest stages of each line are little more than half the lengths of the adults; all intermediate stages may be present, and the adults themselves shorten again as they approach fission. A very wide range of variation in length may be brought about by these growth stages, all within the limits of a single pure line or race. Of course when many different lines are present, an immense number of combinations are thus produced.

(*c*) The collection includes individuals of the various races that have lived under slight or considerable differences in environment, particularly in the matter of nutrition. Those that have been able to get more food will be much larger and will multiply more frequently (thus giving more young) than those that get less. Even slight environmental differences make decided differences in dimensions. While the environment shows its effects most strongly on comparison of different cultures, even within the same culture, and when all the individuals are of one race and of approximately the same age, there are marked differences due to this cause. This is shown, for example, in Table XLI. (appendix); here variations in length from 140 to 200 microns must be considered environmental effects. A few drops of water form a varied microcosm to the infusoria. When diverse pure lines, diverse growth stages, and diverse environmental conditions are found in a culture (as is usually the case), of course, the number of different sizes and forms due to the varied combinations of all these factors are very great. The same sizes may, of course, be produced in different ways; two diverse lines in different stages of growth or in different environments, or in some combination of the two, may produce forms outwardly identical. The actual variety, as defined by the physiological conditions, is therefore much greater than the measurements show, for the latter throw together heterogeneous combinations.

Combinations of all the three factors inducing diversity might give us in a single collection individuals varying in length from 50 microns to 332 microns. While these are the extremes given by our data, presumably the actual extremes would be still more divergent.

(*d*) In different collections the observed *mean* lengths depend upon the three different sets of factors just mentioned. The inclusion of different *lines* or *races,* even if conditions of growth and environment are essentially the same, may give us, as we have seen, mean lengths of somewhat less than 100, or somewhat more than 200 microns, or any intermediate length. Different *stages in growth* may give us, in the same line and in the same environment, means differing to such an extent that one is nearly twice the other, or any intermediate condition. The absolute extreme values will, of course, depend upon the race employed; in the line *i* the variation of mean length caused by growth might be from about 50 to about 100 microns; in *D* it was from about 100 to about 200 microns; in *L* it would be from about 117 to 234 microns. Different *environmental conditions* give us, within the same lines, mean lengths differing to such an extent that the greater is 25 to 30 per cent. more than the less (lines *c* and *D*). In different "wild" cultures we shall have different combinations of all these factors, resulting in extreme diversities in different cases. Fig. 7 shows two extreme sizes drawn to the same scale (page 496).

2. The various different breadths depend upon the same factors as the different lengths. There are certain differences, however. As compared with length, the breadth is affected much less by growth; about the same (though a trifle less) by diversity of race; and much more by environmental differences. Environmental differences produced within the races *D* and *c* such differences in mean breadth that the greater was about twice the less.

3. The observed variation, as measured by the coefficient of variation, of course, depends upon the three sets of factors enumerated above as affecting the length and breadth. If a collection consisted of several different lines or races, all in the same condition as regards growth and environmental conditions, this would, of course, give us a considerable coefficient of variation. For example, if a collection consisted of ten individuals each of all the different lines represented in Table XXVI., page 502, and if all of each set of ten had the mean dimensions for its line (thus excluding differences due to growth and environment within the lines), the coefficient of variation when computed in the same way as for the actual collections given in the text is found to be for length 19.689; for breadth 15.679.

If a collection consists of individuals all belonging to the same line or race, and in the same environment, then the coefficient of variation depends largely upon the stages of growth it contains. By taking specimens nearly in the same stage of growth we were able to reduce the coefficient of variation in length in some cases to 4.521, in breadth to 6.976, while by taking collections including various ages, under similar conditions, coefficients were found as high as 13.729 for length and 13.292 for breadth (Table X.). The most carefully selected lots contain specimens differing a certain amount in age, otherwise the coefficient of variation could be still further reduced in this way. Specimens beginning fission or undergoing conjugation include few growth stages, hence they show a low coefficient of variation. The coefficient for those beginning fission is less than for conjugants (see page 453).

The coefficient of variation for a given line is tremendously affected by environmental conditions. Thus, we see this coefficient changed in twenty-four hours, by a change in environment, from 7.003 to 12.767 for length; from 12.473 to 28.879 for breadth. Different environments give us all sorts of values between such extremes.

It is evident that no particular coefficient of variation can be considered characteristic of *Paramecium,* or of any line of *Paramecium;* certainly not unless the conditions as to growth, environment, etc., are very precisely defined. We have seen that the variations found among different individuals of the same pure line *do not show themselves to be heritable.* This, along with all the rest of the evidence, indicates that if all conditions of growth and environment were made identical throughout a sample of *Paramecia* belonging to a pure line, the coefficient of variation would be very near to zero. In other words, all the variations that we have been able to detect with certainty in a pure line are due to growth and environment. Presumably other variations (congenital and hereditary) must occur at times, but they appear to be so rare that it is difficult to detect them and they would have little effect on the coefficient of variation. By properly varying the conditions, we may get in a pure line all coefficients of variation in length, from a limit near zero up to 20 or more.

4. The ratio of breadth to length (serving to partly define the

form of the body), of course, varies in dependence upon all the three sets of factors with which we have dealt—difference of race, growth and environmental conditions. The smaller races are found to show, under the same conditions, a slightly greater ratio of breadth to length (see Table XXVI.). Within the same race different stages of growth show different ratios; in general, the proportion of breadth to length is greatest in the young, and gradually decreases with age; it increases again very rapidly in preparation for fission. Environmental agents affect in most marked and varied ways the proportion of breadth to length; this is connected with the fact that such agents act more upon the breadth than upon the length. A detailed summary of the different effects of the environment on the proportion of breadth to length is found on pages 478 and 479. The most important general relation is, that increase of nutriment increases the proportional breadth; decrease of nutriment produces the opposite effect. Any agent which suddenly increases the breadth likewise, as a rule, increases the ratio of breadth to length.

5. The coefficient of correlation between length and breadth is the measure of the accuracy with which breadth and length vary proportionately. If the proportion of breadth to length is the same in all individuals of a collection, then the coefficient of correlation of that collection is 1.000.[10] Since, as we have just seen, the proportion of breadth to length is altered by many factors, it follows that all these factors modify the correlation, tending to reduce it below 1.000. The correlation is affected by all the three categories of factors that affect the dimensions in essentially the following ways:

(*a*) The inclusion of different races in a collection, particularly if some of the smaller and some of the larger races occur, makes the correlation less than 1.000, because the proportion of breadth to length is greater in the smaller races. The reduction in correlation produced by this alone is very slight. If we make a collection by

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[10] It is perhaps not necessary to point out that the "coefficient of correlation" is *descriptive;* it shows the observed condition in a given set of measurements. The *cause* of this condition is a matter to be determined. *Correlation* is often conceived physiologically as an underlying something that binds two things together, so that they must change correspondingly. The descriptive correlation of the statistician may be the resultant of many factors.

throwing together ten each of the different lines of Table XXV. (page 494), giving the individuals of each line the mean dimensions of its line (thus nearly excluding variations due to growth and environment), then calculate the coefficient of correlation in the same way as for our other collections, we find it to have the high value of .9735.

(*b*) The inclusion of different stages of growth in a collection reduces the correlation below 1.000, since different growth stages have different ratios of breadth to length. A detailed summary of the effects of growth on correlation is found on pages 455 to 457; here we can notice only the main points. In the earliest stages of growth the length is increasing while the breadth is decreasing; hence if we take a collection including various stages within this period, the correlation between length and breadth becomes negative; it may fall to a value of —.3138 (see Table X.). The inclusion of various early stages in a collection of adults decreases the positive correlation shown by the adults. In later growth, length and breadth increase together; the inclusion of various stages at this period has little effect on the correlation; it does, however, tend to reduce it slightly, since length and breadth do not increase at the same ratio. In old specimens, beginning fission, the length decreases while the breadth increases; a collection including different stages in this process tends again to give negative correlation, or to reduce the positive correlation due to other causes. In a collection from the same pure line, in which all specimens are in the same stage of growth, the correlation between length and breadth is high; this would be true no matter what stage of growth is the one represented. Random samples from any culture usually contain many stages of growth; this lowers the correlation between length and breadth.

(*c*) Environmental differences, like growth, affect length and breadth differently or in different proportions; if individuals thus diversely affected are included in a sample, this tends to decrease the correlation between length and breadth. A detailed analysis of the many and important effects of environmental action on the correlation will be found on pages 481 to 484; here, again, we can but summarize the important points.

1. Certain environmental agents increase the breadth while decreas-

ing the length. Inclusion of different stages of this process in a sample reduces the correlation; it may make it zero or negative.

2. Most environmental agents change the breadth more than the length, even when both are changed in the same direction The inclusion of different stages then reduces correlation.

3. Samples in which some of the specimens are well-fed and plump, others ill-fed and thin, of course, show low correlation, since the ratio of breadth to length is not uniform. This is usually the case in cultures where food is scarce.

4. Addition of abundant nutriment causes the thin specimens to increase in breadth, by taking food, while the plump ones change little. As a result the proportion of breadth to length becomes nearly uniform throughout the lot; the correlation is therefore increased. As a rule, any agent which increases the mean breadth likewise (for the reason just set forth) increases the correlation between breadth and length.

Decrease of nutriment, for the converse reason, decreases the correlation.

5. Any agent that causes rapid multiplication decreases the correlation between length and breadth for the period of multiplication. This is owing to the inclusion in the collection of many stages of growth, showing different proportions of length to breadth.

6. Slight differences in one dimension may be produced without corresponding differences in the other, so that in a collection varying little in length the correlation may be low. But considerable changes in one dimension are usually accompanied by corresponding changes in the other. Hence, when two groups of differing lengths are thrown together, the correlation may become higher than in either one taken separately (for example, see page 437).

In any ordinary sample of *Paramecium* all these varied factors are at work in determining the observed correlation. It is clear that no particular coefficient of correlation can be considered characteristic for *Paramecium* or for any particular race of *Paramecium,* for by various combinations of these factors we may get any coefficient of correlation ranging from a pronounced negative value upward through zero to a high positive value. In Tables X. and XVIII. we see varied collections showing extremes of value for the coefficient of correlation, from —.3138 to +.8500.[11]

## 3. RESULTS ON VARIATION, INHERITANCE AND THE EFFECTS OF SELECTION.

Our general results with regard to variation, inheritance and the effects of selection are then as follows:

In a given "pure line" (progeny of a single individual) all detectible variations are due to growth and environmental action, and are not inherited. Large and small representatives of the pure line produce progeny of the same mean size. The *mean size* is therefore strictly hereditary throughout the pure line, and it depends, not on the accidental individual dimensions of the particular progenitor, but on the fundamental characteristics of the pure line in question.

In nature we find many pure lines differing in their characteristic mean dimensions.

Our results with the infusorian *Paramecium* are, then, similar to those reached recently by certain other investigators working with pure lines of other organisms. Johannsen (1903) showed that in beans and in barley many pure lines, slightly differentiated from each other, exist in nature, but that selection within a pure line has no effect upon its characteristics. These plants are self-fertilized, so that there is no intermingling of different lines. Hanel (1907) has recently found the same state of affairs in *Hydra* when multiplying by budding. Certain lines tend to have a higher mean number of tentacles, others a lower mean number. But within a given line selection of parents with more or fewer tentacles has no effect on the progeny; selection has no effect within the pure line.

It is doubtless too early to draw any very positive conclusions from these facts. While the results with *Paramecium* seem clear, I intend to test them further in every way possible. It is possible that selection may be made on some other basis, with a better

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[11] This fact of course does not render the study of the coefficient of correlation valueless. Its examination under varied experimental conditions is of the utmost importance for determining the real effects of various agents, and in many other ways it furnishes a valuable datum.

chance of avoiding differences due to environment and growth. It is conceivable that congenital hereditary variations exist, but that they are few in number compared with those due to environment and to slight differences in ways of living, so that in our selection we always get the mere environmental variations. There are decided differences between the specimens of the same line beginning fission, as Table XIII. (page 442) well shows; here the length varied from 156 to 204 microns. It is possible that selection among specimens beginning fission might have a better chance for success. I have attempted this, but it is extremely difficult; I hope to return to it.

We must consider, however, that if the non-inheritable differences are so much more numerous and marked than the inheritable ones as to render conscious selection by human beings ineffective, they would apparently have the same effect on selection by the agencies of nature. The same ground for selection offered by heritable variations is offered so much more fully by those not heritable that there would be as little effect in selection by nature as in selection by man.

Certainly, therefore, until someone can show that selection is effective within pure lines, it is only a statement of fact to say that all the experimental evidence we have is against this. The results set forth in the present paper tend to strengthen that explanation of the observed facts regarding selection, regression, etc., in mixed populations, which is set forth by Johannsen (1903). We need not discuss these in detail here; they are essentially as follows:

1. Selection in a mixed population consists in isolating the various different lines already existing.

2. If selection is made, not of single individuals, but of considerable numbers having a certain characteristic, then by repeated selection it will be possible to approach nearer and nearer to a certain end.

Thus, if we select from such a heterogeneous collection as is represented in Table LXI. all the larger individuals, we shall have taken representatives of many different lines. Our selection will include the larger individuals of lines of median size, as well as the average individuals of lines of large size. The progeny of this selected lot will then consist of various lines, some larger, some smaller, but with the average higher than in the original collection. Another selection will raise the average still further by getting rid of some of the smaller lines, etc.

3. It has been noticed that in many cases continued selection will not carry a character beyond a certain point. This is due (on the view we are setting forth) to the fact that we have finally isolated that line (or lines) of the original collection which had this character most strongly marked, and since selection of the fluctuations has no effect within the pure line, we can make no farther progress.

4. The phenomenon of so-called *regression* finds its explanation in the same way. It is found that when extremes are selected, the progeny of these extremes stand nearer the mean than did the parents, though they diverge in the same direction as the parents. The reason for this may again be seen by considering such a heterogeneous collection as that of Table LXI., with the effects of selecting the extremes of size. If we select the largest and the smallest individuals, we shall have taken (1) the largest individuals of the largest lines, and (2) the smallest individuals of the smallest lines. But these, when they propagate, produce, as we have seen, merely the *means* of the lines to which they belong. The largest individuals will produce then progeny that average smaller than themselves; the smallest individuals progeny that are larger than themselves; both sets will then approach the mean of the original collection as a whole.

In working with populations reproducing by cross fertilization among the different lines, the conditions on which these results depend become quite obscured, owing to the introduction of new factors, the union of different factors, the appearance of mendelian results, etc. Work with pure lines perhaps shows the real cause for the observed phenomena above set forth.

It must be admitted, then, that the work with pure lines, indicating that selection of fluctuations within the lines is powerless, leads to a simple and consistent explanation of many of the observed facts. But, of course, it gives no explanation of the origin of the different pure lines. Clear proof of the effectiveness of selection even within a pure line would therefore be of the greatest interest, and the present writer would find great pleasure in being the first to present such proof. But until such proof is forthcoming, it must be admitted that the experimental results go strongly against the effectiveness of selection among slight fluctuating variations in producing new inherited characteristics.

How, then, do the different pure lines rise? This is after all the main problem. Toward its solution further investigations of this series will be directed. It is proposed to study in detail (1) the effects of conjugation on variation, heredity and the production of new races; (2) the effects of long-continued differences in environmental action on different divisions of the same line; (3) the question whether the different lines arise from something like mutations. Further, (4) additional different way of exercising selection within a single line will be tested. The question may be raised whether the production "by mutation" of such slight differences in size as we are here dealing with would not be essentially the same as their production by the inheritance of slight variations—since the extent of the "mutations" would not be greater than what we should call slight variations in size. The difference between the two conceptions almost or quite vanishes when we come to deal with such minute changes in characteristics as those we find in the different lines of *Paramecium*. The "mutation" would be merely a *rare,* heritable, variation, and it is now clear that heritable variations in size are much rarer than had been supposed; their number is so small that in *Paramecium* they are not statistically detectible among the many non-heritable fluctuations due to the environment.

RAQUETTE LAKE, NEW YORK,
August 22, 1908.

## LIST OF LITERATURE.

**Calkins, G. N.**

**1906.** The Protozoan Life Cycle. *Biol. Bul.,* 11, 229–244.

**Calkins, G. N.**

**1906.** Paramecium aurelia and Paramecium caudatum. "Biological Studies" by the Pupils of Wm. T. Sedgwick, Chicago.

**Davenport, C. B.**

**1899.** Statistical Methods, with Special Reference to Biological Variation, New York.

**1904.** Idem. Second edition.

**Donaldson, H. H.**

**1906.** A Comparison of the White Rat with Man in Respect to Growth. Boas Memorial Volume, New York, pp. 5–26.

**Hanel, Elise.**

**1907.** Vererbung bei ungeschlechtlicher Fortpflanzung von Hydra grisea. *Jenaische Zeitschr.,* 43, 321–372.

**Jennings, H. S.**

**1908.** Heredity, Variation and Evolution in Protozoa. I. The Fate of New Structural Characters in Paramecium, with Special Reference to the Question of the inheritance of Acquired Characters in Protozoa. *Journ. Exp. Zool.,* 5, 577–632.

**Johannsen, W.**

**1903.** Erblichkeit in Populationen und in reinen Linien. 68 pp. Jena.

**Johannsen, W.**

**1906.** Does Hybridisation Increase Fluctuating Variability? Report of the Third International Conference (1906) on Genetics. London.

**McClendon, J. F.**

**1908.** Protozoan Studies, I. *Journ. Exp. Zool.,* 6.

**Pearl, R.**

**1907.** A Biometrical Study of Conjugation in Paramecium, *Biometrika,* 5, 213–297.

**Pearl, R., and Dunbar, F.**

**1905.** Some Results of a Study of Variation in Paramecium. Seventh Report Michigan Acad. Sci., pp. 77–86.

**Pearson, K.**

**1902.** Note on Dr. Simpson's Memoir on Paramecium caudatum. *Biometrika,* 1, 404–407.

**Robertson, T. B.**

**1908.** On the Normal Rate of Growth of an Individual and its Biochemical Significance. *Arch. f. Entw.-mech.,* 25, 582–614.

**Simpson, J. Y.**

**1902.** The Relation of Binary Fission to Variation. *Biometrika,* 1, 400–404.

**Yule, G. U.**

**1897.** On the Theory of Correlation. *Journ. Roy. Statistical Society,* 60, 1–44.

# APPENDIX.

## Tables of Measurements.

The first twenty-eight tables are distributed through the text. Tables XXIX. to LXIII. follow.

### Table XXIX.

*Correlation Table for Length and Breadth of 59 Specimens, Age 0 to 5 Minutes.* (See Lot 2, Table 10.) Descendants of *D.*

Length in Microns.

| Breadth in Microns. | 76 | 80 | 84 | 88 | 92 | 96 | 100 | 104 | 108 | 112 | 116 | 120 | 124 | 128 | 132 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 36 | | | | | | | | | | 1 | | | | | | 1 |
| 40 | | | | | | 1 | 1 | 1 | | | | 2 | 1 | | | 6 |
| 44 | | | | | 2 | | 4 | 1 | 2 | | 5 | 1 | 3 | 2 | 1 | 21 |
| 48 | | | 1 | 2 | 3 | 1 | 3 | 1 | 2 | 2 | | 1 | 2 | 1 | 1 | 20 |
| 52 | 1 | 1 | | | 3 | | | | 1 | | 1 | 1 | 1 | | 1 | 10 |
| 56 | 1 | | | | | | | | | | | | | | | 1 |
| | 2 | 1 | 1 | 2 | 8 | 2 | 8 | 3 | 5 | 3 | 6 | 5 | 7 | 3 | 3 | 59 |

Length—Mean, 107.660 ± 1.296μ
St. Dev., 14.780 ± .916μ
Coef. Var., 13.729 ± .868

Breadth—Mean, 46.372 ± .332μ
St. Dev., 3.804 ± .236μ
Coef. Var., 8.200 ± .524

Mean Index, 44.037 per cent.; Coef. Cor., —.3138 ± .0792.

### Table XXX.

*Correlation Table of Length and Breadth for a Random Sample of Lot 2, Table X.—Same Lot from which came Specimens in Tables VII. and XXIX. Descendants of D.* (24 hours in fresh hay infusion: July 17.)

Length in Microns.

| Breadth in Microns. | 140 | 144 | 148 | 152 | 156 | 160 | 164 | 168 | 172 | 176 | 180 | 184 | 188 | 192 | 196 | 200 | 204 | 208 | 212 | 216 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 36 | 1 | | | | 1 | 2 | 1 | | 1 | 1 | | | 1 | | | | | | | | 8 |
| 40 | | | | 1 | 2 | 5 | 4 | 3 | 3 | 5 | 6 | 3 | 6 | 3 | 1 | 1 | | | | | 43 |
| 44 | | | 2 | 1 | 1 | 3 | 1 | 2 | 4 | 5 | 3 | 7 | 7 | 4 | 7 | 6 | 3 | | 1 | | 57 |
| 48 | | | | | 1 | 2 | 2 | 3 | 3 | 2 | 3 | 1 | 2 | 9 | 2 | 4 | 5 | 3 | 1 | | 43 |
| 52 | | | | | 1 | 1 | 1 | | 2 | | | 3 | 2 | 6 | 4 | 4 | 1 | 2 | 3 | 2 | 32 |
| 56 | | | | | 1 | 1 | | | 1 | | 2 | 1 | | | 3 | 2 | 2 | 1 | | 1 | 15 |
| 60 | | | | | | | | | | | | | | | | | 1 | 1 | | | 2 |
| | 1 | 0 | 2 | 2 | 7 | 14 | 9 | 8 | 14 | 13 | 14 | 15 | 18 | 22 | 17 | 17 | 12 | 7 | 5 | 3 | 200 |

Length—Mean, 184.100 ± .776μ
St. Dev., 16.264 ± .548μ
Coef. Var., 8.834 ± .300

Breadth—Mean, 46.020 ± .251μ
St. Dev., 5.256 ± .177μ
Coef. Var., 11.421 ± .390

Mean Index, 25.084 per cent.; Coef. Cor., .4282 ± .0389.

### TABLE XXXI.

*Correlation Table for the Length and Breadth of the Young of Lot 6, between the Ages of 0 and 19 Minutes.* (See Table X., row 7.)

Length in Microns.

| Breadth in Microns. | 108 | 112 | 116 | 120 | 124 | 128 | 132 | 136 | 140 | 144 | 148 | 152 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 52 | | 1 | | | | | | | 2 | | | | 3 |
| 56 | 1 | 1 | 1 | 1 | 1 | | 1 | | | | | | 6 |
| 60 | 2 | | | | | | | 1 | 3 | 1 | | 1 | 8 |
| 64 | | | | 1 | | | | 1 | 1 | | 1 | | 4 |
| 68 | | | 1 | | | | | | | | | | 1 |
| 72 | | | | | | 1 | | | | | | | 1 |
| 76 | | 1 | | | | | | | | | | | 1 |
| | 3 | 3 | 2 | 2 | 1 | 1 | 1 | 2 | 6 | 1 | 1 | 1 | 24 |

| | | | |
|---|---|---|---|
| Length—Mean, | 128.000 ± 1.908μ | Breadth—Mean, | 60.168 ± .788μ |
| St. Dev., | 13.856 ± 1.348μ | St. Dev., | 5.712 ± .556μ |
| Coef. Var., | 10.825 ± 1.066 | Coef. Var., | 9.495 ± .933 |

Mean Index, 47.573 per cent.; Coef. Cor., —.0337 ± .1375.

### TABLE XXXII.

*Correlation Table for Length and Breadth of Young of Lot 7, between the Ages of 0 and 19 Minutes, Descendants of Individual D.* (See Table X., row 13.)

Length in Microns.

| Breadth in Microns. | 108 | 112 | 116 | 120 | 124 | 128 | 132 | 136 | 140 | 144 | 148 | 152 | 156 | 160 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 36 | | | | | | | | | | | | 1 | | | 1 |
| 40 | | | | | | 1 | | 1 | | | | 1 | | | 3 |
| 44 | | 3 | | 1 | 2 | 1 | | | | 1 | 1 | 1 | 1 | 1 | 12 |
| 48 | | | 1 | 1 | 2 | 1 | | | 1 | 1 | 4 | 2 | | 1 | 14 |
| 52 | 1 | 1 | | 1 | 3 | 1 | 1 | | | | | 1 | | | 9 |
| | 1 | 4 | 1 | 3 | 7 | 4 | 1 | 1 | 1 | 2 | 5 | 6 | 1 | 2 | 39 |

| | | | |
|---|---|---|---|
| Length—Mean, | 134.256 ± 1.663μ | Breadth—Mean, | 46.768 ± .408μ |
| St. Dev., | 15.394 ± 1.176μ | St. Dev., | 3.792 ± .288μ |
| Coef. Var., | 11.468 ± .857 | Coef. Var., | 8.109 ± .623 |

Mean Index, 35.643 per cent.; Coef. Cor., —.2546 ± .1010.

## TABLE XXXIII.

*Correlation Table for Length and Breadth of Young of Lot 6, between the Ages of 18 and 28 Minutes.* (See Table X., row 8.)

Length in Microns.

| Breadth in Microns. | 132 | 136 | 140 | 144 | 148 | 152 | 156 | 160 | |
|---|---|---|---|---|---|---|---|---|---|
| 48 | | | | 5 | | | | | 5 |
| 52 | | 4 | 6 | 7 | 2 | 1 | 2 | | 22 |
| 56 | 2 | 4 | 3 | 2 | 1 | 1 | | | 13 |
| 60 | | 1 | 2 | | 1 | 1 | 1 | 1 | 7 |
| 64 | | | | | 1 | | 1 | | 2 |
| | 2 | 9 | 11 | 14 | 5 | 3 | 4 | 1 | 49 |

| | | | |
|---|---|---|---|
| Length—Mean, | 143.348 ± .624μ | Breadth—Mean, | 54.284 ± .364μ |
| St. Dev., | 6.480 ± .440μ | St. Dev., | 3.788 ± .260μ |
| Coef. Var., | 4.521 ± .309 | Coef. Var., | 6.976 ± .478 |

Mean Index, 37.921 per cent.; Coef. Cor., .1937 ± .0927.

## TABLE XXXIV.

*Correlation Table for Length and Breadth of 106 Specimens, Age 18–28 Minutes.* (See row 15, Table X.) (Descendants of *D*, but taken part one day, part another.)

Length in Microns.

| Breadth in Microns. | 112 | 116 | 120 | 124 | 128 | 132 | 136 | 140 | 144 | 148 | 152 | 156 | 160 | 164 | 168 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 36 | 1 | | | | | | | | | | | | | | | 1 |
| 40 | | | | | | | | 1 | | | | | | | | 1 |
| 44 | | | | 1 | 2 | 1 | | 1 | 3 | 2 | 1 | 2 | 1 | | | 14 |
| 48 | | | | | | 1 | 1 | 6 | 16 | 3 | 3 | 2 | | | 1 | 33 |
| 52 | | | | | | 1 | 5 | 6 | 8 | 3 | 4 | 3 | 1 | | | 31 |
| 56 | | | | | | 4 | 4 | 3 | 2 | 3 | 1 | | | | | 17 |
| 60 | | | | | | | 1 | 2 | | 1 | 1 | 1 | 1 | | | 7 |
| 64 | | | | | | | | | | 1 | | 1 | | | | 2 |
| | 1 | 0 | 0 | 1 | 2 | 7 | 11 | 19 | 29 | 13 | 10 | 9 | 3 | 0 | 1 | 106 |

| | | | |
|---|---|---|---|
| Length—Mean, | 143.812 ± .544μ | Breadth—Mean, | 50.832 ± .320μ |
| St. Dev., | 8.296 ± .384μ | St. Dev., | 4.900 ± .228μ |
| Coef. Var., | 5.769 ± .268 | Coef. Var., | 9.640 ± .451 |

Mean Index, 35.438 per cent.; Coef. Cor., 1319 ± .0644.

## Table XXXV.

*Correlation Table for Length and Breadth of Young of Lot 6, between the Ages of 35 and 45 Minutes.* (See Table X., row 9.)

Length in Microns.

| Breadth in Microns. | 132 | 136 | 140 | 144 | 148 | 152 | 156 | 160 | |
|---|---|---|---|---|---|---|---|---|---|
| 48 | | | | 1 | 1 | 1 | | | 3 |
| 52 | 1 | | 1 | | 1 | 1 | 1 | 1 | 6 |
| 56 | | | 2 | 1 | 2 | 1 | 1 | 2 | 9 |
| 60 | | | 1 | | | 1 | | 1 | 3 |
| 64 | | | | | 1 | 1 | 1 | 1 | 4 |
| | 1 | 0 | 4 | 2 | 5 | 5 | 3 | 5 | 25 |

| | | | |
|---|---|---|---|
| Length—Mean, | 149.920 ± 1.012μ | Breadth—Mean, | 55.840 ± .636μ |
| St. Dev., | 7.512 ± .716μ | St. Dev., | 4.724 ± .452μ |
| Coef. Var., | 5.010 ± .479 | Coef. Var., | 8.461 ± .813 |

Mean Index, 37.296 per cent.; Coef. Cor., .2799 ± .1243.

## Table XXXVI.

*Correlation Table for Length and Breadth of Young of Lot 6, between the Ages of 75 and 90 Minutes.* (See Table X., row 10.)

Length in Microns.

| Breadth in Microns. | 140 | 144 | 148 | 152 | 156 | 160 | 164 | 168 | 172 | 176 | 180 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 40 | 1 | | | | | | | | | | | 1 |
| 44 | | | | | | | | | | | | 0 |
| 48 | 1 | | 2 | 1 | 1 | | 1 | 1 | 1 | | | 8 |
| 52 | | | 1 | 2 | 6 | 1 | 4 | | 1 | | 1 | 16 |
| 56 | | | | 1 | | | 4 | | | 1 | | 6 |
| 60 | | | | | | 1 | 2 | 1 | 1 | 2 | 1 | 8 |
| 64 | | | | | | | | | | | | 0 |
| 68 | | | | | | 1 | 1 | | 1 | | | 3 |
| | 2 | 0 | 3 | 4 | 7 | 3 | 12 | 2 | 4 | 3 | 2 | 42 |

| | | | |
|---|---|---|---|
| Length—Mean, | 161.524 ± 1.004μ | Breadth—Mean, | 54.192 ± .600μ |
| St. Dev., | 9.648 ± .712μ | St. Dev., | 5.752 ± .424μ |
| Coef. Var., | 5.974 ± .441 | Coef. Var., | 10.617 ± .790 |

Mean Index, 33.558 per cent.; Coef. Cor., .5232 ± .0756.

## Table XXXVII.

*Correlation Table for Length and Breadth of Young of Lot 9, between the Ages of 3 and 4 Hours.* (See Table X., row 16.)

Length in Microns.

| Breadth in Microns. | 132 | 136 | 140 | 144 | 148 | 152 | 156 | 160 | 164 | 168 | 172 | 176 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 40 | | | | | 1 | | | | | | | | 1 |
| 44 | | 1 | 1 | 3 | 1 | 2 | | | 1 | | | | 9 |
| 48 | 2 | 1 | 9 | 1 | 3 | 3 | 4 | 3 | | 1 | | | 27 |
| 52 | | 5 | 6 | 4 | 3 | 2 | 3 | 4 | 1 | 1 | 1 | | 30 |
| 56 | | | 3 | 2 | 1 | 3 | 3 | 3 | 2 | | | | 17 |
| 60 | | | | 2 | | 1 | 1 | | | 1 | | 1 | 6 |
| 64 | | | | | | | 1 | | 2 | | | | 3 |
| | 2 | 7 | 19 | 12 | 9 | 11 | 12 | 10 | 6 | 3 | 1 | 1 | 93 |

Length—Mean, 149.636 ± .688μ
St. Dev., 9.856 ± .488μ
Coef. Var., 6.587 ± .327

Breadth—Mean, 51.568 ± .322μ
St. Dev., 4.752 ± .236μ
Coef. Var., 9.212 ± .459

Mean Index, 34.546 per cent.; Coef. Cor., .3201 ± .0628.

## Table XXXVIII.

*Correlation Table for the Length and Breadth of Young of Lot 9, between the Ages of 4.20 and 5 hours.* (See Table X., row 17.)

Length in Microns.

| Breadth in Microns. | 164 | 168 | 172 | 176 | 180 | 184 | 188 | 192 | 196 | 200 | 204 | 208 | 212 | 216 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 52 | | 1 | 1 | 4 | 2 | 2 | 1 | | | | | | | | 11 |
| 56 | 1 | 2 | 1 | 2 | 5 | 5 | 5 | 3 | 1 | | 1 | | | | 26 |
| 60 | | 1 | | 2 | 4 | 3 | 4 | 2 | 3 | 3 | 1 | | | | 23 |
| 64 | | | | 1 | 3 | 3 | 7 | 6 | 1 | 2 | 1 | | | | 24 |
| 68 | | | | | 1 | | 1 | 1 | 2 | 1 | | | | | 6 |
| 72 | | | | | | | | | 1 | 2 | | | | 1 | 4 |
| 76 | | | | | | | | | | 1 | | | | | 1 |
| | 1 | 4 | 2 | 9 | 15 | 13 | 18 | 12 | 8 | 9 | 3 | 0 | 0 | 1 | 95 |

Length—Mean, 186.736 ± .652μ
St. Dev., 9.416 ± .460μ
Coef. Var., 5.043 ± .247.

Breadth—Mean, 60.168 ± .360μ
St. Dev., 5.224 ± .256μ
Coef. Var., 8.679 ± .428

Mean Index, 32.225 per cent.; Coef. Cor., .5557 ± .0478.

### Table XXXIX.

*Correlation Table for Length and Breadth of Paramecia at the Age of 12 Hours.* (Descendants of *D;* See Table X., rows 20 and 21.)

Length in Microns.

| Breadth in Microns. | 136 | 140 | 144 | 148 | 152 | 156 | 160 | 164 | 168 | 172 | 176 | 180 | 184 | 188 | 192 | 196 | 200 | 204 | 208 | 212 | 216 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 48 | 1 | | | | | | | 1 | | | | | | | | | | | | | | 2 |
| 52 | | 1 | | | | | | | | 1 | | | | | | | | | | | | 2 |
| 56 | | | | | | | | | 1 | 1 | 1 | 3 | 2 | | 1 | 1 | 2 | | | | | 12 |
| 60 | | | | | | | | | | | 2 | 1 | 2 | 2 | 2 | 1 | 4 | 1 | | | | 15 |
| 64 | | | | | | | | | | | 1 | | 2 | 3 | 5 | 4 | 2 | 3 | | | 1 | 21 |
| 68 | | | | | | | | | | | | | | 4 | 3 | 3 | 2 | 1 | | | | 13 |
| 72 | | | | | | | | | | | | | 1 | 5 | | 1 | | | | | | 7 |
| 76 | | | | | | | | | | | | | | | | | | | | | | 0 |
| 80 | | | | | | | | | | | | | | | 1 | | | | | | | 1 |
| | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 2 | 4 | 4 | 7 | 14 | 12 | 10 | 10 | 5 | 0 | 0 | 1 | 73 |

| | | | |
|---|---|---|---|
| Length—Mean, | 188.988 ± .996μ | Breadth—Mean, | 62.796 ± .464μ |
| St. Dev., | 12.612 ± .704μ | St. Dev., | 5.872 ± .328μ |
| Coef. Var., | 6.672 ± .374 | Coef. Var., | 9.350 ± .526 |

Mean Index, 33.275 per cent.; Coef. Cor., .4868 ± .0602.

### Table XL.

*Correlation Table for Length and Breadth of Paramecia at the Age of 18 Hours.* (Descendants of *D;* See Table X., row 22.)

Length in Microns.

| Breadth in Microns. | 168 | 172 | 176 | 180 | 184 | 188 | 192 | 196 | 200 | 204 | 208 | 212 | 216 | 220 | 224 | 228 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 48 | | | 1 | 2 | 1 | | | | | | 1 | | | | | | 5 |
| 52 | 1 | 1 | | 1 | 1 | 5 | 2 | 6 | 5 | 4 | 3 | 1 | 1 | | | | 31 |
| 56 | | 1 | | 1 | 4 | 2 | 4 | 6 | 5 | | 2 | 5 | | | | | 30 |
| 60 | | | | 2 | 1 | | | 1 | 5 | 4 | 4 | 2 | 5 | 1 | | 1 | 26 |
| 64 | | | | | | 1 | | 1 | 1 | 4 | 1 | 1 | | 2 | | | 11 |
| 68 | | | | | | | | | | | 2 | | | | | | 2 |
| | 1 | 2 | 1 | 6 | 7 | 8 | 6 | 14 | 16 | 12 | 13 | 9 | 6 | 3 | 0 | 1 | 105 |

| | | | |
|---|---|---|---|
| Length—Mean, | 199.048 ± .780μ | Breadth—Mean, | 56.496 ± .292μ |
| St. Dev., | 11.844 ± .552μ | St. Dev., | 4.428 ± .208μ |
| Coef. Var., | 5.949 ± .278 | Coef. Var., | 7.837 ± .367 |

Mean Index, 28.427 per cent.; Coef. Cor., 4304 ± .0536.

## TABLE XLI.

*Correlation Table for Length and Breadth of 300 Paramecia at the Age of 24 Hours.* (Descendants of *D;* See Table X., row 23.)

Length in Microns.

| Breadth in Microns. | 140 | 144 | 148 | 152 | 156 | 160 | 164 | 168 | 172 | 176 | 180 | 184 | 188 | 192 | 196 | 200 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 28 | 1 | | 2 | 1 | 1 | | | | | | | | | | | | 5 |
| 32 | 1 | 4 | 2 | 5 | 8 | 8 | 7 | 6 | 2 | | | | | | | | 43 |
| 36 | | | | 5 | 8 | 8 | 9 | 15 | 10 | 7 | 2 | 1 | | | 1 | | 66 |
| 40 | | | 1 | 2 | 5 | 3 | 10 | 16 | 12 | 7 | 9 | 3 | 1 | | | | 69 |
| 44 | | 1 | | 1 | 2 | 6 | 9 | 10 | 12 | 7 | 6 | 6 | 4 | | 1 | | 65 |
| 48 | | | | | 2 | 2 | 4 | 3 | 1 | 8 | 6 | 3 | 6 | | | 1 | 36 |
| 52 | | | | | | | | 2 | | 3 | 3 | | | 2 | | | 10 |
| 56 | | | | | | | 1 | | 2 | | | 1 | 1 | 1 | | | 6 |
| | 2 | 5 | 5 | 14 | 26 | 27 | 40 | 52 | 39 | 32 | 26 | 14 | 12 | 3 | 2 | 1 | 300 |

Length—Mean, 168.532 ± .419μ
St. Dev., 10.768 ± .296μ
Coef. Var., 6.389 ± .175

Breadth—Mean, 40.320 ± .230μ
St. Dev., 5.892 ± .162μ
Coef. Var., 14.615 ± .411

Mean Index, 23.899 per cent.; Coef. Cor., .5496 ± .0272.

## TABLE XLII.

*Correlation Table for Length and Breadth of 62 Dividing Specimens of Lot 2.* (Descendants of *D;* See Table X., row 31.)

Length in Microns.

| Breadth in Microns. | 144 | 148 | 152 | 156 | 160 | 164 | 168 | 172 | 176 | 180 | 184 | 188 | 192 | 196 | 200 | 204 | 208 | 212 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 40 | | | | | | | | | | | | | | 1 | | | | | 1 |
| 44 | 1 | | | | 2 | 2 | | | | | | | | | | 1 | | | 6 |
| 48 | | | 1 | 1 | 1 | 2 | 1 | 3 | 3 | 2 | 2 | 1 | 1 | 1 | | | | 1 | 20 |
| 52 | | 1 | 1 | 2 | 2 | 7 | 3 | 3 | 5 | 1 | | | | | | | 1 | | 26 |
| 56 | | | | 1 | 2 | 1 | | | | 1 | 2 | 1 | | | | | | | 8 |
| 60 | | | | | | | | | 1 | | | | | | | | | | 1 |
| | 1 | 1 | 2 | 4 | 7 | 12 | 4 | 6 | 9 | 4 | 4 | 2 | 1 | 2 | 0 | 1 | 1 | 1 | 62 |

Length—Mean, 171.548 ± 1.188μ
St. Dev., 13.848 ± .840μ
Coef. Var., 8.072 ± .492

Breadth—Mean, 50.388 ± .308μ
St. Dev., 3.584 ± .216μ
Coef. Var., 7.111 ± .433

Mean Index, 29.583 per cent.; Coef. Cor., —.1136 ± .0840.

### TABLE XLIII.

*Correlation Table for Length and Breadth of Specimens in Early Stages of Fission: Constriction less than one-fourth Breadth. Lot 2.* (See Table 10, row 30.)

Length in Microns.

| Breadth in Microns. | 144 | 148 | 152 | 156 | 160 | 164 | 168 | 172 | 176 | 180 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 44 | 1 | | | | 1 | 2 | | | | | 4 |
| 48 | | | 1 | 1 | 1 | 1 | 1 | 3 | 3 | 1 | 12 |
| 52 | | 1 | 1 | 2 | 2 | 6 | 1 | 3 | 1 | 1 | 18 |
| 56 | | | | 1 | 2 | 1 | | | | 1 | 5 |
| 60 | | | | | | | | | 1 | | 1 |
| | 1 | 1 | 2 | 4 | 6 | 10 | 2 | 6 | 5 | 3 | 40 |

| | | | |
|---|---|---|---|
| Length—Mean, | 165.200 ± .936μ | Breadth—Mean, | 50.700 ± .364μ |
| St. Dev., | 8.788 ± .664μ | St. Dev., | 3.432 ± .260μ |
| Coef. Var., | 5.320 ± .402 | Coef. Var., | 6.769 ± .513 |

Mean Index, 30.765 per cent.; Coef. Cor., .1048 ± .1055.

### TABLE XLIV.

*Correlation Table for Length and Breadth of Early Stages of Fisson, in Lot 3. (Depth of Constriction less than one-fourth Breadth.)* (See Table X., row 24.)

Length in Microns.

| Breadth in Microns. | 152 | 156 | 160 | 164 | 168 | 172 | 176 | 180 | 184 | 188 | 192 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 48 | | | 1 | | | | | | | | | 1 |
| 52 | | | | | | | | | | | | 0 |
| 56 | 2 | | | | 3 | | | | 1 | | | 6 |
| 60 | | 1 | 2 | | | 1 | | | | | | 4 |
| 64 | 1 | | 3 | 2 | | 2 | | 1 | | 1 | | 10 |
| 68 | 1 | | 1 | 2 | | 3 | 2 | | 1 | | 1 | 11 |
| 72 | | | | 1 | 1 | 2 | | | | | | 4 |
| 76 | | | 1 | 3 | | | 1 | | | | | 5 |
| 80 | | | | | | | | 1 | | | | 1 |
| | 4 | 1 | 8 | 8 | 4 | 8 | 3 | 2 | 2 | 1 | 1 | 42 |

| | | | |
|---|---|---|---|
| Length—Mean, | 167.620 ± .996μ | Breadth—Mean, | 65.716 ± .706μ |
| St. Dev., | 9.564 ± .704μ | St. Dev., | 6.784 ± .499μ |
| Coef. Var., | 5.706 ± .421 | Coef. Var., | 10.322 ± .768 |

Mean Index, 39.286 per cent.; Coef. Cor., .2215 ± .0999.

### TABLE XLV.

*Correlation Table for Length of Body and Depth of Constriction in 119 Dividing Specimens of the Aurelia form, Descended from c.*
(See Lot 4. Tables VIII. and X.)

Length in Microns.

| Depth of Constriction, in Microns. | 83.3 | 86.7 | 90.0 | 93.3 | 96.7 | 100.0 | 103.3 | 106.7 | 110.0 | 113.3 | 116.7 | 120.0 | 123.3 | 126.7 | 130.0 | 133.3 | 136.7 | 140.0 | 143.3 | 146.7 | 150.0 | 153.3 | 156.7 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.3 | 1 | 1 | 1 | 5 | 3 | 10 | 11 | 6 | 9 | 3 | 1 | | 2 | 1 | | | | | | | | | | 54 |
| 6.7 | | | | 1 | | 4 | 3 | 3 | 1 | | | | | | | | | | | | | | | 12 |
| 10.0 | | | | | | 1 | | | 1 | 2 | 2 | 1 | | 1 | | | | | | | | | | 8 |
| 13.3 | | | | | | | 1 | 3 | 2 | | 2 | 2 | | | | | | | | | | | | 10 |
| 16.7 | | | | | | | | | | | 1 | 2 | 1 | | 3 | | | | | | | | | 7 |
| 20.0 | | | | | | | 1 | 1 | | 2 | 1 | 4 | 2 | 1 | 1 | | | | | | | | | 13 |
| 23.3 | | | | | | | | | | 1 | | 1 | | | 3 | | | 1 | | | | | | 6 |
| 26.7 | | | | | | | | | | | | 1 | 1 | | | 2 | 1 | | | | | | | 5 |
| 30.0 | | | | | | | | | | | | | | | 1 | | | 1 | | | | | | 2 |
| 33.3 | | | | | | | | | | | | | | | | | | | | | 1 | | 1 | 2 |
| | | 1 | 1 | 6 | 3 | 15 | 16 | 13 | 13 | 8 | 7 | 11 | 6 | 3 | 8 | 2 | 1 | 2 | 0 | 0 | 1 | 0 | 1 | 119 |

Length—Mean, 111.541 ± .797μ Depth of Constriction, Mean, 10.504μ
St. Dev., 12.898 ± .564μ St. Dev. 8.431μ
Coef. Var., 11.563 ± .512

Coef. Cor., 7862 ± .0236. Increase in length with 10μ increase in depth of Constriction, 12.027μ.

### TABLE XLVI.

*Correlation Table for Length of Body and Depth of Constriction in 63 Dividing Specimens of the Aurelia form, Descended from c.* (See Lot 5, Tables VIII. and X.)

Length in Microns.

| Depth of Constriction in Microns. | 93.3 | 96.7 | 100. | 103.3 | 106.7 | 110. | 113.3 | 116.7 | 120. | 123.3 | 126.7 | 130. | 133.3 | 136.7 | 140. | 143.3 | 146.7 | 150. | 153.3 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.3 | 1 | | 3 | | 7 | | 4 | 5 | 4 | | 1 | | | | | | | | | 25 |
| 6.7 | | | | | 1 | | 2 | 2 | 1 | 2 | 2 | | | | | | | | | 10 |
| 10. | | | | | | 1 | 2 | | | | | | | | | | | | | 3 |
| 13.3 | | | | | | | | | 2 | | | 1 | 1 | | | | | | | 4 |
| 16.7 | | | | | | | | | 1 | | | | | | | | | | | 1 |
| 20. | | | | | | | | | | | 2 | | | | | | | | | 2 |
| 23.3 | | | | | | | | | | 1 | 1 | | | | | | | | | 2 |
| 26.7 | | | | | | | | | | | | 1 | | | | 1 | | 1 | | 3 |
| 30. | | | | | | | | | | | | 2 | 1 | 1 | | 1 | | 1 | | 6 |
| 33.3 | | | | | | | | | | | | 1 | | | 2 | 1 | 1 | | 1 | 6 |
| 36.7 | | | | | | | | | | | | | | | | | | | 1 | 1 |
| | 1 | 0 | 3 | 0 | 8 | 1 | 8 | 7 | 8 | 3 | 6 | 5 | 2 | 1 | 2 | 3 | 1 | 2 | 2 | 63 |

## TABLE XLVII.

*Correlation Table for Length and Breadth of Dividing Specimens of Lot 4, in which the Depth of Constriction was Less than one-fourth the Breadth. (Aurelia form, Descendants of c.)* (See Table X., row 33.)

Length in Microns.

| Breadth in Microns. | 83.3 | 86.7 | 90. | 93.3 | 96.7 | 100. | 103.3 | 106.7 | 110. | 113.3 | 116.7 | 120. | 123.3 | 126.7 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 26.7 | 1 | | | | | | | | | | | | | | 1 |
| 30. | | 1 | 1 | 2 | 1 | 3 | 2 | 1 | | | | | | | 11 |
| 33.3 | | | | 2 | | 11 | 6 | 2 | 2 | 1 | | | | | 24 |
| 36.7 | | | | 2 | 2 | | 5 | 4 | 4 | 2 | | | | 1 | 20 |
| 40. | | | | | | | 1 | 2 | 2 | | 1 | | 1 | | 7 |
| 43.3 | | | | | | | | | 2 | | | | 1 | | 3 |
| | 1 | 1 | 1 | 6 | 3 | 14 | 14 | 9 | 10 | 3 | 1 | 0 | 2 | 1 | 66 |

| | | | |
|---|---|---|---|
| Length—Mean, | 103.737 ± .650μ | Breadth—Mean, | 34.850 ± .287μ |
| St. Dev., | 7.823 ± .379μ | St. Dev., | 3.453 ± .203μ |
| Coef. Var., | 7.541 ± .445 | Coef. Var., | 9.911 ± .587 |

Mean Index, 33.623 per cent.; Coef. Cor., .6502 ± .0479μ.

## TABLE XLVIII.

*Correlation Table for Length and Breadth of Dividing Specimens of Lot 5, in which the Depth of Constriction was Less than one-fourth the Breadth. (Aurelia form, Descendants of c.)* (See Table X., row 36.)

Length in Microns.

| Breadth in Microns. | 93.3 | 96.7 | 100. | 103.3 | 106.7 | 110. | 113.3 | 116.7 | 120. | 123.3 | 126.7 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 33.3 | 1 | | | | 2 | | | | | | | 3 |
| 36.7 | | | 1 | | | | | | | | | 1 |
| 40. | | | 1 | | 3 | 1 | | 1 | | | | 6 |
| 43.3 | | | 1 | | | | 1 | 1 | 1 | | | 4 |
| 46.7 | | | | | 2 | | 5 | 3 | 1 | 1 | 1 | 13 |
| 50. | | | | | 1 | | 2 | 2 | 1 | 1 | 2 | 9 |
| 53.3 | | | | | | | | | | | | 0 |
| 56.7 | | | | | | | | | 2 | | | 2 |
| | 1 | 0 | 3 | 0 | 8 | 1 | 8 | 7 | 5 | [illegible] | | 38 |

| | | | |
|---|---|---|---|
| Length—Mean, | 113.333 ± .850μ | Breadth—Mean, | 45.263 ± .597μ |
| St. Dev., | 7.778 ± .603μ | St. Dev., | 5.463 ± .423μ |
| Coef. Var., | 6.862 ± .533 | Coef. Var., | 12.071 ± .947 |

Mean Index, 39.903 per cent.; Coef. Cor., .6744 ± .0507.

## Table XLIX.

*Correlation Table for Length and Breadth of a Random Sample of Lot 4. (See Table 10. Aurelia form, Descendants of c. Many dividing.)*

Length in Microns.

| Breadth in Microns. | 73.3 | 76.7 | 80. | 83.3 | 86.7 | 90. | 93.3 | 96.7 | 100. | 103.3 | 106.7 | 110. | 113.3 | 116.7 | 120. | 123.3 | 126.7 | 130. | 133.3 | 136.7 | 140. | 143.3 | 146.7 | 150. | 153.3 | 156.7 | 160. | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20. | | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | 1 |
| 23.3 | | | | 1 | 1 | | 1 | | | | 1 | | | | | | | | | | | | | | | | | 4 |
| 26.7 | 1 | | | 2 | 2 | 1 | | 2 | 6 | 2 | 3 | 1 | 2 | | | | | 1 | | | | | | | | | | 23 |
| 30. | | 1 | | 2 | 2 | 1 | 5 | 6 | 5 | 6 | 7 | 6 | 6 | 1 | 1 | 2 | | 1 | | | | | | | | | | 52 |
| 33.3 | 1 | 1 | | 1 | | | | 3 | 4 | 3 | 2 | 5 | 7 | 7 | 6 | 2 | 4 | 2 | 3 | 2 | | | | | | | | 53 |
| 36.7 | | | | | | | 1 | 1 | 2 | 2 | 3 | 3 | 2 | 7 | 5 | 5 | | 2 | 4 | 1 | | 3 | | | | 1 | | 42 |
| 40. | | | | 1 | | | | | 1 | | 2 | | | 4 | 3 | 1 | 6 | 4 | 1 | 2 | 1 | 2 | | 1 | | 1 | | 30 |
| 43.3 | | | | | | | | | | | | 1 | | | 1 | | 1 | 2 | | | 1 | 1 | 3 | | | | | 10 |
| 46.7 | | | | | | | | | 1 | | | | | | | | 1 | | | | 2 | | | 1 | 2 | 1 | 1 | 9 |
| 50. | | | | | | | | | | | | | | | | | | | | | | 1 | | | | | | 1 |
| | 2 | 2 | 0 | 7 | 6 | 2 | 7 | 12 | 19 | 13 | 18 | 16 | 17 | 19 | 16 | 10 | 12 | 12 | 8 | 5 | 4 | 7 | 3 | 2 | 2 | 3 | 1 | 225 |

Length—Mean, 114.163 ± .784μ  Breadth—Mean, 34.207 ± .241μ
St. Dev., 17.443 ± .555μ  St. Dev., 5.363 ± .171μ
Coef. Var., 15.279 ± .497  Coef. Var., 15.683 ± .511

Mean Index, 30.177 per cent.; Coef. Cor., .6757 ± .0244.

## Table L.

*Correlation Table for Length and Breadth of a Random Sample of Lot 5* (Table X.). *Aurelia form; Descendants of c. 24 Hours in a Fresh Hay Infusion.*

Length in Microns.

| Breadth in Microns. | 86.7 | 90. | 93.3 | 96.7 | 100. | 103.3 | 106.7 | 110. | 113.3 | 116.7 | 120. | 123.3 | 126.7 | 130. | 133.3 | 136.7 | 140. | 143.3 | 146.7 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 36.7 | | | | 2 | 3 | 1 | 1 | | | | | | | | | | | | | 7 |
| 40. | 1 | 1 | | 3 | 1 | 3 | 3 | 1 | 1 | | | | | | | | | | | 14 |
| 43.3 | | | 1 | 2 | 3 | 1 | 6 | 2 | 2 | 3 | 2 | | | | | | | | | 22 |
| 46.7 | | | | 1 | | | 1 | | 5 | 5 | 1 | | | | | | | | | 13 |
| 50. | | | | | | | 1 | | 4 | 5 | 5 | 1 | 1 | | 1 | | | 1 | | 19 |
| 53.3 | | | | | | | 1 | | | 1 | 2 | 4 | 2 | 2 | 1 | | | | | 13 |
| 56.7 | | | | | | | | | | | | 1 | 2 | 1 | | 1 | 1 | | | 6 |
| 60. | | | | | | | | 1 | | | | 2 | | | | 1 | | | | 4 |
| 63.3 | | | | | | | | | | | | | | | | | | 1 | | 1 |
| 66.7 | | | | | | | | | | | | | | | | | | | 1 | 1 |
| | 1 | 1 | 1 | 8 | 7 | 5 | 13 | 4 | 12 | 14 | 10 | 8 | 5 | 3 | 2 | 2 | 1 | 2 | 1 | 100 |

Length—Mean, 114.033 ± .820μ  Breadth—Mean, 47.300 ± .437μ
St. Dev., 12.140 ± .580μ  St. Dev., 6.490 ± .310μ
Coef. Var., 10.646 ± .513  Coef. Var., 13.720 ± .667

Mean Index, 41.455 per cent.; Coef. Cor., .8152 ± .0226.

### Table LI.

*Correlation Table for Length and Breadth of a Random Sample of the Culture from which came the Young of Lot 6,* Table X., *after 24 hours in fresh hay infusion.* (See row 2, Table XVIII.)

Length in Microns.

| Breadth in Microns. | 156 | 160 | 164 | 168 | 172 | 176 | 180 | 184 | 188 | 192 | 196 | 200 | 204 | 208 | 212 | 216 | 220 | 224 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 44 | | 1 | | | | | | | | | | | | | | | | | 1 |
| 48 | | 2 | | 1 | | | | | | | | | | | | | | | 3 |
| 52 | | | | 3 | 2 | 1 | | 2 | | | | | | | | | | | 8 |
| 56 | 1 | | 2 | | 3 | 2 | | 1 | | | | | | 1 | | | | | 10 |
| 60 | | 1 | | | 1 | 1 | 3 | 1 | 4 | 1 | 1 | 1 | | | | | | | 14 |
| 64 | | | | 1 | 3 | 2 | 1 | 5 | 1 | 4 | | 1 | | | | | | | 18 |
| 68 | | | | | | 1 | 4 | 4 | 2 | 2 | 4 | 1 | | 1 | | | | | 19 |
| 72 | | | | | | 2 | | 3 | 2 | 1 | 2 | | 3 | | | | | | 13 |
| 76 | | | | | | | | 2 | 2 | | 1 | 1 | 2 | 1 | | | | | 9 |
| 80 | | | | | | | | | | | | 1 | | | | | | | 1 |
| 84 | | | | | | | | | 2 | | | | | | | | | 1 | 3 |
| 88 | | | | | | | | | | | | | 1 | | | | | | 1 |
| | 1 | 4 | 2 | 5 | 9 | 9 | 8 | 18 | 13 | 8 | 8 | 5 | 6 | 3 | 0 | 0 | 0 | 1 | 100 |

| | | | |
|---|---|---|---|
| Length—Mean, | 184.680 ± .848μ | Breadth—Mean, | 64.880 ± .580μ |
| St. Dev., | 12.596 ± .600μ | St. Dev., | 8.624 ± .412μ |
| Coef. Var., | 6.821 ± .327 | Coef. Var., | 13.292 ± .645 |

Mean Index or Ratio of Breadth to Length, 35.131 per cent.; Coef. Cor., .6469 ± .0392.

### Table LII.

*Correlation Table for Length and Breadth of Descendants of D, in Culture Fluid where Injurious Bacteria have Multiplied. June 25.* (See row 5, Table XVIII.)

Length in Microns.

| Breadth in Microns. | 140 | 144 | 148 | 152 | 156 | 160 | 164 | 168 | 172 | 176 | 180 | 184 | 188 | 192 | 196 | 200 | 204 | 208 | 212 | 216 | 220 | 224 | 228 | 232 | 236 | 240 | 244 | 248 | 252 | 256 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 36 | | | | | | | | | | | | | | 1 | | | | | | | | | | | | | | | | | 1 |
| 40 | | | | | 1 | | | | | 1 | | | | | | | | | | | | | | | | | | | | | 2 |
| 44 | 1 | | | | 1 | | | | 1 | 2 | 1 | 1 | 1 | 1 | | 2 | | 1 | | | | | | | | | | | | | 12 |
| 48 | | | | | | 1 | 2 | 1 | 3 | 1 | 1 | 6 | | | 1 | 3 | 2 | 1 | 1 | 1 | | | | | | | | | | | 24 |
| 52 | | | | | | | 1 | | 2 | 3 | 8 | 5 | 4 | 2 | 5 | 1 | 3 | | 1 | 1 | | | | | | | | | | | 36 |
| 56 | | | 1 | | 1 | | | | | | 4 | 1 | | 1 | 2 | 6 | 1 | 5 | 1 | 5 | 4 | 1 | 1 | 3 | 1 | 1 | | | | | 39 |
| 60 | | | | | | | 1 | | | 1 | | 2 | 1 | | 1 | 3 | 2 | | 3 | 2 | 2 | 4 | 3 | | 1 | | | | | | 26 |
| 64 | | | | | | | | | | | | | | | 1 | | | 2 | | 2 | 3 | 2 | | 2 | 1 | | 1 | | 1 | | 15 |
| 68 | | | | | | | | | | | | | | | 1 | | 1 | 2 | | 1 | 1 | 1 | 1 | 2 | 3 | 2 | | | | | 15 |
| 72 | | | | | | | | | | | | | | | | | | | 1 | 1 | | | | | | 1 | 1 | | | | 4 |
| 76 | | | | | | | | | | | | | | | | | 1 | | | | | | | | 1 | | | | | 1 | 3 |
| 80 | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | 1 |
| | 1 | 0 | 1 | 0 | 3 | 1 | 4 | 1 | 6 | 8 | 14 | 15 | 6 | 5 | 11 | 15 | 10 | 11 | 7 | 13 | 10 | 8 | 5 | 7 | 7 | 4 | 2 | 1 | 1 | 1 | 178 |

| | | | |
|---|---|---|---|
| Length—Mean, | 201.888 ± 1.147μ | Breadth—Mean, | 56.112 ± .395μ |
| St. Dev., | 22.680 ± .811μ | St. Dev., | 7.808 ± .279μ |
| Coef. Var., | 11.233 ± .407 | Coef. Var., | 13.913 ± .507 |

Mean Index or Ratio of Breadth to Length, 27.850 per cent.; Coef. Cor., .6771 ± .0274.

### Table LIII.

*Correlation Table for Length and Breadth of a Starving Culture of Descendants of D. Eleven days in small watch glass of hay infusion, not renewed.* (See row 6, Table XVIII.)

Length in Microns.

| Breadth in Microns. | 128 | 132 | 136 | 140 | 144 | 148 | 152 | 156 | 160 | 164 | 168 | 172 | 176 | 180 | 184 | 188 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 28 | | 3 | | | | 1 | 2 | | | | | | | | | | 6 |
| 32 | 1 | | 1 | 6 | 2 | 5 | 1 | 2 | | | | | | | | | 18 |
| 36 | 1 | | 2 | 6 | 7 | 2 | 4 | 3 | | | 1 | | | 1 | | | 27 |
| 40 | 1 | 1 | 1 | 1 | 2 | 4 | 6 | 1 | 2 | 3 | 1 | 1 | | | | | 24 |
| 44 | | | | 3 | 1 | 3 | 6 | | 2 | 1 | 2 | | | | | 1 | 19 |
| 48 | | | | | | | 1 | 1 | 2 | | | | | | | | 4 |
| 52 | | | | | | | | | 1 | | | 1 | | | | | 2 |
| | 3 | 4 | 4 | 16 | 12 | 15 | 20 | 7 | 7 | 4 | 4 | 2 | 0 | 1 | 0 | 1 | 100 |

| | | | |
|---|---|---|---|
| Length—Mean, | 149.360 ± .736μ | Breadth—Mean, | 38.080 ± .356μ |
| St. Dev., | 10.896 ± .520μ | St. Dev., | 5.288 ± .252μ |
| Coef. Var., | 7.296 ± .350 | Coef. Var., | 13.881 ± .675 |

Mean Index or Ratio of Breadth to Length, 25.515 per cent.; Coef. Cor., .4481 ± .0539.

### Table LIV.

*Correlation Table for Length and Breadth of Descendants of D, in a rather Ill-fed Culture.* September 15. (See row 13, Table XVIII.)

Length in Microns.

| Breadth in Microns. | 160 | 164 | 168 | 172 | 176 | 180 | 184 | 188 | 192 | 196 | 200 | 204 | 208 | 212 | 216 | 220 | 224 | 228 | 232 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 40 | | | | | | | 2 | 2 | 2 | 1 | | | | | | | | | | 7 |
| 44 | | | | 1 | | 1 | 1 | 3 | | 1 | 2 | | 2 | | | 1 | | | 1 | 13 |
| 48 | 1 | | | | | 1 | 1 | 2 | 2 | 7 | 6 | 1 | 5 | 1 | 2 | 1 | | | | 30 |
| 52 | | | | | 1 | 1 | 2 | 3 | 3 | 3 | | 2 | 4 | 3 | 3 | 3 | 4 | 3 | | 35 |
| 50 | | | | | | | 1 | 2 | 1 | | 1 | 2 | | 1 | | 1 | 1 | 2 | 1 | 13 |
| 60 | | | | | | | | | | | | | | | | | 1 | | 1 | 2 |
| | 1 | 0 | 0 | 1 | 1 | 3 | 7 | 12 | 8 | 12 | 9 | 5 | 11 | 5 | 5 | 6 | 6 | 5 | 3 | 100 |

| | | | |
|---|---|---|---|
| Length—Mean, | 202.280 ± 1.031μ | Breadth—Mean, | 49.600 ± .298μ |
| St. Dev., | 15.284 ± .729μ | St. Dev., | 4.412 ± .210μ |
| Coef. Var., | 7.556 ± .362 | Coef. Var., | 8.896 ± .428 |

Mean Ratio of Breadth to Length, 24.593 per cent.; Coef. Cor.. .4085 ± .0562.

### Table LV.

*Correlation Table for Length and Breadth of the Same Lot Shown in Table LIV., but after 48 hours in fresh hay infusion.* September 15. (See row 14, Table XVIII.)

Length in Microns.

| Breadth in Microns. | 124 | 128 | 132 | 136 | 140 | 144 | 148 | 152 | 156 | 160 | 164 | 168 | 172 | 176 | 180 | 184 | 188 | 192 | 196 | 200 | 204 | 208 | 212 | 216 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 44 | | | | | | | | 1 | | | | | | | | | | | | | | | | | 1 |
| 48 | | | | | | | | | | | | 1 | | | | | | | | | | | | | 1 |
| 52 | | | | | 1 | 1 | | 1 | 1 | | 1 | 2 | 1 | | 2 | | | | | | | | | | 10 |
| 56 | | | | | | | | | 2 | 2 | 3 | | 1 | | 1 | | 1 | | | | | | | | 10 |
| 60 | | | | | | | | 1 | 1 | 3 | 3 | 2 | 3 | 4 | 2 | 3 | 2 | | 1 | | | | | | 25 |
| 64 | | | 1 | | | | | | 3 | | 1 | 1 | 1 | | 1 | 1 | 4 | 1 | | | | | | | 14 |
| 68 | 1 | | | | | | | | | | | 3 | | 3 | 4 | 4 | 1 | 1 | 2 | | | | | 1 | 20 |
| 72 | | | | | | | | | | | 1 | 1 | | 1 | | 1 | 3 | 4 | 2 | 1 | 1 | | | | 15 |
| 76 | | | | | | | | | | | | | | | | | 1 | 1 | | 1 | | | | | 3 |
| 80 | | | | | | | | | | | | | | | | | | 1 | | | | | | | 1 |
| | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 3 | 7 | 5 | 9 | 10 | 6 | 8 | 10 | 9 | 12 | 8 | 5 | 2 | 1 | 0 | 0 | 1 | 100 |

| | | | |
|---|---|---|---|
| Length—Mean, | 175.320 ± 1.060μ | Breadth—Mean, | 63.160 ± .472μ |
| St. Dev., | 15.708 ± .749μ | St. Dev., | 7.000 ± .334μ |
| Coef. Var., | 8.959 ± .431 | Coef. Var., | 11.083 ± .535 |

Mean Ratio of Breadth to Length, 36.123 per cent.; Coef. Cor., .5376 ± .0480.

### Table LVI.

*Correlation Table for Length and Breadth of Descendants of c. August 9.* (See row 17, Table XVIII.)

Length in Microns.

| Breadth in Microns. | 100 | 103.3 | 106.7 | 110. | 113.3 | 116.7 | 120. | 123.3 | 126.7 | 130. | 133.3 | 136.7 | 140. | 143.3 | 146.7 | 150. | 153.3 | 156.7 | 160. | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 23.3 | 2 | 1 | 2 | | 1 | 1 | | 1 | 1 | | | | | | | | | | | 9 |
| 26.7 | 1 | | 1 | 5 | 1 | 3 | | 1 | | | | 1 | | 1 | | | | | | 14 |
| 30. | | | 2 | 1 | 3 | 1 | 4 | | | 1 | 1 | | | | | | | | | 13 |
| 33.3 | | | | 2 | 2 | 3 | 2 | 2 | 1 | 4 | 3 | 2 | | | | | | | | 21 |
| 36.7 | | | | | 2 | 1 | 4 | 4 | 2 | 1 | 3 | | 1 | 3 | 1 | | | | | 22 |
| 40. | | | | | | 1 | 2 | 1 | | 5 | 1 | | | | 2 | | | | | 12 |
| 43.3 | | | | | | | | | 1 | 2 | | 1 | 1 | | 1 | | | | 1 | 7 |
| 46.7 | | | | | | | | | | | | 1 | | | | | | | | 1 |
| 50. | | | | | | | | | | | | | 1 | | | | | | | 1 |
| | 3 | 1 | 5 | 8 | 9 | 10 | 12 | 9 | 5 | 13 | 8 | 5 | 3 | 4 | 4 | 0 | 0 | 0 | 1 | 100 |

| | | | |
|---|---|---|---|
| Length—Mean, | 123.666 ± .813μ | Breadth—Mean, | 33.600 ± .400μ |
| St. Dev., | 12.040 ± .573μ | St. Dev., | 5.917 ± .283μ |
| Coef. Var., | 9.736 ± .469 | Coef. Var., | 17.608 ± .865 |

Mean Ratio of Breadth to Length, 27.136 per cent.; Coef. Cor., .6528 ± .0410.

## TABLE LVII.

*Correlation Table for Length and Breadth of a Sample of the Non-Conjugants of a Conjugating Culture of Descendants of the Individual c. Flourishing culture in a large vessel. September 25, 1907.* (See row 21, Table XVIII.)

Length in Microns.

| Breadth in Microns. | 124 | 128 | 132 | 136 | 140 | 144 | 148 | 152 | 156 | 160 | 164 | 168 | 172 | 176 | 180 | 184 | 188 | 192 | 196 | 200 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 16 | | | | 1 | | | | | | | | | | | | | | | | | 1 |
| 20 | | | 1 | | | | | | | | | | | | | | | | | | 1 |
| 24 | | 2 | 1 | 1 | 2 | | | | | | | | | | | | | | | | 6 |
| 28 | 2 | | 4 | 4 | 1 | 5 | 1 | 1 | 1 | | | | | | | | | | | | 19 |
| 32 | | 1 | 3 | 2 | 1 | 3 | 3 | 3 | 3 | | 2 | 1 | | 1 | | | 1 | | | | 24 |
| 36 | | | 1 | 5 | 5 | 8 | 5 | 2 | 7 | 2 | 5 | 1 | | 1 | | | | | | | 42 |
| 40 | | | | | 2 | 3 | 2 | 9 | 5 | 7 | 3 | 1 | 5 | 4 | 2 | 3 | 1 | | | 1 | 48 |
| 44 | | | | | | | 2 | 2 | 1 | 2 | 4 | | 2 | 5 | 1 | 3 | | 2 | | 1 | 25 |
| 48 | | | | | | | 1 | 1 | 2 | | 1 | 4 | | 2 | 2 | 3 | 3 | 2 | 1 | | 22 |
| 52 | | | | | | | | | | | | 1 | | 1 | 1 | 3 | | 1 | 2 | | 9 |
| 56 | | | | | | | | | | | | | | | | | | | | 1 | 1 |
| 60 | | | | | | | | | | | | | | | | | | 2 | | | 2 |
| | 2 | 3 | 10 | 13 | 11 | 19 | 14 | 18 | 19 | 11 | 15 | 8 | 7 | 14 | 6 | 12 | 5 | 7 | 3 | 3 | 200 |

| | | | |
|---|---|---|---|
| Length—Mean, | 158.800 ± .877μ | Breadth—Mean, | 38.560 ± .353μ |
| St. Dev., | 18.384 ± .620μ | St. Dev., | 7.396 ± .249μ |
| Coef. Var., | 11.578 ± .396 | Coef. Var., | 19.176 ± .670 |

Mean Ratio of Breadth to Length, 24.244 per cent.; Coef. Cor., .7135 ± .0234.

## TABLE LVIII.

*Correlation Table for Length and Breadth of Descendants of c, Five Days after Cessation of Conjugation. Food getting scarce. September 30, 1907.* (See row 22, Table XVIII.)

Length in Microns.

| Breadth in Microns. | 100 | 104 | 108 | 112 | 116 | 120 | 124 | 128 | 132 | 136 | 140 | 144 | 148 | 152 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20 | | 1 | | | 1 | | | | | | | | | | 2 |
| 24 | 1 | | | 1 | | | | 2 | | | | | | | 4 |
| 28 | | | 4 | 5 | 1 | | 3 | | | 1 | | | | | 14 |
| 32 | | | 2 | 3 | 4 | 3 | 1 | 2 | 2 | 2 | 1 | | | | 20 |
| 36 | | | | 1 | 1 | 1 | 2 | 2 | 5 | 4 | | 1 | 2 | | 19 |
| 40 | | | | | | 1 | 1 | 1 | 3 | 5 | 10 | 6 | 2 | 2 | 31 |
| 44 | | | | | | | | | | | 4 | 2 | 1 | | 7 |
| 48 | | | | | | | | | | 1 | 1 | | 1 | | 3 |
| | 1 | 1 | 6 | 10 | 7 | 5 | 7 | 7 | 10 | 13 | 16 | 9 | 6 | 2 | 100 |

| | | | |
|---|---|---|---|
| Length—Mean, | 129.640 ± .867μ | Breadth—Mean, | 35.440 ± .400μ |
| St. Dev., | 12.848 ± .613μ | St. Dev., | 5.928 ± .283μ |
| Coef. Var., | 9.911 ± .477 | Coef. Var., | 16.730 ± .820 |

Mean Ratio of Breadth to Length, 27.262 per cent.; Coef. Cor., .7576 ± .0287.

TABLE LIX.

*Correlation Table for Length and Breadth in a Large, Old Culture of Descendants of c, January 23, 1908.* (See row 23, Table XVIII.)

Length in Microns.

| Breadth in Microns. | 100 | 104 | 108 | 112 | 116 | 120 | 124 | 128 | 132 | 136 | 140 | 144 | 148 | 152 | 156 | 160 | 164 | 168 | 172 | 176 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 32 | | | | | | 2 | | | | | | | | | | | | | | | 2 |
| 36 | | | | 1 | 3 | 1 | | | | | | | | | | | | | | | 5 |
| 40 | | | | | 1 | 1 | | 1 | 1 | 2 | | 1 | | | | | | | | | 7 |
| 44 | | | | | | | 2 | 2 | 3 | 1 | 1 | | | | | | | | | | 9 |
| 48 | 1 | | | | | 1 | | 1 | 2 | 4 | 2 | 7 | | 1 | | | | | | | 19 |
| 52 | | | | | | | | | 1 | 1 | 2 | 1 | 3 | 1 | | 1 | | | | | 10 |
| 56 | | | | | | | | | 1 | 1 | 2 | 1 | 1 | 5 | | 2 | 1 | | | | 14 |
| 60 | | | | | | | | | | | | 2 | 2 | 1 | 1 | 3 | 1 | | | | 10 |
| 64 | | | | | | | | | | | 1 | 1 | 1 | 1 | | 1 | 2 | 1 | | | 8 |
| 68 | | | | | | | | | | | | | | | 1 | | 2 | | 3 | | 6 |
| 72 | | | | | | | | | | | | | | | | | 1 | 2 | 1 | | 4 |
| 76 | | | | | | | | | | | | | | | 1 | 1 | | | 2 | | 4 |
| 80 | | | | | | | | | | | | | | | | | | | | | 0 |
| 84 | | | | | | | | | | | | | | | | | | 1 | | 1 | 2 |
| | 1 | 0 | 0 | 1 | 4 | 5 | 2 | 4 | 8 | 9 | 8 | 13 | 7 | 9 | 3 | 8 | 7 | 4 | 6 | 1 | 100 |

Length—Mean, 144.880 ± 1.097μ Breadth—Mean, 54.160 ± .765μ
St. Dev., 16.264 ± .776μ St. Dev., 11.346 ± .541μ
Coef. Var., 11.224 ± .542 Coef. Var., 20.948 ± 1.042

Mean Ratio of Breadth to Length, 37.106 per cent.; Coef. Cor., .8500 ± .0187.

TABLE LX.

*Correlation Table for Length and Breadth of Descendants of c. Same Culture shown in Table LIX, but cultivated in small watch glass, January 30 to February 15, 1908.* (See row 27, Table XVIII.)

Length in Microns.

| Breadth in Microns. | 76 | 80 | 84 | 88 | 92 | 96 | 100 | 104 | 108 | 112 | 116 | 120 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 16 | | | 1 | | | | | | | | | | 1 |
| 20 | 1 | | | 6 | 2 | 3 | 1 | | | | | | 13 |
| 24 | | | 2 | | 6 | 11 | 6 | 3 | 2 | | | | 30 |
| 28 | | | | | 3 | 1 | 11 | 11 | 11 | 1 | 1 | | 39 |
| 32 | | | | | | | 3 | 5 | | 4 | 1 | | 13 |
| 36 | | | | | | | | | 1 | 2 | | 1 | 4 |
| | 1 | 0 | 3 | 6 | 11 | 15 | 21 | 19 | 14 | 7 | 2 | 1 | 100 |

Length—Mean, 100.320 ± .528μ Breadth—Mean, 26.480 ± .266μ
St. Dev., 7.828 ± .373μ St. Dev., 3.944 ± .188μ
Coef. Var., 7.804 ± .374 Coef. Var., 14.895 ± .753

Mean Ratio of Breadth to Length, 26.321; Coef. Cor., .7671 ± .0278.

### Table LXI.

*Correlation Table for Length and Breadth of a Random Sample of the "Wild" Conjugating Culture M, January 29, 1908. 200 Non-conjugants, 38 Conjugants.*

Length in Microns.

| Breadth in Microns. | 132 | 136 | 140 | 144 | 148 | 152 | 156 | 160 | 164 | 168 | 172 | 176 | 180 | 184 | 188 | 192 | 196 | 200 | 204 | 208 | 212 | 216 | 220 | 224 | 228 | 232 | 236 | 24 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 28 | | | | | | | | | 1 | | | | | | | | | | | | | | | | | | | | 1 |
| 32 | | | | 1 | | | | | | | | | 2 | | | | | | | | | | | | | | | | 3 |
| 36 | | 1 | | | | 1 | 3 | | 3 | | 1 | 1 | 1 | | | | | | | | | | | | | | | | 11 |
| 40 | | | | | 2 | | 2 | 2 | 7 | 4 | 4 | 5 | 1 | 2 | | 1 | 1 | | | | | | | | | | | | 31 |
| 44 | | | | | | 1 | 2 | 1 | 5 | 6 | 7 | 5 | 4 | 1 | 2 | 6 | 2 | 1 | 2 | 1 | | | 1 | | | | | | 47 |
| 48 | 1 | | | | 1 | 1 | | 3 | 1 | 4 | 5 | 5 | 6 | 2 | 6 | 7 | 1 | 5 | 2 | 1 | | 1 | | | | | | | 52 |
| 52 | | 1 | | | | | | 1 | 1 | 5 | 2 | 4 | 3 | 1 | 2 | 5 | 6 | 1 | 4 | 3 | | | | | 1 | | | | 40 |
| 56 | | | | | | | | | | | | | 1 | 3 | 2 | 4 | 1 | 1 | 1 | | 3 | 2 | | | | | | | 18 |
| 60 | | | | | | | | | | | | 2 | | | | | 2 | | | | | | | | | | | | 4 |
| 64 | | | | | | | | | | | | | | | | 2 | 2 | 1 | 1 | 2 | | | 1 | | | | | 1 | 10 |
| 68 | | | | | | | | | | 1 | | 2 | | | 3 | | 2 | 1 | | | 1 | | | | 1 | | | | 11 |
| 72 | | | | | | | | | | | | | | | | 1 | | | | | | | 1 | | | | | | 2 |
| 76 | | | | | | | | | | | | | | | 2 | | | 1 | | 1 | | | | | | | | | 4 |
| 80 | | | | | | | | | | | | | | | | | 1 | | | | 1 | | | | | | | | 2 |
| 84 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 0 |
| 88 | | | | | | | | | | | | | | | | | | 1 | | | | | 1 | | | | | | 2 |
| | 1 | 2 | 0 | 1 | 3 | 3 | 7 | 7 | 18 | 20 | 19 | 24 | 18 | 9 | 17 | 26 | 18 | 12 | 10 | 8 | 5 | 3 | 4 | 0 | 2 | 0 | 0 | 1 | 238 |

### Table LXII.

*Correlation Table for Length and Breadth of Dividing Specimens of Lot 1 (Table X.), in which Lengthening had begun. (Constriction more than 4 microns deep.)*

Length in Microns.

| Breadth in Microns. | 160 | 164 | 168 | 172 | 176 | 180 | 184 | 188 | 192 | 196 | 200 | 204 | 208 | 212 | 216 | 220 | 224 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 40 | | | | | 2 | | | | | | 1 | | 1 | | | | 1 | 5 |
| 44 | 2 | 1 | | 3 | 2 | | | 2 | 5 | 2 | 4 | 2 | 2 | 3 | 1 | | 1 | 30 |
| 48 | | 2 | 10 | 9 | 5 | 7 | 8 | 8 | 8 | 4 | | 3 | 2 | | 3 | 2 | | 71 |
| 52 | | 2 | 2 | 10 | 10 | 4 | 12 | 2 | 2 | 4 | 1 | 1 | | | 1 | | | 51 |
| 56 | | | | | 3 | 4 | 2 | | 1 | 1 | 3 | 3 | 1 | | | | | 18 |
| 60 | | | | | 1 | 1 | | 3 | | 1 | | | | | | | | 6 |
| 64 | | | | | | | | | | | | | | | | | | 0 |
| 68 | | | | | | | | | | | | | | | 1 | | | 1 |
| | 2 | 5 | 12 | 22 | 23 | 16 | 22 | 15 | 16 | 12 | 9 | 9 | 6 | 3 | 6 | 2 | 2 | 182 |

| | | | |
|---|---|---|---|
| Length—Mean, | 186.066 ± .710μ | Breadth—Mean, | 49.540 ± .215μ |
| St. Dev., | 14.208 ± .502μ | St. Dev., | 4.296 ± .152μ |
| Coef. Var., | 7.636 ± .271 | Coef. Var., | 8.671 ± .309 |

Mean Ratio of Breadth to Length, 26.796 per cent.; Coef. Cor., —.0938 ± .0496.

### Table LXIII.

*Correlation Table for Length and Breadth of Dividing Specimens of the Aurelia Form (Descendants of c), in which Lengthening had begun.*

(See Lot 4, Tables VIII. and X.)

Length in Microns.

| Breadth in Microns. | 100. | 103.3 | 106.7 | 110. | 113.3 | 116.7 | 120. | 123.3 | 126.7 | 130. | 133.3 | 136.7 | 140. | 143.3 | 146.7 | 150. | 153.3 | 156.7 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 26.7 | | | 1 | | 1 | | | | | 1 | | | | | | | | | 3 |
| 30. | | | 1 | 1 | 1 | 1 | | 2 | | 2 | 1 | | 1 | | | | | | 10 |
| 33.3 | 1 | 1 | 2 | 2 | 2 | 2 | 4 | 1 | | 1 | 1 | 1 | | | | | | | 18 |
| 36.7 | | 1 | | | | 3 | 5 | | | 2 | | | | | | | | | 11 |
| 40. | | | | | 1 | | 2 | 1 | | 2 | 1 | | | | | 1 | | 1 | 9 |
| 43.3 | | | | | | | | | 1 | | | | | | | | | | 1 |
| 46.7 | | | | | | | | | | | | | 1 | | | | | | 1 |
| | 1 | 2 | 4 | 3 | 5 | 6 | 11 | 4 | 1 | 8 | 3 | 1 | 2 | 0 | 0 | 1 | 0 | 1 | 53 |

| | | | |
|---|---|---|---|
| Length—Mean, | 121.383 ± 1.053μ | Breadth—Mean, | 34.590 ± .383μ |
| St. Dev., | 11.367 ± .743μ | St. Dev., | 4.147 ± .273μ |
| Coef. Var., | 9.365 ± .613. | Coef. Var., | 11.989 ± .797. |

Mean Ratio of Breadth to Length, 28.648 per cent.; Coef. Cor., .3100 ± .0837.

## CONTENTS.

# ON THE MORPHOLOGY OF THE EXCRETORY ORGANS OF METAZOA: A CRITICAL REVIEW.

BY THOS. H. MONTGOMERY, JR.

(*Read April 24, 1908.*)

The desire to acquaint myself with modern ideas as to the homologies of the excretory organs has led to the present review. These organs constitute a chapter in comparative anatomy that is one of the most compendious and intricate of all. Their relations are so broad and manifold that no morphologist can go far without touching upon them, and one need not wonder at this because their function is above all others necessary to the continuance of the life of the individual.

Among those who have contributed largely to this subject are Balfour, Bergh, Bürger, Cuénot, Eisig, Goodrich, Hatschek, Lang, Eduard Meyer, Sedgwick and Vejdovský, but the bibliography shows how many well-known investigators have added to our knowledge. There is a wealth of accumulated facts that have never been treated critically in their entirety, and on that account the present bringing together of them may be of help to future students.

This memoir is divided into two portions: (*A*) a descriptive one, in which the groups of Metazoa and their particular excretory organs are treated in succession; and (*B*) a comparative one, in which all the excretory organs are reduced to certain types, and then the homologies of these discussed. It is in this second part that a standpoint is reached different, so far as I know, from previous ones, one that I hope puts the facts in a clearer light.

## A. DESCRIPTIVE.

The following is a brief summary of our knowledge of the general structure and embryogeny of special excretory organs considered separately for each group. Histological details are not entered upon. I have endeavored to consult all the more important literature up to 1907, but at the same time to refer in the citations to only the more comprehensive accounts; the literature references therefore do not by any means represent complete bibliographies, but refer the reader to the more important memoirs.

The Orthonectida, Dicyemida, Cnidaria and Porifera lack special excretory organs; and such structures are still unknown for *Cephalodiscus, Rhabdopleura,* the Chaetosomatidæ, Desmoscolicidæ, and Pentastomida.

### 1. CTENOPHORA.

Here there are short, presumably entoblastic, canals that connect the aboral canal (funnel canal) of the gastro-vascular cavity with the aboral surface of the body; there may be two or four of these openings; these discharge injected carmine, while there is no evidence that water is taken in through them (Chun, 1880).

### 2. PLATHELMINTHES.

These possess branching, tubular organs whose finest branches (capillaries) have intracellular cavities and terminate in closed flame cells, the latter being very small and numerous. Nothing is known as to their embryonic origin, except the one observation of Lang (1884) that in Polyclades a pair of solid ingrowths of the ectoblast seems to represent their beginnings. The main structural variations are with regard to the number, ramification and degree of anastomosis of the main canals, and the number and position of nephridiopores and excretory canals.

#### (1) *Turbellaria.*

*Polycladidea.*—Discovered by Max Schultze (1854) these organs have received subsequent description only by Lang (1884), who found that the terminal flames are unicellular and who could trace the supposed excretory canals of *Thysanozoon* to the dorsum, but could not find their openings there. Accordingly, a complete knowledge of their structure is still a desideratum. I have not been able to find them on sectioned material.

*Rhabdocœlida.*—Here they appear to be absent only in the

Acœla. Three chief types have been distinguished (v. Graff, 1882): a single main canal with a single nephridiopore (*Stenostoma*); a pair of main canals with independent nephridiopores, and a pair of main canals with a common nephridiopore. In *Bothrioplana* (Vejdovský, 1895) there are two pores different in structure, one at the middle and the other at the anterior end of the body; into the former open two main canals, each of the latter divides into an anterior and a posterior branch, and these anterior branches connect also with the anterior nephridiopore. In the Eumesostomina (Luther, 1904) the main canals open independently either on the surface of the body, or into the mouth, or into the genital atrium (all these being ectoblastic), and besides the terminal flame cells there are other flames (without nuclei) interpolated in the course of the canals. In these forms there is never more than one pair of main canals, or more than two nephridopores.

*Tricladidea.*—In *Planaria* but more specially *Gunda* Lang (1881) described two main ducts on each side of the body, each bearing numerous capillaries ending in flame cells; there are anastomoses between the former but not between the latter; from each main duct proceeds a series of excretory ducts each of which opens dorsally by a small contractile vesicle. And Böhmig (1906) adds to this account of *Gunda* by the discovery of four pairs of main canals, and of ventral as well as dorsal nephridiopores. In *Dendrocœlum* Ijima (1885) found similar relations, though he held there to be but one main canal on each side; while Wilhelmi (1906) found two of them with a segmental arrangement of eight pairs of excretory ducts, and (in opposition to the earlier observations of Chichkoff) no openings into the pharynx. The Tricladidea differ from the Rhabdocœlida in the presence of numerous serial excretory ducts.

### (2) *Trematoda.*

The chief characteristic of the excretory organs is their dendritic branching and their degree of anastomosis. In the Monogenea there are usually paired nephridiopores (in *Gyrodactylus* a single one) placed in most cases at the anterior end but sometimes at the posterior. The excretory vesicle of the Digenea is at the posterior end, terminal or dorsal, and into it open usually two but sometimes four or even six main canals (Braun, 1893). In the larva (miracidium) of *Distomum* there is a single large flame cell on each side of the body with a capillary opening on the surface (Coe, 1896). Bugge (1902) has shown that each flame cell and its capillary "develop out of one cell and are to be compared with a unicellular gland," a practical confirmation of Lang's (1884) suggestion.

### (3) *Temnocephaleæ.*

The excretory system of these curious forms has been made known particularly by Weber (1889). There is a pair of separated dorsal nephridiopores, each communicating with main canals that branch and anastomose with those of the opposite side, so that the general arrangement is like that of the Trematoda.

### (4) *Cestoda.*

Here the main canals have no dendritic branching but frequent anastomoses, so that quite generally each proglottid has one or two pairs of transverse canals connecting the main lateral ones; the main lateral canals open by a common contractile vesicle at the posterior end of the ripest proglottid (Pintner, 1896). In the most detailed contribution on the subject (Bugge, 1902) muscle fibrils of the main canals are described and also valves within them (the latter discovered by Köhler in 1894); in the cysticercus stage foramina secondaria were found connecting the main canals with the surface of the body. Bugge uses the term "Wimperflamme" to include the "Terminalzelle" ("Geisselzelle, Deckzelle"), with the "Wimper" and "Trichter" and "Capillare." He traced such Wimperflammen as outgrowths from the walls of the main canals: a cell of the latter projects outwards then divides into a group of four; of these four one forms three Trichter and the capillary (the cavities of these parts being intracellular), while each of the three others becomes a flame cell with a ciliary flame.

Anatomically considered there are two main kinds of excretory organs in the Platyhelminthes: (1) with numerous serial excretory canals, found only in the Tricladidea; and (2) with only one or two excretory canals, found in all the others (though the relations are not yet known for the Polyclades).

### 3. NEMERTINI.

From the comprehensive treatment given by Bürger (1895), based largely upon his own researches, it follows that the excretory organs are as a rule in the form of two main canals parallel with the lateral blood vessels and not communicating together; each opens to the exterior of the body by one, or more rarely by a series of several (up to about forty), excretory ducts; the main canals are usually restricted to the region of the stomach, but in some genera they extend the length of the body. From them proceed delicate capillaries that terminate blindly in multicellular "Endkölbchen"; the latter may project into the walls of blood vessels, but (contrary to the earlier opinion of Oudemans) there is no open communication of any portion of the nephridia with these vessels or other internal cavities. In the freshwater *Stichostemma* I showed (1897) that an unusual condition obtains, in that in the adult instead of a single canal on each side there is a series of them, some with and some without excretory canals; and then Böhmig (1898) demonstrated that the latter are produced by a secondary segmentation of originally continuous ducts.[1] Punnett (1900) and Coe (1906) found in *Tæniosoma* besides excretory pores opening on the surface of the body others that connect with the œsophagus; the latter are clearly embryonic ducts persisting in the adult.

The larvæ do not possess special excretory organs. The definitive ones arise, according to Bürger, as a pair of hollow evaginations of the ectoblastic stomodæum of the larva, soon abstrict from the œsophagus and then open into the amniotic cavity at a ventral point near the mouth, a position quite different from that of the adult excretory pores. The origin of the latter is not known, and

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[1] I had described the terminal bulbs of this genus as closed from the capillaries, with an internal cuticular lining but no flame, while Böhmig found them essentially as described by Bürger except that each consists of usually not more than two cells. I have recently had opportunity to examine living material and to compare it with my former sections, and find I had overlooked the true flame cells and that Böhmig had described them correctly. Each terminal bulb consists of from one to five cells.

Bürger suggests they may either be secondary invaginations of the epidermis, " or the nephridium itself must break a new way through the body wall. Judging from the adult animal the first alternative must be the case."

### 4. GASTROTRICHA.

There is a single pair of much convoluted tubules, lateral from the intestine, opening near each other on the ventral surface without excretory vesicles. Each ends internally with a single closed bulb, but it is not determined whether it contains a single flagellum or a row of cilia (Zelinka, 1889).

### 5. ROTATORIA.

The excretory organs have been most carefully described for the Philodinidæ (Zelinka, 1886, 1888, 1891, Plate, 1889), Flosculariidæ (Montgomery, 1903, Gast, 1900), Melicertidæ (Hlava, 1904, 1905), Atrochidæ (Wierzejski, 1893) and Asplanchnidæ (Hudson and Gosse, 1886, Rousselet, 1891, Weber, 1898). There is always a right and left main canal; the flame cells may be directly attached to these (most Philodinidæ), but more usually are placed at the ends of capillaries, branches of a main capillary that open into the main canal at one or two points. The number of flame cells on eash side of the body is small, usually from three to six, and in that case they are relatively large; but in the Asplanchnidæ there are some fifty of them on each side sessile on a main capillary. Their great number here may be due to the large size of these species. The main canals unite posteriorly into a short unpaired duct that opens into the cloaca; and anteriorly they are usually connected by a transverse commissure (absent in some Philodinidæ). The main canals have an intracellular cavity, are composed of a few cells and are usually without cilia; terminal flame and capillary is a single cell, the termination of which is entirely closed from the body cavity and contains an internal flame of cilia and (in *Asplanchna*) has a couple of long flagella on the outer surface.

The early development of these structures has not been determined (Zelinka, 1891).

### 6. Endoprocta.

Joliet (1880) described for *Pedicellina* and *Loxosoma* a pair of short ciliated canals with a common nephridiopore, and with their inner ends open to the body cavity. Prouho (1890) leaves the question unsettled whether these ends are open or closed. All other observers describe the inner termination of each canal as closed by a flame cell: so Foettinger (1887) and Ehlers (1890) for *Pedicellina,* Harmer (1885, *Loxosoma*), and Davenport (1893, *Urnatella*). The cavity of these canals is intracellular, and only in *Loxosoma* are there paired nephridiopores.

Besides this "Chief excretory apparatus" Davenport found in the stalk of *Urnatella* "elongated spaces terminating blindly at one end in structures which must be regarded as flame cells . . . I have not, however, been able in any instance to trace an individual tubule to any considerable distance, or until it opens into any other organ."

Accordingly, all Endoprocta seem to have a pair of nephridia internally closed that do not serve as genital ducts, and in one genus flame cells seem to occur in the stalk.

In regard to their development, Hatschek (1877) found in the full-formed larva of *Pedicellina* a pair of ciliated canals like those of the adult, but did not determine either their structure or origin. It would seem probable that this excretory organ persists in the adult.

### 7. Rhodope.

For this curious form that has been variously related to the Turbellaria and the opisthobranch mollusks, Böhmig (1893) described a nephridiopore on the right side just anterior to the anus, into which opens a "Urinkammer"; into the latter discharge ramified ducts, and to each of these are attached about forty flame-bearing terminal organs, each completely closed from the body cavity and consisting of from four to eight cells. Nothing is known of the development.

### 8. Acanthocephala.

The excretory organs of this group are known only from the observations of Kaiser (1892, 1893). They occur only in the large *Echinorhynchus gigas* and seem to be absent in the smaller species (I also have looked for them in vain in a number of American species). In the female there is a pair of them discharging into the oviduct; each is a broad spade-shaped organ composed of three cells, the free end branched dendritically, each finest subdivision of which terminates in a perforated membrane bearing on the luminal side a tuft of long cilia; there are about five to six hundred of these terminal flames to each nephridium, though the whole organ it will be recollected is composed of only three cells. The Acanthocephala are specially characterized by the small number but great degree of specialization of their cells. In the male the nephridia open into the ductus ejaculatorius, and are similar to those of the female save that the terminal flames are less numerous. Kaiser supposes that in the smaller species lacking these organs the oviduct is excretory, since in them the uterus bell is open to the body cavity.

They arise conjointly with the genital ducts from the ectoblast.

### 9. CHÆTOGNATHA.

No excretory organs were found by Hertwig (1880), while Grassi (1883) suggests that a pair of small glands opening at the junction of the head and prepuce may be urinary.

The genital ducts are not comparable with nephridia because they do not develop until maturity, and because the vasa deferentia are ectoblastic and the oviducts are outgrowths of the ovaries (Doncaster, 1902).

### 10. KINORHYNCHA.

The genus *Echinoderes* exhibits one pair of short, pyriform canals, ciliated throughout, with enlarged closed inner ends, that open separately and dorso-laterally (Reinhard, 1887).

### 11. NEMATODA.

As first made known by Anton Schneider (1866) and confirmed by most subsequent writers there is usually an excretory duct in each lateral line (though one may be wanting) that extend from the posterior region of the body to the œsophagus, where they converge and open by a single median nephridiopore. The inner ends of these canals are closed, and each is lined by a cuticula. Four types of these have been distinguished according to their form and position of the nephridiopore (Jägerskiöld, 1898). A more careful description has been furnished by Goldschmidt (1906) for *Ascaris lumbricoides,* who found that the whole apparatus is composed of but two cells, with a single nucleus for both main canals and one for the anterior unpaired duct. Goldschmidt further considers these canals to be simply for discharge, and that a peculiar solid tissue of the lateral lines is the true secretory portion; these glandular masses are multinuclear and do not touch the walls of the canals, but fine pores appear to extend towards them from the lumina of the canals. In his own words: "The excretory system of *Ascaris* . . . consists of the excretory gland proper (analogous to a kidney) that lies within the lateral lines, and of the discharge duct (analogous to a ureter) that consists of two horseshoe-shaped limbs composed of a single cell and of an unpaired terminal portion represented by one cell."

Little is known of the development of these canals. They lie within the lateral lines, and Zur Strassen (1892) has shown that the latter are mesoblastic. Conte (1902) found the excretory apparatus to arise from a single mesoblast cell that becomes secondarily placed in the lateral line.

## 12. GORDIACEA.

For this group specific excretory organs are still unknown, though it has received much study. Vejdovský (1886, 1894) has interpreted the peri-intestinal cavity as excretory, but this has no opening to the exterior; and he has suggested that the oviducts and vasa deferentia are modified nephridia,—a conclusion drawn from his idea that the Gordiacea are degenerate annelids, a standpoint that has been combated by me (1903*a*). In late embryonic stages he found a "braune Drüse" opening into the intestine near the mouth; this is not found in the adult, unless the problematical supra-intestinal orgon described by me for *Paragordius* may be an excretory organ conveying fluids from the peri-intestinal space to the intestine. It is probable that excretion must take place through either the genital ducts or the intestine, since the thick cuticula on the surface of the body is hardly permeable.

The gland of the larva construed by Villot (1874) as an excretory organ has been considered by me (1904) to be rather a poison gland; I have shown that its body develops as an abstriction of the entoblast, and that its duct opens at the base of the proboscideal stilets; it is completely closed from the body cavity and does not possess cilia.[2]

### 13. Ectoprocta.

For the Phylactolæmata the fullest description is that of Cori (1893, *Cristatella*), according to whom there is a nephridium just above the anus, between the body wall and the peritoneum, consisting of two ciliated nephrostomes opening into the cœlom, connecting with an enlarged sac that has a single nephridiopore near the cerebral ganglion. He proved experimentally that lymphocytes ingest waste particles, and then are discharged by this organ.

In the Gymnolæmata there is in some species an organ discovered by Hincks (1880), and more fully described by Prouho (1892) who names it the "organe intertentaculaire"; this occurs only in sexual individuals, is primarily a genital duct, and is a ciliated canal with an inner nephrostome. In most Gymnolæmata special excretory organs are absent (Ostroumoff, 1886, Harmer, 1891). Harmer concludes from injection experiments that excretion is performed "partly by the cells which I have described as leucocytes, partly by the walls of the alimentary canal, and partly by the funicular tissue," while he and Ostroumoff have proved that the formation of the "brown body" and the death of the polypid is due to an accumulation of waste substances especially in the intestine.

The larvæ lack excretory organs, and the development of those of the adult has not been described.

### 14. Sipunculida.

There are as a rule two "excretory tubes," but within the same genus either two or one may occur. In most cases each of these has

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[2] In the marine *Nectonema,* that shows some similarity to the diplobiotic Gordiacea, excretory organs are unknown.

a nephridiopore on the ventral surface of the body, and a ciliated nephrostome placed at the inner end of the tube or else near the external opening. But in *Sternaspis* Goodrich (1897) found no nephridiopores, and in an immature individual of *Phascolosoma proki* Sluiter (1882*b*) found no nephrostomes. In all cases these serve as genital ducts. Metalnikoff (1900), in the most detailed memoir, concludes that the nephrostome cannot serve excretion but acts merely to swallow the germ cells, while excretion must be accomplished by osmosis through the wall of the organ that is lined by cells resembling the chloragogue of annelids. Goodrich holds these are not true nephridia, but " peritoneal funnels peculiarly modified."

The embryological data are conflicting. In *Phascolosoma* Gerould (1906) found no excretory organs in the trochophore, and in the " larva " (that succeeds the trochophore) the definitive nephridia arise as solid ectoblastic ingrowths (" a pair of ingrowths, probably of ectoderm "), to which are added funnels of mesoblastic origin. In *Sipunculus* Hatschek (1883) described a pair of " Nierenzellen " in the mesoblast of the embryo; each of these divides into four cells which acquire an intracellular cavity, then one end of each cell cord becomes attached to the ectoblast while the other opens into the cœlom. Gerould's account is the much more detailed and thorough, and renders it probable that both ectoblast and mesoblast enter into these nephridia. The trochophore lacks nephridia.

### 15. PRIAPULIDA.

For these animals we have only the brief description of Schauinsland (1886), unaccompanied by figures. From each side of the posterior end there is said to invaginate a pair of ectoblastic tubes. Then a series of short excretory tubules grow out from the walls of these; the " Endorgane " are multicellular, closed from the body cavity, each cell with a long flagellum. Still later other folds evaginate from the walls of the main ducts, and their cells become the reproductive elements. According to this description this would be a unique ectoblastic organ, not unlike that of the Plathelminthes, that proliferates germ cells.

### 16. PHORONIDEA.

In the adult just behind the transverse septum Cori (1890) found a pair of ciliated canals with open nephrostomes, and determined that their function is both genital and urinary. In *Phoronis australis* Benham (1889) found that each tube has two nephrostomes, and a similar relation was discovered by Cowles (1905).

There is quite general agreement that the larval nephridia are ectoblastic (Ikeda, 1901, Longchamps, 1902, Shearer, 1906, Cowles, 1905); from a nephridial pit at the posterior end grow out the two canals whose cavity is intercellular. The observers already cited together with Caldwell (1882) and Goodrich (1903), in contradiction to Masterman (1897), agree further that the nephridia of the actinotrocha are closed at their inner ends from the blastocoel in which they lie; and Shearer, who gives the most complete account of the development of these structures, shows that their inner ends are closed by a group of solenocytes that represent outgrowths from the tubes. Longchamps states that these larval organs persist into the adult; this is assumed by Shearer who decides that these canals "acquire openings into the cœlom by means of ciliated funnels of unknown origin"; while Ikeda concludes: "We may assume that the formation of the infraseptal nephridial funnels of the adult is due to secondary outgrowths of the infraseptal portion of the atrophied, larval nephridial canals." The only point not fully decided is that of the origin of the funnels.

### 17. BRACHIOPODA.

According to the monographs of Van Bemmelen (1883), Blochmann (1900) and Morse (1902) there is usually one pair of supposed excretory organs, with nephrostomes and nephridiopores, that serve as genital ducts; in *Hemithyris* and *Rhynchonella* there are two pairs.

Nothing is known of their development, and there appear to be no larval nephridia.

### 18. ECHINODERMATA.

*Crinoidea.*—Special excretory structures are unknown.

*Echinoidea.*—The axial organ (ovoid gland) has been considered an excretory organ (Hamann, 1887, Sarasin, 1888, Ludwig, 1889) and proved to be so by carmine injection (Kowalevsky, 1889), while to it has also been ascribed the function of producing cœlomic cells (Leipoldt, 1893). It is a slender axial sac, the oral end of which ends blindly, opening by a delicate canal under the madreporite close to the stone canal; it is composed of a meshwork of trabeculæ of connective tissue, covered internally by an epithelium, in the meshes of which lie amœboid cells (Ludwig). Hamann described its cavity as communicating with blood lacunæ and the Sarasins as connecting with the body cavity by nephrostomes, but these results have not been confirmed and the bulk of evidence points to its being closed from other body cavities.

*Ophiuroidea.*—Here both respiration and excretion take place osmotically through the walls of the genital bursæ (Cuénot, 1888).

*Asteroidea.*—By injection Kowalevsky (1889) found that the bodies of Tiedemann are the excretory organs of the ambulacral system. Cuénot (1901) distinguished (1) amœbocytes, floating cells in the cœlom, blood vessels and ambulacral system, that are first phagocytic, and when they become laden with excretory products leave the organism by passing through the walls of the gill sacs; and (2) nephrocytes. Of the latter he distinguished: those that take up indigo (epithelium of the intestinal cæca), and those that ingest carmine (peritoneum, epithelia of perihæmal spaces and ambulacral vessels, inner cells of septal organs).

*Holothurioidea.*—In the Synaptids the "ciliated funnels" have been proved to collect waste products, by their ciliary action and agglutinating secretion; such products and amœbocytes loaded with them become caught in these organs, and ultimately make their way through the solid tissues to become deposited beneath the skin (Schultz, 1895, Cuénot, 1902). These funnels are generally arranged in rows on either side of the mesenteric radix, and project into the cœlom either separately or in groups. Each is a somewhat spoon-shaped, flattened prominence, with a concave ciliated surface, attached to the wall of the cœlom by a slender stalk, both plate and stalk being composed of solid connective tissue covered by peritoneum. Thus they are really not funnels at all, but solid projections into the body cavity, and cannot in any way be compared with the peritoneal funnels (peritoneal evaginations) of other forms. In the Pedata the respiratory trees have been considered as in part excretory (Schultz, 1895); and the organs of Cuvier, tubes that also open into the cloaca behind the preceding, have been regarded as excretory by Hérouard (1893), but it is proven that these are rather eversible defensive structures (Minchin, 1892, Russo, 1889).

The ambulacral system of the echinoderms seems to mainly subserve locomotion, respiration and nutrition; but the bodies of Tiedemann, as mentioned above, that occur in it are excretory, and the Polian vesicle in holothurians may contain an "irregular non-living mass of brown spherules" which may be waste substances derived from the brown wandering cells occurring elsewhere in this system (Gerould, 1896).

The larvæ lack nephridia, and there appear to be no organs in this group comparable with excretory organs in others. The only representatives of peritoneal funnels are ciliated evaginations from the embryonic hydrocœl that join secondarily with ectoblastic invaginations; there is usually only one of these and it persists as the stone canal, but there may be two; Field (1892) compared the enterocœls with nephridia that have secondarily come into the service of locomotion.

There is little known of the development of the genital organs of Holothurioids. In Asteroids they have been described as coming from a solid mesenchyme mass that invaginates the peritoneum; only in Echinoids is the gonad stated to be peritoneal, a proliferation of cells of the left posterior enterocoel. Accordingly, there is no evidence that the gonads or their ducts stand in relation to nephridia.

## 15. TUNICATA.

Special organs of excretion fail in the Appendiculariæ (Seeliger, 1893), and I have not found them described for the Doliolidæ. For other forms Dahlgrün (1901) has distinguished the following kinds: (1) Scattered excretory cells, in the visceral region (in *Botryllus, Botrylloides, Polycyclus, Ciona, Salpa*); (2) vesicles, rather numerous in the connective tissue, each with a wall formed of prismatic cells and with fluid or solid contents (*Ascidiella,* *Ascidia*); (3) sacs, less numerous, on both sides of the body below the mantle, with walls of cubical cells (*Cynthia, Microcosmus*); and (4) renal organs, a single voluminous sac on the right side of the body with epithelial wall (*Molgula*). Todaro (1902*a, b*) described them for the Salpidæ as hollow vesicles in the number of three pairs, to which waste products are carried by the blood corpuscles.

Thus in the majority of Tunicates they are vesicles without ducts placed in the mesenchyme. Van Beneden and Julin (1886) found them to be derived from mesenchyme, and concluded that this embryonic tissue is a modification of what was ancestrally enterocœlic mesoblast; Conklin (1905), however, has shown that all the mesoblast is peristomial, consequently the tissue from which these organs develop may be mesectoblast.

The genital ducts are outgrowth of the gonads, therefore probably have no relation to nephridia.

### 16. DINOPHILEA.

Korschelt (1882) described for *Dinophilus apatris,* and Weldon (1887) for *D. gigas,* a nephridial system of the platyhelminthan type, though both of them saw clearly only the flame cells. Subsequent observations have demonstrated that there are metamerically arranged, separated nephridia. Thus Schimkewitsch (1895) found in *D. vorticoides* four pairs of these in the male and five pairs in the female; Harmer (1889) and Shearer (1906) for *D. tæniatus,* Nelson (1907) for *D. conklini,* and E. Meyer (1887) for *D. gyrociliatus* discovered five pairs. These are ciliated tubes each with its own nephridiopore, closed internally, and (according to Shearer) beset with solenocytes. In *D. conklini* the first pair is much more complex than the others and consists of a considerable number of cells; each of those of *D. gyrociliatus* is described by Meyer as consisting of only two cells.

Schimkewitsch considered the genital ducts of the male to be a fifth pair, and the corresponding ducts of the female to be a sixth pair of nephridia, and Harmer regarded the seminal vesicles as segmental organs. This is, however, little more than a supposition, since the genital ducts are quite different in structure from the nephridia and are in connection with the cœlom (genital chamber), and since the development of the nephridia is unknown.

The mid-gut has also been demonstrated to be excretory (Schimkewitsch, 1884).

### 17. HIRUDINEA.

*Adult Meganephridia.*—There is a series of separated pairs, less numerous than the somites. Nephrostomes may be lacking as in the case of five out of the seventeen pairs of *Hirudo* (McKim, 1895) the three most anterior pairs of *Nephelis* (Graf, 1893), and all of *Branchellion* (Bourne, 1884). Leuckart (1894) discovered the anatomical connection of the nephridia with the nephrostomes, and this has been corroborated by Voinov (1896), McKim, Graf and Schultze (1883), in opposition to the results of Bolsius (1892) that the "organes ciliés" have no connection with the loop. But even when they are connected there need not be an open communication between the two (Graf, 1899). When present the funnel lies in the segment preceding that of the loop. The cavity of the nephridia is much branched and intracellular. An excretory bladder may be present as a part of the excretory duct, but this is lacking in *Clepsine.*

The nephridia arise from segmentally arranged mesoblastic nephroblasts, that lie deep below the embryonic epidermis. Each of these divides into two cells, the anterior of which gives rise to the funnel and the posterior to a cord of cells that forms the secretory portion of the loop; the cavity into which the nephrostomes open is a true cœlom; the excretory ducts and vesicles are ectoblastic ingrowths (Bürger, 1891, 1894, 1902, Bergh, 1891, McKim, 1895). Bürger is very positive with regard to the mesoblastic origin of the nephridia, in opposition to the earlier view of Whitman (1887).

*Adult Plectonephridia.*—Bourne (1884) first found net-like nephridia in *Branchellion, Pontobdella* and *Piscicola;* in *Pontobdella* they consist of a network of canals extending from the ninth to the nineteenth segment, with ten pairs of nephridiopores, while in *Branchellion* they have only one pair of such openings. They have been redescribed by Johansson (1898), and I am acquainted with his account only from the citation given by Lang (1903, p. 103). "In *Pontobdella* the nephridia consist of very richly branched and reticularly anastomosing tubes, among which one cannot distinguish main trunks. The two nephridia of the same segment are many times joined together, and the nephridia of the several segments equally so. In *Cystobranchus* each nephridium has attained a complete independence and connects neither with the other nephridia of the same segment, nor with those of neighboring segments. It consists then also only of a single, coarse, unbranched tube. The remaining genera correspond in this relation more or less with *Pontobdella;* one can, however, always distinguish particular trunks. In *Piscicola* one part of the nephridium, that is much more strongly developed than the remaining part, corresponds exactly in position with the nephridium of *Cystobranchus. Pontobdella* departs, finally, from all the other genera in this, that the nephridia have inner openings." Nothing is yet known of the development of these reticular organs.

*Genital Ducts.*—These were considered by Nusbaum (1885) to be modified nephridia. Bürger first (1894) opposed this comparison, but later (1902) he maintained that the female genital apparatus and the terminal portions at least of the vasa deferentia are possibly homologous with nephridia in developing from gonoblasts that are homodynamous with nephroblasts.

*Larval Nephridia.*—In the Hirudinea three of the blastomeres of the 4-cell stage give rise to a larval body that later perishes, while the fourth blastomere alone produces the adult body (Brandes, 1901). This larval body produces no nephridia. The "Urnieren" arise from the germ band that develops within this larval body, and they last only as long as the latter does. Bergh (1884, 1901) has shown that there are three pairs of these in *Aulastoma* and *Hirudo* and two pairs in *Nephelis,* all developing from the germ band; and he and Sukatchoff (1900) demonstrated that the inner ends are closed and the cavity intracellular. These larval nephridia arise from cell rows of the germ band that are generally considered mesoblastic, though this point is hardly finally settled.

*Excretophores.*—Excretory cells within the connective tissue

(Graf, 1899), that develop from the splanchnic layer of the mesoblast (Bürger, 1902).

*Chloragogue* (*Botryoïdal Tissue*).—Excretory cells placed upon the blood vessels (Graf, 1893).

### 18. OLIGOCHÆTA.

*Adult Nephridia.*—There are two main kinds of these which it will be convenient to consider separately: *meganephridia,* larger and in separated pairs; and *plectonephridia,* networks of smaller nephridia.

*Meganephridia.*—Of these there is usually one pair to each trunk segment, though exceptions are very numerous; each has a preseptal open funnel and a postseptal loop with intracellular cavity; their nephridiopores are usually separated and placed latero-ventral. The smallest number known is two pairs (*Bdellodrilus,* Moore, 1897). In *Brachydrilus* there are two pairs to each somite (Benham, 1888). The anterior five pairs open into the pharynx in *Dichogaster* (Beddard, 1888*b*), and probably also in *Eminea* (according to Benham, 1890*b*, who terms this a "peptonephridium"). In *Limnodrilus* the two anterior pairs perforate septa while the others do not (Rybka, 1899). *Libyodrilus* is characterized by the nephridia opening into a tubular system situated in the musculature, consisting of four main longitudinal vessels extending from segment to segment and of segmental ring vessels, there being numerous excretory ducts from the latter; this integumental network is secondary and develops after hatching (Beddard, 1891). Numerous other deviations from the general type are known that it is not necessary to mention here, beyond the fact that nephrostomes are lacking in the Chætogastrids (Vejdovský, 1885).

*Plectonephridia.*—A plectonephridium is a complex that in each segment is composed of numerous micronephridia, without nephrostomes, that are joined by a network of canals. In *Acanthodrilus* there is one such micronephridium to each of the eight setæ of each posterior segment, and in each anterior segment there are about one hundred nephridiopores; somewhat similar relations obtain in *Typhœus* (Beddard, 1888*a*). In *Megascolides* there are a great number of bundles of micronephridia which clothe the body wall except medially, these opening into a network of intracellular ducts placed outside of the peritoneum, and the latter discharge at the surface by irregularly arranged canals (Spencer, 1889). In *Mahbenus* each micronephridium has its own excretory duct (Bourne, 1894). The network of fine canals may be continuous from segment to segment, as in *Perichæta,* or only the micronephridia of one and the same segment may be so connected as exemplified by *Deinodrilus, Acanthodrilus,* and *Dichogaster* (Beddard, 1888*b*).

Both of these kinds of nephridia may occur in the same animal and even in the same segment, as in *Megascolides;* and in this genus there is a pair of ventral longitudinal canals continuous from segment to segment into which both open (Spencer). In *Dichogaster* the posterior segments contain both kinds (Beddard, 1888*b*).

*Development of the Meganephridia.*—With great hesitation I attempt to give a brief review of this subject, that has proved the Austerlitz of many a theory. Kowalevsky (1871) was the first to demonstrate the mesoblastic origin of these organs in *Euaxes* (*Rhynchelmis*) and *Lumbricus.* Vejdovský and Bergh have furnished more observations on the subject than any other writers. Vejdovský's results (1885, 1892*a*, 1900) on *Rhynchelmis, Stylaria* and *Tubifex* are as follows: Each nephridium arises from three separated anlages: (1) A large preseptal funnel cell, giving rise to the nephrostome; (2) a cord of small cells budded off behind the former, producing the secretory loop; and (3) an ectoblastic invagination that joins with the latter and forms the distal canal and the excretory vesicle. Bergh's studies (1888, 1890, 1899) on *Lumbricus, Criodrilus* and *Rhynchelmis* differ from those of Vejdovský mainly in deriving each nephridium from a single mesoblastic anlage instead of from three parts; in his mind the organ is essentially an embryonic unit. Wilson (1889) concluded for *Allolobophora* that the funnel arises from a large mesoblast cell, and the loop from a postseptal mass of cells that is continuous with the ectoblastic nephridial cell cords, though he admits the loop may nevertheless be mesoblastic. And Lehman (1887, *Allolobophora*) derived the nephridium from a large preseptal cell.

These researches agree in finding that the nephridia arise segmentally, to which the conclusions of Roule (1889) alone are opposed, and that their first beginning is the preseptal funnel cell. But there is considerable conflict of opinion as to what germ layer produces these cells and the cords that arise behind them. They arise in that cell row of the germ band formed by proliferation of the posterior nephroblasts. The germ band is covered by a thin ectoblast, and the funnel cells lie at points where the mesoblastic dissepiments meet the ectoblast; they are blastocœlic in position. Bergh is positive that funnel cells and nephridial cords are mesoblastic, derived from what he terms the "innere Muskelplatten," and Lehmann and Roule express the same opinion. Wilson hesitates to decide whether the nephridial cords are ectoblastic, though he ascribes this origin to the funnel cells. Vejdovský considers that at this early stage of the embryo, when these parts are first definable, there is no mesoblast but only the two primary germ layers and that the funnel cells may have emigrated from the ectoblast. It is to be noted in this connection that the funnel cells when they are first distinguishable have never been seen actually in the ectoblast, but always beneath it. And the nephridial development is so correspondent with that of the Hirudinea, for which Bürger shows so convincingly that the nephridia are mesoblastic, that the view of Bergh would seem to be correct. Consequently Goodrich (1895) in his summary of the literature on this subject would seem to have misunderstood the facts of the case. We may at least conclude, that in light of the evidence at hand all the inner portion of the nephridium is mesoblastic, and only its distal outer termination comes from the ectoblast.

Remarkable postembryonic changes have been described by Rosa (1903*a*) for *Lumbricus*. In a newly hatched individual two canals extend through the whole trunk and join posteriorly into an ampulla that opens dorsally into the intestine (for which reason the describer compares it with the nephridia of Rotatoria). From each of these canals tubes branch off segmentally and connect with the nephridia of the corresponding segments, while the nephridia still lack nephridiopores; later in each segment a diverticulum grows out from each canal and opens on the surface in the position wherein the adult the nephridiopore lies, while in each segment the main canals swell into a pair of vesicles; in the adult these longitudinal canals have disappeared, probably by segmenting into segmental excretory vesicles and nephridiopores.

*Development of the Plectonephridia.*—In *Megascolides* each segment has one pair of nephridial anlages, each consisting of a preseptal cell and a postseptal cord; so far the development is like that of the meganephridia; then the postseptal cord originates many loops and by a rupture of their connecting bridges the micronephridia result; the longitudinal canals connecting the latter arise later and are therefore secondary (Vejdovský, 1892*b*). In *Mahbenus* Bourne (1894) described an essentially similar process: that the funnels degenerate, that the loops form secondary and the latter tertiary branches, until each segment comes to contain about fifty micronephridia. These observations indicate clearly that the plectonephric condition is a modification of the primary macronephric by a subdivision of originally single organs. This is the position taken by Vejdovský, Bourne and Beddard (1892) which is contrary to the hypothesis of Benham (1890, 1891*a*), Spencer (1889) and Beddard (1891) that the plectonephric condition is primitive and comparable with that of the Plathelminths. Micronephridia lack nephrostomes because they are division products of the loops only, and not of the funnels. Therefore Vejdovský is probably correct in his conclusion that the micronephridia are homologous with the meganephridia, because both arise from a common anlage, comparable with the embryonic pronephridium of *Rhynchelmis.*

In *Acanthodrilus* deverticula grow out from the intestine, at a region probably anterior to the proctodæum, and join with the plectonephridia of that region of the body; this connection is secondary (Beddard, 1889, 1890, 1892).

*Embryonic Nephridia.*—For *Rhynchelmis* three sets of embryonic excretory structures have been found by Vejdovský (1892*a*). These are (1) "Schluckzellen," cleavage cells containing canals, which had been previously considered to digest the albumen of the egg; (2) larval pronephridia, "Kopfnieren" placed between the germ band and the ectoblast; and (3) embryonic nephridia, which later change into the definitive nephridia. Bergh (1888) found in *Criodrilus* a pair of tubes closed internally that he called Urnieren, though on account of the lateness of their origin Vejdovský considered they are rather embryonic nephridia. Wilson (1889) described for *Allolobophora* a pair of head kidneys, and Hoffmann (1899) found these opened into the head cavity. In the opinion of Vejdovský the larval nephridia develop either from the Schluckzellen, or else come from mesenchyme of ectoblastic origin. But it is yet by no means decided from what germ layer these kidneys originate.

*Genital Ducts.*—It was Williams (1858) who first indicated the homology of the genital ducts with nephridia, and he held the excretory function to be secondary. Claparède pointed to the typical absence of nephridia in the genital segments as evidence that the genital ducts are modified nephridia. Then Lankester (1865), reasoning from the condition in the Lumbricids, suggested that genital ducts represent the sole traces of a ventral set of nephridia that must originally have existed together with the dorsal set in all the segments; according to this view the primitive relation would be two pairs of these organs to each segment. This idea was adopted by Benham (1886*a, b*) who maintained that in *Lumbricus, Titanus* and *Pontodrilus* the ventral series of nephridia disappears except those that change into genital organs, and that in *Rhinodrilus, Eudrilus, Anteus, Urochæta* and *Moniligaster* just the opposite condition obtains. But Balfour (1885), as most students after him concluded that one pair of nephridia to a segment is primitive, and that "in the generative segments of the Oligochæta the excretory organs had at first both an excretory and a generative function, and that, as a secondary result of this double function, each of them has become split into two parts, a generative and an excretory." Here it is to be recalled that two pairs of nephridia to a segment is unusual, and that only in the Lumbricidæ do both genital ducts and nephridia occur in the same segment; anatomical relations therefore do not bear out Lankester's theory. With regard to the embryogeny of the genital ducts, Vejdovský (1885) found them to arise independently of the nephridia, though he considered they might be wholly or in part homodynamous with the latter; at least the funnels of the two he considered to have this relation. Similar results were reached by Bergh (1886), Roule (1889) and Beddard (1892). Lehmann (1887) opposed the idea of homodynamy on the grounds: (1) That two pairs of nephridia to a segment is not typical; (2) that in the embryo nephridia develop in the genital segments; and (3) that the genital ducts arise later than the nephridia. Finally there may be mentioned the view of Benham (1904) according to whom the phylogenetic series is as follows: (1) The nephridia acted as genital ducts; then (2) a special cœlomostome became added to the nephridia, forming a nephromixium; finally (3) the cœlomostome formed "its own cœlomo-duct, which may either co-exist in the genital segment with the nephridium (as in most 'terricoline' Oligochætes), or the nephridium . . . disappears from the segment during or before the development of the genital duct (as in 'limicoline' Oligochætes and *Protodrilus*). We have, then, to some extent a parallel series of phenomena analogous to those described with so much care by Goodrich in the Polychæta."

There is much in these relations that is still puzzling. But at least the funnels of both organs seem to be homodynamous since they have an approximately similar mode of growth. In the Lumbricids the two organs of a genital segment might well have arisen, as Balfour intimated, as division products of a common embryonic anlage. And in those species where nephridia are wanting in the genital segments, the genital ducts, as Vejdovský argued, are to be considered as in part at least modifications of the nephridia of such segments.

*Chloragogue* (*Pericardial Gland*).—This is peritoneal in origin and particularly excretory (Grobben, 1888, Rice, 1902, Rosa, 1903*a*).

*Peritoneum and Cœlomic Fluid.*—These have been considered excretory by Grobben (1888), who holds that the cœlomic fluid is in great part an excretory product though at the same time it has the functions of blood and lymph.

*Other Excretory Organs.*—Here are to be reckoned the bacteroidic cells of the connective tissues, the yellow cells of the intestine, and the amœbocytes of the blood (Cuénot, 1897).

## 19. POLYCHÆTA.

*Adult Nephridia.*—There is usually one pair to each trunk segment. In the Phyllodocidæ, Glyceridæ and Nephthyidæ their inner ends are closed and the loops are beset with solenocytes, each of which is a cell projecting into the body cavity "containing a deeply-staining rounded or oval nucleus, attached by a sort of neck to the extremity of a thin tube which opens at its opposite end into the lumen of the nephridial canal . . . Working inside the tube and attached at its distal end is a single long flagellum, which passes far down the nephridial canal" (Goodrich, 1900). In the other families the inner end is open to the cœlom, with the exception of *Polygordius* (Hempelmann, 1906) where the first pair is closed. The nephridiopores usually open separately. Each pair of nephridia stands in relation to two segments in Archiannelids, Alciopidæ, Typhloscolecidæ, certain Nereids (Eisig, 1887), Terebelloids and Cirratulidæ (Meyer, 1887), Aphroditidæ (Darboux, 1900) and Disomidæ (Allen, 1904); in the other families, therefore in the majority of species, to only a single segment. Some of the main deviations from this type are the following:

(*a*) In Capitellids each nephridium may have several nephrostomes, there may be several pairs to a segment and they may discharge into the skin and not on the surface of the latter (Eisig, 1887). In *Lanice* and *Ploimia* the fourth segment possesses two pairs (Meyer, 1887).

(*b*) In the Terebelloid *Lanice conchilega* the three anterior pairs of nephridia connect with a pair of longitudinal canals from each of which a single nephridiopore discharges on the surface; while the four following pairs of nephridia open into a longer pair of posterior canals which end blindly at about the sixteenth thoracal segment, and each of which discharges by four nephridiopores. *Ploimia* presents quite similar relations. Meyer (1887) who described these conditions holds it probable that the longitudinal canals are formed secondarily by a meeting and fusion of separate nephridial loops, incipient stages of which are to be noted in other genera. Also in *Owenia* (Gilson, 1894) do the nephridia open into longitudinal canals, that are here described as formed by an infolding of the epidermis.

(*c*) In the Terebelloids an impervious dissepiment separates the anterior from the posterior thoracal cavity; in the former there are no germ cells, and the three pairs of nephridia have small funnels; in the posterior space, which communicates with the abdominal cœlom, occur germ cells, and there the nephridia have large nephrostomes (peritoneal funnels) for the discharge of these cells. In the Cirratulids, Serpulacea and Hermellids only the first pair of nephridia are strictly excretory, and the others serve as genital ducts (Meyer, 1887).

(*d*) In Hermellids and Serpulacea the pair of thoracal nephridia unite dorsally into an unpaired duct that opens near the anterior end of the trunk (Meyer, 1887). And in *Dybowscella* the pair of the "head" has a single medio-dorsal pore (Nusbaum, 1901).

*Development of the Definitive Nephridia.*—The nephrostome of *Polymnia* (Meyer, 1887) arises as a fold of the peritoneum that grows backward to join the loop; the latter developes independently, simultaneously or a little later, from retroperitoneal tissue (whether mesectoblastic or mesentoblastic was not determined) that is at first solid and later acquires a cavity; the distal excretory duct is probably ectoblastic. In *Psygmobranchus* (Meyer, 1888) there first appears in the unsegmented larva a pair of large cells in the blastocœl, apposed to the ectoblast and separated from the mesoblast, these two cells become placed between the two layers of the first dissepiment and give rise to the tubes, while there evaginates to meet each of them a peritoneal funnel. Meyer holds that all the funnels of Terebelloids must have originally been parts of dissepiments, and with the degeneration of the latter have either become independent organs or else have become grafted upon nephridia. In what is the most detailed account of any polychætous nephridium, Lillie (1905) finds for *Arenicola* that the nephridia arise segmentally and independently, entirely from the somatic layer of the mesoblast; at first they are small tubes with intracellular cavities and a minute opening into the cœlom; "the anterior region of these organs . . . together with a portion of the adjoining septum, constitutes the primitive nephrostome, from which the adult nephrostome is directly derived." The terminal vesicle is also not ectoblastic, but "is formed as a differentiation of the most posterior portion of the primitive nephridium. There is no ectodermal invagination," but the terminal portion comes from a region where mesoblast and ectoblast join, probably from a region that was originally ectoblastic.

The work of Meyer, Fraipont and Woltereck shows that Hatschek (1878) was entirely wrong in deriving the nephridia from a continuous anlage, and in stating the adult nephridia of *Polygordius* arise as branches of longitudinal ducts of larval nephridia.

*Larval Nephridia.*—There is one pair of these in *Polymnia* (Meyer, 1887), each with a long flagellum placed upon the outer surface of the closed inner end, on which region follows a loop composed of two cells and then an excretory canal with intercellular cavity; these persist until the first definitive nephridia function. In *Psygmobranchus* (Meyer, 1888) there is also one pair, each composed of two cells and probably without internal opening, that open on the ectoblast and do not touch the mesoblast; they belong to the first somite (that just behind the metastomium). Meyer (1887) has figured the larval nephridia of *Nereis* as internally closed canals; Hatschek (1885) finds this structural relation in *Eupomatus,* and holds the nephridia to be mesoblastic. In *Hydroides* the head kidney opens into the proctodæum (Wilson, 1890). Drasche (1884, *Pomatoceros*) held the head kidneys to have funnels, and to be mesoblastic.

The larva about which there has been the most discussion is that of *Polygordius.* For *P. neapolitanus* Hatschek (1878) described the branched head kidney as having open nephrostomes and being joined by longitudinal canals with the trunk nephridia, a condition that has led to manifold comparisons with platodan relations. But Fraipont (1888) and Meyer (1901) found that such longitudinal canals do not exist, and that the inner ends of these tubes do not possess funnels but are beset with slender cells (solenocytes) that project into the blastocoel. Meyer described also a second pair of larval nephridia behind these, which differ from trunk nephridia only in the lack of funnels. Then Woltereck (1905) in disagreement with these writers states that the two-branched first pair of larval nephridia belong to the second somite, are mesenchymatous and degenerate entirely; while the second larval nephridium belongs to the third somite and consists of two parts: (1) A mesenchymatous portion, composed of two "Köpfchenzellen" beset with ciliated tubes, that later degenerates, and (2) a segmental portion, at least in part ectoblastic in origin, that joins with the mesenchymatous part. Woltereck finds this second pair to become the first pair of definitive nephridia that differs from the others in the absence of funnels.

In *Polygordius lacteus* Woltereck (1902) found also two pairs of larval nephridia: (1) Hauptnephridia, close to the epidermis of the ventral hyposphere, beset proximally only with tube-cells; and (2) Seitennephridia, lined with such cells along most of their lengths. In the adult of this species also one of these pairs must persist, since the foremost definitive nephridia lack nephrostomes (Hempelmann, 1906).

The present evidence is that the head kidneys are closed internally, and Meyer accounts for this by the lack of a dissepiment in front of them from which a nephrostome could form. But while Meyer and Woltereck incline to an ectoblastic and mesenchymatous origin, Lillie concludes a mesoblastic. There is no evidence that the adult nephridia are division products of larval ones, but when there is a second pair of larval nephridia it may persist in the adult.

*Provisory Nephridia.*—Following on the larval nephridia and before the adult one are formed there are in the Capitellids (and so far as is known only here among the Polychæta) provisory nephridia, each of which participates in two segments (Eisig, 1887).

*Relation of Genital Ducts and Nephridia.*—This question has been so ably reviewed by Goodrich (1895, 1900), and his investigations have contributed so much to its solution, that I need to discuss it only briefly. Williams (1858) held that these organs are homologous, and derived from a common "viscus." Then Cosmovici (1880) concluded that the segmental organs of Annelids are of two kinds: excretory organs (organs of *Bojanus*), and genital ducts, and that the two may be separated or may be united. It is the particular service of Eisig (1887) and Meyer (1887 and later papers) to have demonstrated by their anatomical and embryological studies that the peritoneal funnels, the original genital ducts, are evaginations caudad of dissepiments, and that they may or may not join secondarily with the nephridium proper that develops independently from retroperitoneal tissue.[3] But it is Goodrich who has made the most comprehensive comparative investigation of these relations (1895, 1897, 1898, 1900). He calls the peritoneal funnel (Genitalschlauch) a cœlomoduct, and its opening a cœlomostome; when the latter preserves its original strictly genital function it is a gonostome. According to his terminology, further, a nephridium is an excretory organ with its own inner opening, and the latter is a nephridiostome. The cœlomoducts may open on the surface of the body entirely separate from the nephridia, the primitive condition, and in this case the nephridia are purely excretory and possess small nephridiostomes; or the cœlomostomes may become secondarily grafted upon the nephridia, forming compound nephromixia which are genito-urinary and possess large funnels (cœlomostomes). These relations in the Polychætes he tabulates as follows (1900):

| | | |
|---|---|---|
| Nephridium closed internally. | Genital funnel distinct, but opening into nephridial canal may be acquired at maturity. | Phyllodocidæ.<br>Glyceridæ.<br>Nephthyidæ. |
| Nephridium open internally. | Genital funnel with independent external opening. | Capitellidæ.<br>? Nereidæ (Lycoridea). |
| | Genital funnel becomes connected with the nephrostome, and loses its primitive opening to the exterior. | Hesionidæ (all?).<br>Syllidæ.<br>Aphroditidæ.<br>Eunicidæ.<br>Spionidæ.<br>Terebellidæ.<br>Sabellidæ.<br>Etc., etc. |

Goodrich adduces the various evidence for this conclusion and adds: "Moreover, it must be remembered that the two organs are mutually exclusive; never do we find a separate genital funnel in those forms which possess wide-mouthed excretory organs; and conversely, with the one possible exception of Polygordius, never do we find Polychætes having nephridia with only small true nephro-

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[3] Meyer (1890) has shown that Kleinenberg (1886) was mistaken in deriving the genital ducts from the ectoblast.

stomes without genital funnels."[4] Allen (1904) has demonstrated that in *Pœcilochætus* both kinds of organs occur, nephridia with small nephridiostomes in the anterior somites, and nephromixia with large funnels in the posterior.

Thus the evidence is convincing that cœlomoduct and nephridium are two distinct organs, with originally separate origins and functions, but that the two frequently unite to produce a compound nephromixium.

*Mid-gut.*—This is excretory in the Polynoidæ (Schimkewitsch, 1884), and so are the intestinal cæca in the Aphroditidæ (Darboux, 1900).

*Chloragogue.*—Schæppi (1894) found the chloragogue of only the peritoneum, nephridia and intrasinous connective tissue is excretory (contains guanin). In *Arenicola* some of the vessels have cæca whose walls possess chloragogue cells (Willem, 1899). For the chloragogue of peritoneal origin (peritoneal glands) Meyer (1901) uses the term "phagocytic organs."

Eisig (1887) has made the most thorough study of excretion in the Polychætes; he determined that carmine is taken up by the mid-gut, then by the peritoneum, and that the hæmolymph is the vehicle of its transport to the nephridia, blood vessels being absent in the Capitellids; it ultimately reaches also the setal glands and the skin; the skin is not excretory though it becomes the seat of excretory substances, and it is by the accumulation of such material that the skin in necessitated to undergo moults.

## 20. ECHIURIDA.

*Segmental Organs.*—These serve mainly if not wholly as genital ducts and in *Bonellia* the male lives within those of the female. *Bonellia* has but a single one, while in *Echiurus* and *Thalassema* there are from one to four pairs. Structurally (Greef, 1879, Spengel, 1880) these are long tubes each with a nephrostome close to a nephridiopore. Nothing seems to be known of their development.

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[4] Hempelmann (1906) has since shown that in *Polygordius* the nephridiostomes are too small for the discharge of the germ cells, and that the latter escape by rupture of the posterior end of the body.

*Anal Tubes.*—There is one pair of these opening into the most posterior portion of the intestine. On their surfaces there are numerous "Wimpertrichter," and Greef supposed these not to open directly into the cœlom, but Spengel demonstrated that they do make such a direct connection and that their ciliated lining is continuous with the peritoneum. Their function is not ascertained. From their position Spengel concluded them to be ectoblastic, but not to be homodynamous with the segmental organs. But Hatschek (1880) describes them as arising not from the rectum but from the somatic mesoblast of the telson; and according to this account they form first the Wimpertrichter, then later the external pores that lie lateral from the anus.

*Larval Nephridia.*—These are known only from Hatschek's account (1880) of *Echiurus;* the first origin of these "Kopfnieren" was not determined; each becomes a much branched organ with intracellular cavity, from the surface of which delicate blind capillaries grow out. Torrey (1903) was unable to find larval nephridia in *Thalassema,* and determined that in this form excretion is accomplished by certain mesenchyme cells.

## 21. MYZOSTOMIDA.

The single pair of nephridia were first recognized as such by Beard (1894), and their structure particularly described by Wheeler (1896) and Stummer-Traunfels (1903). Their relations differ somewhat in different species: they may be separated from each other, or their open and large nephrostomes may be united, their nephridiopores may be separated or united; in one species nephrostomes appear to be absent. In some species they are purely excretory, in others also spermiducal. From their development Wheeler concluded that they originally opened on the surface of the body and not into the cloaca (their usual termination in the adult), because in one species the unpaired excretory duct opens "on the surface of the body through a papilla lying just ventral to the cloacal orifice."[5]

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[5] The segmental sacs (suckers) supposed by Nansen (1885) to be nephric, have been shown by Wheeler to be probably sensory.

### 22. ENTEROPNEUSTA.

*Nephridia.*—There is a left canal (or a right and left) connecting the cœlom of the proboscis with the exterior, a pair of similar canals in the collar region, and in *Spengelia* (Willey, 1899) rudimentary pores along the whole trunk. Spengel (1893) considered them to take in water from without and to subserve locomotion; Willey regarded them as having lost their former excretory function, while Bateson (1884) showed by carmine injection that the collar pores are excretory.

An ectoblastic origin of these structures was the result of the study of Spengel and Morgan (1894). But Dawydoff (1907), examining those of the proboscis in the process of regeneration, found that they develop from a peritoneal evagination that connects with an ectoblastic ingrowth, and from this concluded that they are true nephridia—a view previously reached by Schimkewitsch (1888).

The genital ducts seem to bear no relation to nephridia, and the larva (tornaria) lacks special excretory organs.

*Glomerulus.*—A vascular structure connected with the pericardium, considered the only excretory organ in the adult (Willey, 1899); I have not seen the original description and consequently am unable to add further details.

### 23. MOLLUSCA.

*Adult Nephridia.*—I have not attempted to labor through the compendious literature on the anatomy of these organs, but shall simply give a brief summary drawn mainly from the excellent treatment by Hescheler (1900). These are essentially similar and homologous throughout the group, and consist typically of a pair of sacs which communicate internally by open nephrostomes (renopericardial apertures) with the cœlom (pericardial cavity), and externally by nephridiopores with the mantle cavity. They are paired in all the groups except the Gasteropods, and among the latter in most of the diotocardial prosobranchs; among living forms there is more than one pair only in *Nautilus*. They may be simple tubes, or may be twisted or excessively ramose. Functionally they may be exclusively excretory, the usual condition, or mainly genital (*Solenogastra*), or genito-urinary.

*Development of the Adult Nephridia.*—According to one view the glandular portion of the nephridium arises as a peritoneal funnel, an evagination of the pericardium, this joining later with an ectoblastic ingrowth, the duct or ureter; in support of this view is the work of Rabl (1879, *Planorbis*), Erlanger (1891*a, Paludina*), Bütschli (1877, *Paludina*), Salensky (1885, *Vermetus*), Schimkewitsch (1888, *Limax*), Drummond (1902, *Paludina*), Ahting (1901, Pelecypods), Pelseneer (1901, *Helix*), and Stauffacher (1898, *Cyclas*). That these organs are wholly mesoblastic is the opinion of Salensky (1872, *Calyptræa*), Erlanger (1892*b, Bythinia*), Georgevitch (1900, *Aplysia*), and Faussek (1900, *Loligo*). The third view is that they are altogether ectoblastic: Fol (1875, Pteropods), Bobretzky (1877, *Nassa*), Joyeux-Laffuie (1882, *Onchidium*), Sarasin (1882, *Bythinia*), and Meisenheimer (1898, *Limax*, 1901*a, Dreissensia*, 1901*b, Cyclas*).

The first of these views has the greatest support, pointing to the pericardial origin of the funnel and glandular portion, and to ectoblastic origin of some portion of the ureter only. For the third view, wholly ectoblastic origin, it will be noted that the only recent work is that of Meisenheimer. Now almost all the writers conclude a common origin of the glandular portion of the nephridium and the pericardium and Meisenheimer does so likewise, but in opposition to almost all preceding study he regards the pericardium and heart as ectoblastic abstrictions. Meisenheimer must surely be incorrect in interpreting the peritoneum and with it the nephridium as ectoblastic, *i. e.,* he must have defined the germ layers quite differently from other embryologists, since the pericardial cavity is justly considered cœlomic yet in no other animal group is the cœlom regarded as lined by ectoblast.

These definitive nephridia seem to arise independently of the larval ones, save that Rho (1888) and Mazzarelli (1892, 1898) state that the mesoblastic anal kidneys of opisthobranch larvæ become transformed into the adult ones.

*Genital Ducts.*—" Relations between the nephridial and genital system, similar to those in the Worms, exist in the Solenogastrids where the nephridia function as discharge ducts for the genital products. . . . And again in some Lamellibranchs, Diotocardians and the Scaphopods there exist relations between sex glands and nephridia in that the sex glands open into the nephridia, so that a shorter or longer portion of the latter functions not only as kidney or ureter but also as discharge duct for the genital products' (Hescheler, 1900). In those prosobranchs with only one adult nephridium, Drummond (1902) has shown for *Paludina,* and after a full discussion of the literature, that the right nephridium of the embryo persists as the left one of the adult, in agreement with Erlanger, but contrary to his results she finds the left nephridium of the embryo does not disappear but becomes the genital duct.

*Larval Nephridia.*—These are known only in Gasteropods and Pelecypods (Lamellibranchs), and it will be most convenient to treat separately the groups in which they occur.

(*a*) *Prosobranch Gasteropods.*—Two kinds of these have been described. (1) External nephridia (Aussennieren, excretory cells). These are ectoblastic, unicellular or multicellular organs, usually projecting from the surface of the body just behind the velum; there is one pair of them, and their cavity communicates with the blastocœl; sometimes they have an opening to the exterior. They have been described most carefully for *Crepidula* (Conklin, 1897) and *Fasciolaria* (Glaser, 1905), also for *Nassa, Natica, Fusus* (Bobretzky, 1877), *Paludina* and *Bythinia* (Sarasin, 1882, who calls them "ansæ"), *Fasciolaria* and *Fulgur* (McMurrich, 1886), *Fissurella* (Boutan, 1885), and *Capulus* (Erlanger, 1892*a*). Glaser has demonstrated that they are first digestive, later serve as reservoirs for waste products, and subsequently fall off from the surface of the larva; Sarasin and McMurrich supposed they were originally parts of the preoral velum, and that with excretory specialization they separated off from it; but Conklin and Glaser show that they arise independently of and before the velum. As "secondary outer kidneys" Glaser has described certain excretory cells placed in the velum and the head vesicle.

(2) The second kind of larval excretory organs of the prosobranchs are mesoblastic. These arise from a mesoblastic anlage that is at first solid, while more or less of the duct is ectoblastic;

they are ciliated with exterior apertures. These have been found in *Bythinia* and *Paludina* (Bütschli, 1877, Erlanger, 1891*a*, 1892*b*).

(*b*) *Opisthobranch Gasteropods.*—Here there are distinguished nephrocysts and anal kidneys. The nephrocysts were discovered and named by Trinchese (1881) for *Ercolania, Amphorina, Bergia* and *Doto;* and were described also by Mazzarelli (1892) for *Aplysia* and by Casteel (1904) for *Fiona.* These are rounded bodies lying anterior to the anus in the blastocœl, without external ducts; nothing positive is known of their origin, and Trinchese supposes them mesoblastic simply from their position. They may occur in the same embryo together with the following organs. The anal kidneys were first interpreted as excretory by Langerhans (1873, *Doris* and *Acera*). They are a pair of single cells, or groups of cells, that originate near the anus but may migrate further forward. Trinchese (1881) and Guiart (1901) derived them from the mesoblast, and so also did Mazzarelli (*Aplysia,* 1892, 1898) who ascribed the occasional unpaired condition to the fusion of a pair. But Lacaze-Duthiers and Pruvot (1887) described them as ectoblastic, and this conclusion was reached also in the careful studies of Heymons (1893, *Umbrella*) and Casteel (1904, *Fiona*). Casteel's work is the most thorough on any opisthobranch, and he states: "There is no point regarding the cytogeny of *Fiona* of which I am more certain than that the group of cells constituting the anal kidney is of ectodermal origin."

(*c*) *Pulmonate Gasteropods.*—Here again there are two kinds of larval kidneys. The external kidneys (äussere Nieren) occur one on either side of the body, each a projecting group of vacuolated cells forming part of the ectoblastic velum. These were discovered by Bütschli (1877), and have been described by Fol (1880) and Rabl (1879) for *Planorbis.* Much more attention has been given to the head kidneys (Urnieren). The most detailed description of these in their perfected condition is that of Meisenheimer (1898, 1899): in the Basommatophora (*Ancylus, Physa, Planorbis, Limnæa*) these are much alike, each consisting of but four cells with intracellular cavity, the innermost of which closes the canal against the blastocœl and bears a ciliary flame. In the Stylommatophora (*Limax, Succinea, Helix, Arion*) the cells are much more numerous and the inner end is composed of a number of large amœboid cells all of which have long cilia; for a while the inner end may be open (as described by Rabl, 1879, and Erlanger, 1894) since the cells there may become loosened from their epithelial connection, but later this end becomes completely closed even though at places by a very thin membrane. These are the most complicated larval nephridia found in Gasteropods; they subsequently degenerate completely. As to the development of these head kidneys: Rabl (1879) and Holmes (1900) considered them mesoblastic; Erlanger (1893) interpreted them as mainly mesoblastic with a portion of the duct ectoblastic, and Pelseneer (1901) stated that the large distal portion is ectoblastic. But Fol (1880), Wolfson (1880) and Meisenheimer (1898) concluded that they are entirely ectoblastic; the last named investigator speaks of them as arising as paired tubular invaginations at the level of the proctodæum.

(*d*) *Pelecypods* (*Lamellibranchs*).—In *Teredo* there is a pair of ciliated Urnieren in the young larva (Hatschek, 1880). Only the left one is developed in *Cyclas,* and opens externally in the region of the head vesicle; it consists of three highly complex cells with intracellular cavity, the innermost branched cell closing it from the blastocœl (Stauffacher, 1898). In *Dreissensia* each of the larval kidneys consists of three cells, the innermost provided with a ciliary flame and closing the canal, the next forming the tube, and the third constituting a duct connecting with the surface (Meisenheimer, 1901*a*). With regard to the embryogeny, Hatschek described these organs as appearing first at the anterior ends of the mesoblastic bands, at first with no connection with the ectoblast, and concluded that the nephridium of each side "is probably derived from only one or a few mesoderm cells"; Stauffacher held that in *Cyclas* only the innermost cells is mesoblastic and the others ectoblastic; while Meisenheimer (*Dreissensia,* 1901*a, Cyclas,* 1901*b*) described them as arising conjointly with the heart and pericardium from the ectoblast.

*Homologies of the Larval Nephridia.*—Salensky (1872) and Bobretzky (1877) homologized the outer kidneys of prosobranchs with the Urnieren of Pulmonates. Bütschli (1877) suggested that the Urnieren of *Paludina* are possibly homologous with those of the pulmonates, but that there is no homology between the outer kidneys of these groups. Rabl (1879) concluded that the outer kidneys of *Planorbis* are probably comparable with the outer kidneys of freshwater prosobranchs, but not with the Urnieren. Fol (1880) maintained that the outer kidneys of Pulmonates are homologous with the Urnieren of prosobranchs. Erlanger (1893) regarded all the larval nephridia as homologous with each other and probably also with the head kidneys of Annelids, and distinguished the following kinds: (1) Outer ectoblastic kidneys (marine prosobranchs); (2) inner mesoblastic, and these either (*a*) purely mesoblactic (opisthobranchs), or (*b*) mesoblastic with the canal at least in part ectoblastic (pulmonates, pelecypods, freshwater prosobranchs). Mazzarelli (1904) considered the Urnieren of pelecypods, pulmonates and freshwater prosobranchs to be homologous, but the external nephridia of marine prosobranchs to be different structures; and the nephrocysts of opisthobranchs to be organs that have secondarily lost their ducts and that correspond with the excretory cells of the Urnieren of other Mollusks. Finally Glaser (1905) has given a good review of the question, and maintains there are at least three distinct and dyshomologous larval excretory organs (1) Urnieren, mesectoblastic structures of prosobranchs and pulmonates; (2) Aussennieren, modified ectoblastic cells of prosobranchs and pulmonates; and (3) excretion cells, those of *Umbrella* placed near the anus; the Urnieren are further of two kinds because some of them appear to be wholly ectoblastic.

There is so much confusion of opinion with regard to the development of even the same kind of excretory organ in the same species, that I fully agree with Casteel (1904) "that much more work must be done upon these organs of molluscan larvæ before we are ready to come to definite conclusions regarding their mutual relations and homologies, if such exist." There are certainly two distinct kinds that may occur at the same stage in the same species, and that on account of their differences in position, structure and origin are not homodynamous, and these are: (1) Projecting vesicles, wholly ectoblastic, forming part of or placed near to the velum; and (2) vesicular or tubular organs placed below the ectoblast and behind the preceding, which in most cases appear to be in part mesoblastic. All those of the first kind may well be homologous, but those of the second kind are more probably heterogeneous structures.

*Other Excretory Organs.*—According to Cuénot (1899) the following structures are excretory: in the Amphineura and Scaphopoda connective tissue cells; in prosobranch and opisthobranch Gasteropoda similar cells as well as cells of the liver; in the Pelecypoda pericardial glands; and in the Cephalopoda phagocytes and the gill-hearts.

## 24. TARDIGRADA (ARCTISCOIDEA.)

A pair of glands opening into the rectum were supposed by Plate (1888) to be excretory, and he compared them with the Malpighian vessels of the Acarina. But neither he nor Basse (1905), who has furnished a fuller description, were able to find excretory products in these organs. Nothing is known of their development.

## 25. PYCNOGONIDA (PANTOPODA).

Dohrn (1881) has described problematical "Excretionsorgane" within the cavity (blastocœl) of the fourth or fifth joint of the second extremity, or the third or fourth joint of the third; each has an external opening placed upon a small tubercle; in genera where the named extremities are absent, these organs are found in the wall of the body at points opposite the missing extremities. These organs lie in extremities that lack reproductive organs, and for that reason Dohrn suggested they may have some homodynamic relation to the latter.

Kowalevsky (1892) found by injections of acid fuchsine that the stain is taken up by small hypodermal glands placed in *Phoxichilus* on the borders of the three anterior segments and on the bases of extremities fourth to seventh, and in *Pallene* and *Ammothea* in the lateral processes of trunk segments and in the first joints of the extremities.

## 26. CRUSTACEA.

*Shell Glands (Maxillary Glands).*—These have been described for the Phyllopoda (Leydig, 1860, Weismann, 1874, Claus, 1875, Dohrn, 1870, Nowikoff, 1905), Copepoda (Claus, 1877, Nettovich, 1900), Isopoda (Vejdovský, 1901; and Nemec, 1896, who states that in *Ligidium* they are modified into salivary glands), Cirripedia, (Bruntz, 1903, Berndt, 1903; in *Balanus* they communicate with the cœlom only in the cypris-stage according to Gruvel, 1894), Stomatopoda (Bruntz, 1903), and freshwater Ostracoda (Claus, 1895, Daday, 1895). These open at or near the base of the second maxillæ, each has a closed enlarged end sac lined by an excretory epithelium, and they are placed in the shell duplicature except in *Leptodora* where the greater portion of the organ lies in the thorax. According to Richard (1892) their ducts are longest in freshwater and shortest in brackish water species. In freshwater Cladocera (*Simocephalus*) I have found that the end sac takes up injected carmine at the end of a few hours.

*Antennal Glands.*—These have been described for the larvæ (but not adults) of Copepoda and Phyllopoda (Grobben, 1881), for Amphipods (Grobben, 1881, Bonnier, 1891, Bruntz, 1903, Vejdovský, 1901, Della Valle, 1893), Schizopoda (Grobben, 1881, Bruntz, 1903), Ostracoda (Claus, 1890, 1895), Cirripedia where they are modified into cement glands but may still continue excretory (Koehler, 1890), Isopoda (in *Asellus* where they are degenerate, Nemec, 1896), and Decapoda (Marchal, 1892, Waite, 1889). The antennal glands are essentially similar to the maxillary. Both have closed end sacs, are without cilia, and both (Vejdovský, 1901) possess at the junction of the gland and duct a narrow "Trichter" composed of a few large cells with a peripheral muscular sphincter.

*Development of the Preceding Organs.*—According to the earlier observers (Reichenbach, 1886, Ischikawa, 1885) the shell and antennal glands are ectoblastic, but other studies (Kingsley, 1889, Waite, 1899, Grobben, 1879, Lebedinsky, 1891) show that each arises as a reduced cœlomic sac (or portion of one) connecting with an ectoblastic duct. The end sac of the adult thus corresponds to the cœlomic sac of the embryo.

*Maxillipedal Glands.*—In *Diaptomus* there is a pair of these opening at the basis of the first maxillipeds; their structure is like that of the preceding glands (Richard, 1892). It is probable that some of the glands described as maxillary are really maxillipedal.

*Coxal Glands.*—In *Gammarus* (Della Valle, 1893) there are small groups of gland cells, that take up carmine, placed at the bases of the maxillipeds, thoracic and abdominal extremities. Similar appear to be the "Segmentalorgane" of the Ostracoda (G. W. Müller, 1894), which in *Paradoxostoma* lie above each leg pair, and in *Bairdia* above the first pair; and the glands opening on the maxillipeds of Cyprids (Claus, 1890).

*Genital Ducts.*—The first origin of these seems to have been little investigated, but Pedaschenko (1899) finds them to arise from a proximal mesoblastic and a distal ectoblastic portion.

*Homologies of the Preceding Organs.*—The maxillary, antennal and maxillipedal glands are probably homodynamous, and seem to differ only in antero-posterior position. Sometimes they occur at the same time in the same individual, or (as in Phyllopods and Copepods) the antennal gland is the larval and the shell gland the adult excretory organ. Sometimes both antennal and shell glands are absent in the adult, as in some Copepoda (Nemec, 1896). Waite (1899) has discussed these homologies at some length, and resumes: "The nephridium of Annelids is *probably* represented in Crustacea in the second (antennal) segment by the antennal gland of Malacostraca; in the fifth (second maxillary) segment by the shell gland of Entomostraca and some Malacostraca; in the sixth (first maxillipedal) segment of *some* Malacostraca by the 'Segmentalorgan' of Lebendinski; it is *possibly* represented in the fourth (first maxillary) segment by the excretory organ described by Boutchinsky, and in the sixth to thirteenth (maxillipedal and pareiopodal) segments in part by the branchial glands, and in part (in the eleventh and thirteenth segments) by the genital ducts."

*Nephrocytes.*—Bruntz (1903) has found these excretory cells to be distributed as follows: they are absent in the Cladocera; there is one cephalic pair in the Isopoda, Amphipoda and Cirripedia; up to eight pairs placed in the thorax in the Schizopoda, Decapoda (in the gills), and Copepoda parasitica (diffuse); from one to eight pairs in the abdomen in the Isopoda and Stomatopoda (in the legs); and eleven pairs in the thorax and abdomen in the Amphipoda.

*Other Excretory Organs.*—As such have been described the ferment cells of the liver of Decapoda, Amphipoda and Isopoda, and the mid-gut cæca of Amphipoda (Bruntz, 1903); the mantle in the Cirripedia (Gruvel, 1894); and connective tissue cells of Copepoda when the antennal and maxillary glands are lacking (Nemec, 1896).

## 27. ONYCHOPHORA (PROTRACHEATA).

*Nephridia.*—According to the observations of Balfour (1883) and subsequent investigators, one pair of nephridia occurs in each trunk somite, *i. e.,* one pair to each pair of legs, except in the penultimate or antepenultimate segment. Each opens ventrally at the basis of a leg, and consists of an outermost excretory bladder, a loop and a nephrostome that opens into the cœlom; but the portion of the cœlom that has such a connection is, as in the case of the antennal and maxillary glands of the Crustacea, completely abstricted from the remainder of the cœlom and with excretory function, therefore each such cœlomic sac may rightly be considered a closed inner end sac of the nephridium. This is in agreement with the facts of the embryogeny, as detailed by Sedgwick (1885–8) and Evans (1901), according to whom each right and left cœlomic sac pinches into a dorsal and a ventral portion, and the latter portion sends an outgrowth reaching to and opening at the leg.

The salivary glands and genital ducts develop like the nephridia and represent them in segments where they are lacking, are accordingly homodynamous with them (Sedgwick); and the receptaculum ovorum is homodynamous with an end sac of a nephridium (Evans).

*Anal Glands.*—These also have been considered homologous with nephridia by v. Kennel (1885). But Purcell (1900) has indicated that the so-called "accessory glands" of the postgenital segments may rather be dyshomologous; that while those (anal glands) of the American *Peripatus* are nephridia, those of other genera are probably ectoblastic crural glands.

*Nephrocytes.*—There are medio-dorsal bands of these, also masses of them near the bases of the legs (Bruntz, 1903).

## 28. INSECTA.

*Malpighian Vessels.*—These are absent in Japyx (Grassi, 1888) and also in the Collembola where Folsom and Welles (1906) found that the whole ventriculus is excretory and periodically moults its epithelium; they are not, as generally supposed, absent in the Aphidæ, for Witlaczil (1882) has shown that the so-called pseudovitellus represents them. In all other Insects these vessels are present, and are usually delicate, cylindrical tubes, rarely varicose or ramose, with their inner ends closed and the distal ends joining with the intestine usually at the junction of the mid-gut and proctodæum, and they may insert there singly or by one or several common ducts. In some cases there are two different kinds in the same species. Their number is often constant for a group as may be seen from the following summaries taken from the observations of Dufour (1833, 1841, 1851): in the Diptera there are usually four, rarely five (*Culex*), and never more than four in the Hemiptera; there are generally less than eight in the Coleoptera; six in Phryganids, Termes, Megaloptera (*Corydalis, Sialis*), *Panorpa,* eight in *Hemerobia* and *Myrmeleo;* they are much more numerous in the Orthoptera, Hymenoptera, Libellulidæ and Ephemeridæ.[6]

While Dufour called them "organes hepatiques ou biliaires," subsequent work has proved conclusively that they are the main excretory organs.

According to the majority of investigators they arise as evaginations of the ectoblastic proctodæum, and only in some Hymenoptera do they first appear as ectoblastic evaginations at the posterior end before the proctodæum forms. The largest number known in any embryo is ten (*Melanoplus,* Packard), which seems to be the single case not in agreement with Wheeler's conclusion (1893*a*) that no more than six occur in embryos. Wheeler concludes that six is the primitive number, while others have reasoned this to be four. Only in the Termites are they more numerous in the larvæ than in the adults.

*Homologies of the Malpighian Vessels.*—These have been compared specially with the sericteries and tracheæ and more generally with nephridia of the annelidan type; and it is most convenient to treat these relations at this place. Bütschli (1870) showed that the sericteries and Malpighian vessels develop like the tracheæ, re-

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[6] A good review of their numerical and other relations is given by Packard (1898). In the Thysanura (except *Japyx*) their number was found by Grassi (1888) to vary from eight to sixteen.

garded the sericteries and tracheæ as homologous, but questioned whether the Malpighian vessels are related to them. Then, following Semper's (1874) suggestion that the tracheæ are metamorphosed segmental organs, Mayer (1875) went further in concluding that the tracheæ, sericteries and Malpighian vessels are homodynamous and all homologous with nephridia of Annelids. Grassi (1885) has in the main supported Mayer, in reasoning that the Malpighian vessels, sericteries, the two transitory invaginations on the head and the homodynamous tracheæ are all probably excretory in the larva; and (1888) supports the idea of the homology of Malpighian vessels with tracheæ on the ground that the former occur in segments where the latter are lacking and are most abundant when the latter are least numerous. But several strong objections have been made to these comparisons, and especially by those who have studied the embryogeny more in detail. Thus Hatschek (1877*b*) has argued against the homology of the sericteries and salivary glands with the tracheæ, that in the segments where the former occur tracheal invaginations are formed independently of them. Then Palmén (1877) concluded that the Malpighian vessels, developing from the proctodæum, were originally hypodermal glands that have come to group themselves around the inner end of the proctodæum and that their number is "in no way dependent upon the number of particular body segments"; while against the homology of the tracheæ with nephridia, he adducted the case of their coincident segmental occurrence in *Peripatus*. Wheeler also (1893*a*) judged that if the Malpighian vessels are homologous with nephridia they can be only with the ectoblastic portion of the latter; and that they are not homodynamous with tracheæ, but rather with the mass of œnocytes that represent the ectoblastic remains of nephridia. Heymons (1896) also concluded that the Malpighian vessels are not to be compared with nephridia, that they are only local evaginations of the hind-gut.

The evidence is that the Malpighian vessels are certainly not homologous with annelidan nephridia, because they are strictly ectoblastic and are not segmental. Their resemblance to the sericteries and tracheæ is only a very general one in that all of these are ectoblastic invaginations, so that at the most we must conclude, with Palmén, that while these may all have had an essentially similar beginning no one of them has been derived from the others. The Malpighian vessels may well have been hypodermal glands that have invaginated with the proctodæum, and for this speaks their independent origin in the embryos of some Hymenoptera. In this connection it is interesting to note the conditions in the larvæ of Phryganids, as described by Henseval (1896): here there are three pairs of ventro-median glands (glands of Gilson); and Henseval regards the Malpighian vessels as homologous glands of the last segment, and the proctodæum as their unpaired portion that has secondarily joined with the mid-gut. If we omit this explanation of the proctodæum as being problematical, the comparison of Malpighian vessels with segmental glands placed anteriorly on the hypodermis might well hold.[7]

*Homologues of Nephridia.*—Here there are in the first instance the genital ducts, that develop as cœlomic evaginations (Wheeler, 1893, Nassonow, 1886); Wheeler has shown that all the abdominal cœlomic sacs develop such peritoneal funnels, but that only those of one particular somite reach the exterior and become functional genital ducts. He also (1893*a*) holds that the œnocytes represent ectoblastic remains of nephridia. The prothoracic gland of Dicranura has been considered homologous (Latter, 1897). Nassonow (1886) has concluded a like relation for the head glands of *Campodea,* all salivary glands, the maxillary glands of *Lepisma,* and the extensible vesicles of the Thysanura; but Oudemans (1887) and Haase (1889) combat this view and regard the extensible glands at least as not nephridial but as respiratory skin glands. Wheeler (1893*a*) considers the fat-body to represent mesoblastic remains of nephridia; some of its cells are proved to be excretory (Wheeler, Cuénot, 1895, Bruntz, 1903), and Anglas (1901) suggests that such cells compose an "accumulating kidney" that functions during the substitution of Malpighian vessels in the metamorphosis.

*Nephrocytes.*—According to Bruntz (1903) these cells are labial in *Machilis,* and in it as in *Lepisma* are found also on the fat-body; in larval Neuroptera on the wing muscles; in *Ephemera*

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[7] Other ectoblastic glands regarded as excretory are the segmental globiform glands of *Ocypus* (Georgevitch, 1898).

on the fat-body; in the Hymenoptera, Hemiptera and Coleoptera on the pericardium; in the Lepidoptera usually dorsal in the abdomen; in the Diptera along the heart. The pericardial cells of Cuénot (1895) are perhaps to be reckoned with these.

### 29. DIPLOPODA.

*Malpighian Vessels.*—One pair proved to be excretory by Kowalevsky (1896) and Bruntz (1903).

*Homologues of Nephridia.*—Here are to be placed the genital ducts, that develop like those of *Peripatus* (Heathcote, 1888); and probably the salivary glands that are mesoblastic in origin (Heathcote), and which on account of their closed end sacs are named "rein labial" by Bruntz.

Fat-body and nephrocytes have been shown to be excretory (Bruntz).[8]

### 30. CHILOPODA.

*Malpighian Vessels.*—There is one pair of these in all genera (Verhœff, 1902), and they develop as outgrowths from the proctodæum (Sograf, 1883, Heymons, 1901).

*Homologues of Nephridia.*—The genital ducts are mesoblastic and to be compared with nephridia (Heymons); and Herbst (1891) has described for *Lithobius* a pair of glands with thin-walled end sacs opening behind the second maxillæ, and has suggested that these may be modified nephridia. The salivary glands are ectoblastic and not to be compared with nephridia (Heymons, 1898).

### 31. SYMPHYLA (SCOLOPENDRELLA).

There is one pair of Malpighian tubules; the ventral sacs are simply respiratory skin glands (Haase, 1889).

### 32. PAUROPODA.

*Malpighian Vessels.*—There is one pair of these in *Eurypauropus* but apparently only in the female (Kenyon, 1895). In *Pauropus* they are absent (Schmidt, 1895), and in this genus there are groups of cells in the fat-body that may be excretory (Kenyon).

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[8] Haase (1889) has demonstrated that the ventral sacs are neither excretory in function nor nephridial in origin.

### 33. Xiphosura (Limulus).

*Coxal Glands.*—A very thorough account has been given by Patten and Hazen (1900). The adult gland consists of four nephric lobes at the bases of the second, third, fourth and fifth legs, respectively, and these are connected medially by a stolon of collective tubules; the duct lies dorso-lateral from the latter, is much convoluted and opens at the basis of the fifth leg. The duct arises from a plate of cells of the somatic mesoblast of the fifth somite, this plate invaginating to produce a funnel opening into a thin-walled end sac that represents the fifth cœlomic sac; the distal end of the duct is formed by an ectoblastic invagination. Outgrowths of the end sac finally unite with cell chains of adjacent nephric lobes. In each of the six thoracic somites a mass of nephric cells arises independently of the duct from the somatic mesoblast, and these masses, of which the first and sixth ultimately disappear, form the nephric lobes; offshoots from the four persisting masses produce the canals of the stolon. Thus there are in the embryo six pairs of coxal glands, but only four of them persist in the adult.

The *genital ducts* arise as deverticula of the opercular mesoblastic sacs, and are to be compared with nephridia (Patten and Hazen).

### 34. Arachnida.

#### (1) *Araneida.*

*Malpighian Vessels.*—These are excessively dendritic and their delicate end branches form a fine felt-work around the liver lobes; by a pair of main ducts these open into the intestine just anterior to the rectal vesicle. They have been proved to be excretory (Marchal, 1889, Bruntz, 1903). Balfour (1880) and Morin (1888) described them as arising from the ectoblastic proctodæum; but with the exception of Kishinouye (1890, 1894) who derived them from the mesoblast, the other embryologists (Loman, 1887, Schimkewitsch, 1897) find that they develop from the entoblastic mid-gut. Locy (1886) described them as coming from the prestercoral tube, but though the latter is probably entoblastic its origin was not definitely settled. Renewed investigation is needed on this question, but the entoblastic origin seems to be best authenticated.

*Coxal Glands.*—Evidently these are not functional but are degenerate in the adult; Bruntz (1903) has proved they are excretory. In the young of *Atypus* there is a pair of these opening on the third coxæ (Sturany, 1891), but the duct is lacking in the adult (Sturany, Bertkau, 1885). In the young of *Mygale* Loman (1888) states it is degenerate, while Pelseneer (1885) finds no ducts but on each side of the body a four-lobed gland corresponding to the four extremities of the thorax. Sturany and Hansen and Sörensen (1904) state that in the Tetrapneumones it opens behind the fifth extremity (third leg) and in the Dipneumones behind the third (first leg). Kishinouye (1890) maintained that these organs arise from the ectoblast, though he showed that the anlage opens by a funnel into the cœlom.

*Genital Ducts.*—Purcell (1895) has shown that these arise as evaginations of the cœlomic sacs; "the similarity of their development with that of the coxal glands in Arachnids generally indicates their nephridial origin."

*Hind-gut.*—This is said to serve as an excretory organ until the Malpighian vessels are developed (Bertkau).[9]

### (2) *Scorpionidea.*

*Malpighian Vessels.*—These are branched, four in number (Dufour, 1854); though generally supposed to have the same function as those of other arachnids they are stated by Bruntz (1889) to be not urinary. They arise from the entoblastic mid-gut (Brauer, 1895).

*Homologues of Nephridia.*—The genital ducts develop like and are homodynamous with the coxal glands (Brauer, 1895). The latter are in one pair and open behind the fifth extremity (third leg); Bruntz has shown that they have an excretory function. These have each a narrow duct and an enlarged inner end sac. Bernard (1893) held these glands to be ectoblastic, independent of the cœlom, homologues of acicular glands. But the researches of Laurie (1890), Sturany (1891) and Brauer (1895) have demonstrated that they arise each as an outpushing of the somatic mesoblast that

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[9] The spinning glands are ectoblastic, and may be equivalent to crural glands, but are neither excretory nor nephridial.

reaches to and opens upon the skin, then later loses this opening; Brauer found that a series of them arise, in segments third to sixth, inclusive, but that all but those of the fifth segment soon disappear.

### (3) *Cyphophthalmidea.*

*Malpighian Vessels.*—There is one pair of these in *Gibocellum,* opening at the junction of the mid-gut and hind-gut; they are of great size and each is remarkable in having a net-like branching at its middle only (Stecker, 1876).

*Coxal Glands.*—Sturany (1891) holds what Stecker called "Speicheldrüsen" to be probably coxal glands; there is one pair of them on the sides of the stomach.

### (4) *Phalangida.*

There are here no Malpighian vessels, and their absence is due, according to Loman (1888), to the functional persistence of the coxal glands. The latter are organs with an inner closed end sac (Faussek, 1892), that open in the Opiliones laniatores behind the third, and in the Opiliones palpatores and Chelonethi behind the fifth extremity. They develop as mesoblastic outgrowths of the particular extremities in which they are placed (Sturany, 1891, Faussek, 1892).

### (5) *Pseudoscorpionidea* (*Chernetidæ*).

Here also there are no Malpighian vessels. The coxal glands are stated to have no exterior openings, to lie at the base of the fifth extremity, and to be of mesoblastic (nephridial) origin (Sturany, 1891). The spinning glands that have two pairs of opening on the chelicera are considered by Bertkau (1888) to be homologous with them.

### (6) *Solifugæ* (*Galeodidæ*).

*Malpighian Vessels.*—These are one pair of branched tubes.

*Coxal Glands.*—There is one pair placed between the third and fourth coxæ; Bernard (1893) considered the end sacs to be prolongations of the ducts, but his account is not convincing. Loman (1888) has suggested that the poison glands are homologous with them.

### (7) *Microthelyphonida* (*Palpigradi*).

There are no Malpighian vessels but the adult excretory organs are the coxal glands, and have been described by Rucker (1901) and Börner (1904). There is one pair of these extending forward from the third abdominal segment to their opening between the second and third legs; the great size of these Börner gives as the explanation for the loss of Malpighian vessels.

### (8) *Pedipalpi* (*Thelyphonida*).

*Malpighian Vessels.*—According to Börner (1904) there is one very ramose pair of these; they develop from the entoblastic stercoral pocket near its posterior end (Laurie, 1894).

*Coxal Glands.*—These are strongly developed, function in postembryonic life, and their ducts open on the third pair of coxæ (Börner).

### (9) *Acarina.*

My account of this group is necessarily very defective because for the most part I have seen only reviews of the literature.

*Malpighian Vessels.*—These seem to be absent in many species, but a pair of them has been described for *Ixodes* (Wagner, 1894), Gamasidæ (Michael, 1892, Winkler, 1888), *Halarachne* (Kraemer, 1885), and Tyroglyphidæ (Nalepa, 1884, 1885, Haller, 1880). In the nymphs of Gamasids these penetrate deep into each leg. For *Bdella* Karpelles (1893) has described an unpaired excretory organ of entoblastic origin opening into the rectum.

*Caudal* (*Proctodæal*) *Excretory Organs.*—These are urinary structures opening at the posterior end of the trunk without connection with the mid-gut, and are tubular or saccular, closed internally. These may be present (1) when the intestine is provided with an anus, as in *Hydrodroma* (Schaub, 1888); or (2) when the mid-gut ends blind and has no anus, as in Prostigmata (Thor, 1904), Gamasidæ (Michæl, 1892, 1895), and *Trombidium* (Croneberg, 1879, Henking, 1882). The suggestion was made by Thor that the second type probably represents a rectal bladder with Malpighian vessels that have become separated from the mid-gut. But the first type, that has an opening separate from the anus, cannot have been so formed, but would rather seem to be ectoblastic like the Malpighian vessels in Insects.

*Unicellular Glands of the Intestine.*—Nalepa (1888) has described for Phytopids three large unicellular glands in connection with the rectum, and supposed they may be excretory.

*Coxal Glands.*—In *Limnocharis* Thon (1905) found a pair of glands in the region of the second coxæ; in *Eulais* they are most active in the nymphal stage while they degenerate in the adult (by substitution of the proctodæal organ), but in *Limnochares* they function even in late life. Supposed coxal glands have also been described by With (1904) for the Notostigmata, by Sturany (1891) for *Trombidium,* by Winkler (1888) for Gamasidæ, and by Michæl (1883) for Oribatids. The lateral abdominal glands of Gamasids, Tyroglyphids and Oribatids may be homodynamous. The development of these various glands seems to be quite unknown, so that nothing can be said of their homologies.

## 35. LEPTOCARDII.[10]

The nephridia in *Amphioxus* were discovered by Weiss (1890) and particularly described by Boveri (1892). The latter found them to be segmentally arranged, in about ninety pairs in the branchial region, there being one pair to every two branchial arches. Each nephridium was described by Boveri as a canal with one opening into the ectoblastic atrium, and several into the cœlom (subchordal cavity); inserting into the orifice of each of these nephrostomes, but not into that of the nephridiopore, is a tuft of long Fadenzellen. Goodrich (1902) has reinvestigated these organs, and while he confirmed the preceding account in most particulars, he found that the Fadenzellen are solenocytes, each hollow with a long cilium and each closed from the body cavity, and that there are no open communications of nephridia with the cœlom: "These tubules are situated 'morphologically' outside the cœlom, being covered with cœlomic epithelium; the solenocytes alone push through into the cœlomic cavity." And he concluded "that in their

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[10] The Leptocardii exhibit so many morphological peculiarities that they are to be removed from the group of the Vertebrata; the Craniota by themselves compose a homogeneous assemblage.

segmental arrangement, in their function, and in their histological structure, the excretory organs of *Amphioxus* and the nephridia of *Phyllodoce* are in all essentials identical." In a second communication Boveri (1904) maintained the occurrence of true nephrostomes, and held the solenocytes to be modified peritoneal cells and not to be covered by a peritoneal investment.

Unfortunately nothing is known of the development of these structures.

## 36. Vertebrata (Craniota).

With regard to the excretory organs of this group I shall deal reather summarily, because they have been much more studied than the excretory organs of other animals, and because most of the larger contributions on the subject deal extensively with the literature.

*Nephridia.*—Good reviews of the embryogeny of these structures have been presented particularly by Rückert (1892), Boveri (1892), Wheeler (1899) and Brauer (1902). There are three kidney systems which occur in the ontogeny in the order of their naming; the pronephros, mesonephros and metanephros. The first two occur in all vertebrates, the third in amniotes only. The pronephros is purely an embryonic structure except in *Bdellostoma, Lepidosteus* and some Teleosts (*e. g., Fierasfer*) in which it functions also in the adult. The mesonephros is the adult kidney of all other anamniotes, and the metanephros of the amniotes. All these organs are paired and segmented.

*Pronephros.*—This develops in the anterior trunk segments as serial solid thickenings of the somatic mesoblast, each of which secondarily becomes tubular and pushes towards and opens into the cœlom. Their lateral ends unite to form the collecting tubule. The arterial connection is in most cases by a paired glomus, an unsegmented vascular inpushing of the dorsal peritoneum medial from and opposite the nephrostomes. The duct, generally known as the segmental duct, also as the pronephric or Wolffian duct, arises just lateral from the tubules and grows back from them to open into the cloaca; in the Selachii and Mammals, possibly also in *Lepidosteus,* it is ectoblastic and joints secondarily with the tubules; in all other forms it arises from the somatic mesoblast in conjunction with the tubules and like them is at first solid. Some of the more important papers on the development of these structures are the following: for the Amphibia, Fürbringer (1878), Mollier (1890), Field (1891), Semon (1891), and Brauer (1902); for the Cyclostomes, Wheeler (1899), Price (1897); for the Selachii, Balfour (1881), Van Wyhe (1889), Rückert (1888), Rabl (1896); for the Teleostei, Hoffmann (1886), Henneguy (1888), H. V. Wilson (1891), Swæn and Brachet (1901); for the Ganoidei, Parker and Balfour (1882), Beard (1889); for the Reptiles, Hoffmann (1889), Gregory (1900); for Aves, Sedgwick (1881), Balfour (1881), Renson (1883), Felix (1891); and for the Mammals, Spee (1884), Flemming (1886), Kollman (1891), Martin (1888).

*Mesonephros.*—These tubules develop usually in the segments behind the pronephroi, but there are certain segments that may contain both of them, and they are more numerous and more differentiated that the pronephroi. To understand their origin it is necessary to recall that the cœlom becomes divided into the dorsal myocœls (cavities of the myotomes or somites), the middle nephrocœls, both of these being segmented and paired, and the large unsegmented hypocœl that is imperfectly paired; these relations were established particularly by Van Wyhe. Very early the myocœls pinch off from the nephrocœls, whereby the latter are left as short tubes, the dorso-lateral end of each ending blindly while the ventral opens into the hypocœl. These peritoneal nephrocœls become the mesonephroi and grow laterad to join with and open into the segmental duct, for they develop no duct of their own. The arterial connection is segmental: From the aorta a vessel grows towards each tubule and ends in a capillary glomerulus against the wall of the latter above the nephrostome; the wall of the tubule forms a partial sheath (capsule of Bowman) around the glomerulus, In *Petromyzon* there is a larval as well as a definitive set of these tubules, and there may be several in each segment (Wheeler).

The principal studies on the mesonephros are these: For Selachii, Rückert (1888), Van Wyhe (1889), Rabl (1896); for Teleostei, Felix (1897); for Cyclostomata, Wheeler (1899), Price (1897), Maas (1897); for Amphibia, Semon (1891), Brauer (1902), Hall (1904); for Reptiles, Gregory (1900), Mihalkovics (1885), Wiedersheim (1890); for Aves, Sedgwick (1880), Felix (1891); and for Mammals, Janosik (1887), Martin (1888), H. Meyer (1890).

*Metanephros* (*Kidney of Amniotes*).—This consists of the duct or ureter, and the kidney proper, both developing behind the mesonephros. The ureter is a dorsal outgrowth from the segmental duct. There are two views concerning the origin of the glandular kidney. According to the first and older of these the kidney tubules arise as evaginations from the anterior end of the ureter (Kölliker, 1861, Waldeyer, 1870). There is much more evidence for the second view, origin independent of the ureter from mesoblastic tissue (Emery, 1883, Hoffmann, 1889, Wiedersheim, 1890). The ureter grows forward into an embryonic cell mass known as the kidney blastema, of somewhat uncertain origin, but possibly homodynamous with the anterior mesonephric anlage (Wiedersheim). According to the description of Emery (1883) the so-called collective tubules of the kidney arise as blind outgrowths of the ureter, and these join with the secretory tubules that arise independently from the kidney blastema. There is still much to be decided concerning the exact method of formation of the kidney, but certainly a considerable portion of it arises independent from the ureter from somatic mesoblast. Each tubule of the metanephros commences proximally with a Malpighian corpuscle, that is, a vascular glomerulus enclosed in a capsule of Bowman, a vascular relation like that of the mesonephroi; metanephric tubules lack nephrostomes or other connections with the cœlom.[11]

*Relations of these Nephridial Systems.*—That the pronephros and mesonephros are homodynamic is the view of Balfour (1881), Sedgwick (1881), Price (1897) and Brauer (1902). Field (1891) argued that the two are differentiated parts of one ancestral organ, that differ structurally because they develop at different periods. But the majority of investigators hold them to be not homodynamous, and here may be mentioned W. Müller (1875), Fürbringer (1878), Van Wyhe (1889), Rückert (1892), Semon (1891), Rabl (1896), Wheeler (1899), and Maas (1897). If we omit the conditions in the Gymnophiones in which the relations of the pronephros

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[11] Adult mesonephric tubules may still maintain their nephrostomes, or may lose them; cf. Spengel, 1876.

appear strongly modified or at least quite different from those in other groups, then it is highly probable that these two organ systems are not strictly homodynamous. For the pronephroi arise as solid thickenings of the somatic mesoblast, that later become tubular and only secondarily join with the cœlom; and their vascular supply is an unsegmented glomus opposite their nephrostomes. On the other hand the mesonephroi are abstricted portions of the cœlom (nephrocœls), they are from the start peritoneal and in open communication with the cœlom; and the vascular connection of each is a Malpighian corpuscle. The pronephroi are retroperitoneal, the mesonephroi, peritoneal funnels in the main; the former develop in close connection with the segmental duct, while the latter arise much later than it and join it secondarily. In view of these differences pronephros and mesonephros are probably only incompletely homodynamous.

As to the metanephros, its ureter being an outgrowth of the segmental duct is a new structure; while the glandular kidney arises from mesoblast that may represent a late generation of mesonephric tubules. Accordingly, the metanephros can be only in part homodynamous with the mesonephros.

*Homologues of Nephridia.*—Here are to be placed the genital organs that I will treat very briefly. Particular genital ducts are absent in the Cyclostomes, *Læmargus* and certain Teleostei; here the genital cells fall into the cœlom and are discharged through peritoneal canals, supposed peritoneal funnels (Weber, 1886), the development of which has not been studied.

In the males of Teleosts and certain other fishes the genital ducts are simply outgrowths of the gonads, while in all other forms the segmental ducts (or portions of them) are urogenital. The vasa efferentia of the testis, the paradidymis and the hydatid of Morgagni are modified mesonephric tubules.

In the females of all forms except most Teleosts and *Lepidosteus,* where the ducts are outgrowths of the gonads, the oviduct (with uterus when present) is distinct from the urinary canal (segmental duct or ureter) and is known as the Müllerian duct. This is paired and arises in the Selachii as a longitudinal abstriction of the segmental duct, but in other forms as a structure independent of the latter, *i. e.*, as a longitudinal peritoneal groove, showing sometimes (Reptiles) traces of segmental origin, that becomes a tube closed from the cœlom except at its anterior end (ostium). These two kinds of Müllerian ducts cannot be homologized, for the first is an abstriction from the segmental duct, while the second arises as a peritoneal infolding and may be compared with an elongated peritoneal funnel or with a series of them. The ovaries differ from testes in lacking vasa efferentia connecting them with the ducts, but other remnants of mesonephric tubules are found in amniotes in form of the epoöphoron and paroöphoron.

*Other Excretory Organs.*—The liver forms urea, while the sudoriparous glands, respiratory organs and skin aid in the discharge of waste substances.

## B. GENERAL COMPARISONS.

### I. Main Types of Excretory Organs.

We use the idea homology to denote that relation between a certain organ of one animal and a certain organ of another, which is dependent upon derivation from a common ancestral organ. In other words, homology denotes community of descent of parts. To elucidate such relations, to demonstrate change of both form and use of parts, is the first object of comparative anatomy; later all such knowledge may be so compounded as to give the general history of phylogeny. When one considers such manifold and diverse organs as those that subserve excretion, difficulties of interpretation that are almost insuperable arise to perplex and bewilder, yet at the same time compel, the attention. Any conclusions with regard to the homologies of these organs must be tentative because our knowledge of them is so very imperfect; in fact for most of the animal groups only the outlines have been made known. Therefore the following attempt to arrange the excretory organs according to their genetic relations should be regarded as only an essay.

The criteria of homology are still a matter of dispute. I have discussed this matter in another place (1906), and will simply state here that similarity of relative position to other parts seems to be the surest criterion, together with general similarity in mode of ontogenetic formation. We shall place first relative position with regard to the outer skin, the blastocœl and cœlom, the intestine and the genital organs. These relations involve genetic connections with the particular germ layers, and a word of discussion may be in place with regard to these. The concept of the essential homology of the primary germ layers has been many times attacked since its formulation by Huxley and Kowalevsky. Yet these objections have been weakened by much of the more recent work. Ectoblast always furnishes nervous elements, entoblast originates digestive and assimilative parts, from the mesoblast come the reproductive cells; these are cardinal distinctions that seem to hold throughout the Metazoa. Therefore it is no valid objection to the idea of the homology of these layers to cite the observations of Chun on Ctenophores, that in the process of gemmation an ectoblastic outpushing gives rise to both ectoblast and entoblast. This observation can rather prove only that such an ectoblastic bud is not purely ectoblastic but mixed in its nature. And when Heymon's studies on Insects, resulting in the completely ectoblastic formation of the whole intestine, are brought up as an objection, it may be answered that the observational distinction of the germ layers in insects is very difficult, and also that these conclusions have not been corroborated by all subsequent examiners. The oft-cited case of the Trematodes, to the effect that the embryo throws off its whole ectoblast, must now be allowed to drop since Goldschmidt has demonstrated that it is not the true ectoblast but only a follicle cell layer that becomes so moulted. For these and other reasons those critics are becoming fewer who maintain that ectoblast is not always homologous with ectoblast, and entoblast with entoblast throughout the Metazoa; and the most painstaking of all embryological work, that on cell-lineage, bears out most strongly the well-founded general homologies of these primary layers. The discussion has shifted rather to the significance of the mesoblast, the existence of which was so stoutly denied by Kleinenberg. This long and wearying discussion has brought out the result, first clearly stated by Meyer, that two kinds of mesoblast are to be sharply distinguished, the primary or mesectoblast, and the secondary or mesentoblast. The probable correctness of this distinction is amply substantiated by the cell-lineagists, and the arguments for it have been well presented by Torrey. The mesectoblast is of ectoblastic origin, it is in part equivalent to the mesenchyme of the Hertwigs; it forms larval and to less extent adult structures, but never gives rise to germ cells. The mesentoblast form adult structures and contains the germ cells. These again are fundamental differences, so that it is no longer sufficient to state a part is mesoblastic, it is necessary to know whether it is mesectoblastic or mesentoblastic. The mesectoblast is in reality an emigrant or delaminant of the ectoblast, it is genetically related with that layer and not with the mesoblast.

Relation of position to, and origin from, these four embryonic layers gives then a primary criterion for deciding the homologies of the excretory organs. And these relations of position involve also place-relations with regard to the primary cavities of the body: The blastocœl, the space between ectoblast and mesoblast; the cœlom, the space lined by mesentoblast; and the gastrocœl, the space lined by entoblast.

Using the relations of position and origin as of primary importance, and anatomical and histological relations as of secondary, we will proceed to arrange the excretory organs in genetic groups. Many of the organs described in the preceding part of this paper could not be entered here on account of the insufficiency of our knowledge concerning them; and some others have to be marked doubtful for the same reason. It is at the best a hazardous undertaking to classify other men's results, and the danger is multiplied when descriptions are imperfect.[12]

(*a*) *Wholly Ectoblastic Excretory Organs, not Opening into the Cœlom and not Serving as Genital Ducts.*

1. Hypodermal skin glands. These are perhaps the most primitive excretory organs, and are of wide distribution. Excretory function of them has been proved for Pycnogonids, Insects, Arachnids, Vertebrates and certain others; but probably most hypodermal glands are rather secretory than excretory.

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[12] Here may be mentioned a generalized embryonic excretory organ, the blastocoel, which Kofoid has shown to have the value of a discharging vesicle and to continue that function up to the gastrula stage; Meisenheimer has accepted Kofoid's conclusions.

2. Evaginated vesicles, open to the blastocœl. Here are to be reckoned the outer nephridia of prosobranch and pulmonate molluscan embryos, and probably the anal kidneys of opisthobranchs. The latter have a method of formation similar to that of the others, but they differ in position.

3. Tubular invaginations terminating blindly in flame cells, with the cavities of at least the capillaries intracellular. Their origin from the ectoblast has been proved only in the case of the Nemertini and Acanthocephala and with some doubt in the Polycladidea. Here are to be placed the definitive nephridia of the Platodes, Nemertini, Gastrotricha, Rotatoria, *Rhodope,* Acanthocephala, and the larval nephridia of *Phoronis;* probably those of the Endoprocta should be placed here (if they are not mesectoblastic), and perhaps those of the Priapulida and the head kidneys of some Molluscan larvæ. This type of excretory organ has been named by Hatschek (1888) protonephridium, though he extended this term to cover also organs of mesectoblastic and even mesentoblastic origin. This is a very natural group of excretory organs, showing great similarity in both structure and development. The only case of a larval or head kidney among them is that of *Phoronis,* yet here this kidney persists into the adult though it later joins with a cœlomostome. Kaiser (1892) is inclined to compare the organs of the Acanthocephala with those of Annelids or even with the anal kidneys of *Bonellia,* but their strictly ectoblastic origin renders this view unlikely; while those of the Acanthocephala open into the genital ducts, so also do those of certain Turbellaria, consequently this relation does not speak against their community.

4. Tubular invaginations with wholly intercellular cavity, without flame cells of cilia. These are the Malpighian vessels of Insects and Chilopods (? and of other Myriopods), the proctodæal organs of the Acarina, and possibly the rectal tubes of the Tardigrada. All of these either open into the proctodæum or upon the surface of the body near the anus; it is probable they secondarily acquired the proctodæal position when the ectoblast invaginated to produce the end-gut. These tubes are usually unbranched, but in some Insects they are dendritic. They differ from type 3 mainly in lacking cilia and in possessing a wholly intercellular cavity; but the

lack of ciliated epithelia is a histological characteristic of the groups that possess them.

### (*b*) *Mesectoblastic Organs.*

Here are to placed the following structures:

5. Scattered excretory cells, such as connective tissue elements of the Mollusca, and possibly the bacterioidic cells of the Oligochæta.

6. Closed vesicles, the kidney sacs of Tunicata, and possibly the nephrocysts of nudibranch Mollusca. These seem to act as centers of accumulation of waste substances.

7. Tubes communicating with the exterior, the inner ends blind and terminating with a flame cell or solenocytes. In all probability the larval nephridia (head kidneys) of Oligochæta and Polychæta belong here (in the latter sometimes a portion of the duct is strictly ectoblastic); possibly the nephridia of the Dinophilea fall also into this category, but nothing is known as yet of their development. In their structure these are very similar to the organs of type 3, the protonephridia in the restricted sense, the only difference being that the one come directly from the ectoblast, the others from the mesectoblast.

### (*c*) *Organs Wholly or Partially Mesentoblastic.*

These represent the more specialized kinds of excretory organs, correspond in part to the metanephridia of Hatschek, and may be subdivided into the following main types:

8. An ectoblastic invagination joining directly (without participation of retroperitoneal mesentoblast) with a cœlomostome (peritoneal funnel), the involved portion of the cœlom not exclusively excretory. Examples are the adult nephridia of *Phoronis,* and the head and collar pores of the Enteropneusta; homologous with these is the stone canal of the Echinodermata. The present evidence does not allow us to decide whether the segmental organs of the Sipunculida, Ectoprocta, Brachiopoda, Echiurids and Myzostomes belong with this type or with type 11.

9. An ectoblastic invagination joining directly (without participation of retroperitoneal mesentoblast) with a reduced cœlomic sac, the latter being an exclusively excretory end sac. There are

two main kinds of these: (1) The ectoblastic portion very small, and the end sac representing only a portion of the cœlom of a segment, as in the case of the salivary glands, nephridia, and genital ducts of the Protracheata. And (2) the ectoblastic portion relatively larger, the end sac being a whole cœlomic sac, as in the case of the coxal glands of Arachnids, Xiphosura, Crustacea, the salivary glands of Diplopods, and the antennal, maxillary and maxillipedal glands of Crustacea.

10. An ectoblastic tube joining with retroperitoneal mesentoblast, the latter neither joined with a cœlomostome nor serving as a genital duct; the inner end is either quite closed or else has a small opening (nephridiostome) into the cœlom; the cavity is usually intracellular. Here belong the larval nephridia of the Hirudinea, and the definitive nephridia of the Hirudinea, Oligochæta and some Polychæta (Phyllodocidæ, Glyceridæ, Nephthyidæ, Capitellidæ, and perhaps the Nereidæ). Probably the anal kidneys of Echiurids belong here, and perhaps also the nephridia of the Nematoda. In essential agreement with this type is the pronephros of the Vertebrata, which also consists of a retroperitoneal mesentoblastic tube whose inner end opens secondarily into the cœlom (not by a peritoneal funnel) and whose outer end joins with the segmental duct that is of either mesentoblastic or ectoblastic origin. Possibly the nephridia of the Leptocardii are also homologous, as Boveri has suggested, but nothing is known of their development; it will be recalled that Boveri homologized the atrial chamber of the Leptocardii with the segmental duct of the Vertebrata.[13] There is no homology between the segmental duct of Vertebrates and the longitudinal canals of the Polychætes *Lanice* and *Ploimia,* for the latter seem to be formed by a late fusion of the secretory portions of the

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[13] As to the phylogeny of this segmental duct, Balfour considered it to be the foremost modified pronephric tubule, and Field has accepted this view. Haddon (1886) and Beard (1887) suggested that the pronephroi first opened separately into an open ectoblastic groove, that later closed to become the segmental duct. Rückert (1888) also concluded that originally the pronephric tubules opened independently to the exterior, and that they extended through the whole trunk; he maintained that the segmental duct arose by the meeting and fusion of their lateral ends, that is, by a backward growth of collective tubules.

nephridia. Indeed, the segmental duct of Vertebrates appears to have originated in this class.

11. An ectoblastic tube (though this portion may be very small) joining with retroperitoneal entomesoblast, and the latter connecting with a cœlomostome; these are generally either urogenital or homodynamous with genital ducts, and the cavity is usually intercellular. The inner end is widely open at least in the embryo. These correspond to type 10, with the addition of a cœlomostome. In this type fall the nephridia of the Mollusca, and those of most Polychæta. As mentioned above, the segmental organs of the Sipunculida, Ectoprocta, Brachiopoda, Echiurida and Myzostomida probably belong either here or with type 8. Essentially homologous are the mesonephroi, therefore probably also the metanephroi, of the Vertebrates, which consist to great extent of peritoneal funnels. And Boveri has argued that the gonads of the Leptocardii may be homologous with these mesonephroi.

12. Non-tubular peritoneal differentiations of excretory nature. Here are the so-called ciliated funnels of the Holothurians, that are not funnels (cœlomostomes) at all, and the widely represented peritoneal glands (phagocytic organs, chloragogue *in parte*).

13. Non-tubular retroperitoneal mesentoblastic cell masses. With these belong a variety of structures the development of most of which has been little examined, such as the excretophores of the Hirudinea and the fat-body of Insects (the latter perhaps representing, as Wheeler has suggested, the remains of nephridia).

### (*d*) *Entoblastic Excretory Organs.*

14. These are relatively few in number and seldom have an exclusively excretory function. In the first place there are tubular evaginations of the mid-gut, as the Malpighian vessels of Arachnida, then the mid-gut cœca of the Polycladidea and Amphipoda and probably of the Arachnida; these are all essentially homologous. The whole mid-gut has been shown to be excretory in the Collembola, *Dinophilus* and the Ectoprocta; it seems to be specially so only when other excretory organs are wanting, and in that case there is either periodical moulting of the lining of the mid-gut

(Collembola), or when this fails there is rapid death of the individual from poisoning of the intestinal tract (Ectoprocta).

### 2. Homologies of the Preceding Types.

The entoblastic type (14) is *sui generis* and not related to the others. Types 12 (peritoneal glands) and 13 (retroperitoneal differentiations) are so generalized in both structure and function, that it is hardly advisable to attempt to draw homologies between them; and the same holds for types 1 (ectoblastic skin glands), 2 (ectoblastic vesicles), 5 (scattered mesectoblastic cells) and 6 (mesectoblastic vesicles). There remain then for consideration all those distinctly tubular organs, nephridia proper, into the composition of which entoblast does not enter.[14] The earliest and most uniform of these are those of type 3, ectoblastic invaginations terminating in flame cells, which are referable, as argued by Lang, to still simpler skin glands. Type 4, ectoblastic invaginations like 3 but without cilia, are essentially similar; for no one would hesitate to homologize the mid-gut of the Turbellaria and the Insects, though the former is ciliated and the latter is not; therefore one should not object to drawing homology between the water vascular system of the former and the Malpighian vessels of the latter. The lack of cilia is not a characteristic merely of these vessels, it marks all the tissues of the Insects. The only differences between types 3 and 4 is the lack of cilia in the latter, and this is a difference that is of little homological importance, a merely histological character. And essentially similar to both of these is type 7, tubes of mesectoblastic origin; they do not come immediately from the ectoblast, but from tissue of ectoblastic derivation which is but a step removed. These three types, accordingly, 3, 4 and 7 are anatomically and embryologically essentially alike, they are to be considered homologous; they stand in no relation to the cœlom, never conduct the genital prod-

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[14] The term nephridium has been used very variously since its coinage by Lankester (1877). It might be well to limit it in the future to tubular excretory organs not containing entoblast. In the descriptive part of the paper I have discussed special homologies of excretory organs within the same group, such as relations of embryonic to adult nephridia, of meganephridia and plectonephridia, homologies of tracheæ, etc.; these need not be repeated here.

ucts, and contain no mesentoblast. I would propose that Hatschek's (1888) term protonephridium be limited to them.

From such protonephridia the other types of nephridia have probably been derived by the persistence of only the discharge ducts, or portions of them, of the former and by the substitution of mesentoblastic elements for their other portions. The only elements of the protonephridia that have been retained, it should be repeated, are their distal nephridiopores with more or less of the connectant discharge ducts, while the remainder of the protonephridia, all the excretory portion proper, has been replaced by mesentoblastic elements. Accordingly, the two other main kinds of nephridia of which we shall have to speak can be at the most compared only in part with these protonephridia, only their distal nephridioporal ends can be so compared. The more specialized kinds of nephridia have probably originated from the protonephridia, not as further specializations of them but rather by addition of extraneous elements; on the whole they are not homologous.

These more specialized nephridia with mesentoblastic constituents fall into two main groups.

The first of them consists of types 8 and 9, both of which have in common the union of an ectoblastic duct with the peritoneum but have no retroperitoneal mesentoblast. They are either urogenital, or are homodynamous with genital ducts (?also in the Enteropneusta). Their main difference is that in type 8 the peritoneal invagination is more pronounced as a rule, and that in type 9 the connectant cœlom has become exclusively excretory. These differences are not important, and these two types are in general homologous. Until retroperitoneal elements are discovered for them they must be considered distinct from the following; and to them the name *cœlonephridium* might be given.

The second kind of the more specialized nephridia comprises types 10 and 11, both characterized by the union of ectoblast with retroperitoneal mesentoblast. Type 11 differs from 10 by the addition of a cœlomostome (peritoneal funnel), in the manner made known particularly by the studies of E. Meyer and Goodrich. Their essential peculiarity is the retroperitoneal mesentoblast, not the peritoneal funnel. Hatschek (1888) classed these together with the preceding as metanephridia, and diagnosed them by the presence of a cœlomostome; but the difference with regard to the retroperitoneal element seems to me so important that these should be held distinct from the preceding, and in that case it would be well to limit the term metanephridium to types 10 and 11.

The three main kinds of nephridia that these considerations lead us to distinguish may be briefly compared as follows: *Protonephridium* (types 3, 4, 7), wholly ectoblastic or mesectoblastic (possibly in some cases both ectoblastic and mesectoblastic); *cœlonephridium* (types 8, 9), distal ectoblastic portion joining directly with a cœlomostome; *metanephridium* (types 10, 11), distal ectoblastic portion joining with retroperitoneal mesentoblast, and the latter connecting or not connecting with a cœlomostome. Only the second and third of these ever serve as genital ducts or are homodynamous with them. The metanephridium is the most complex because it may consist of as many as three elements, and it contains the smallest amount of the ectoblastic constituent.

The protonephridium in the course of transmutation and division of labor has not become entirely replaced, but it has rather become reduced in amount by the substitution of other elements for certain of its parts. And there have been two paths in this process. By the one, a relatively larger portion of the protonephridium has persisted and a cœlomostome has become directly connected with it, exemplified by the cœlonephridium. By the other a relatively smaller portion of it has maintained itself, to this has been added a secretory tube of retroperitoneal mesentoblastic tissue, and to the latter in some cases a cœlomostome, as illustrated by the metanephridium. The cœlomostome is homologically a genital funnel, as demonstrated by Meyer and Goodrich, comparable with a genital duct of, *e. g.*, a Nemertean. But what the retroperitoneal mesentoblastic element was originally, before it attached itself to a protonephridium, we are unable to decide; it may have originated from the outer layer, that outside of the peritoneum, of a primitive gonadal pouch.

We have now to see how these conclusions relate themselves to the views of other students. It will not be necessary to attempt a full historical review of the various opinions because a good discussion of them has been recently furnished by Lang (1903). There are two main views: (1) That the nephridia of all the Metazoa are essentially homologous, and (2) that those of the higher Metazoa are dyshomologous with the protonephridia.

The first of these has been maintained particularly by Lang (1881, 1884, 1903). To him the starting point is the condition in the Turbellarian *Gunda,* where there are continuous longitudinal main trunks, and more or less regularly arranged excretory ducts. He holds that such a condition has maintained itself in the case of the plectonephridia of the Hirudinea and Oligochæta, but that it has become modified in other Annelids by the segmentation of the longitudinal trunks. This idea is in a sense a necessary corollary of his view of the close relationship of the Turbellaria and Hirudinea. Besides the similarity in the Turbellaria and the Hirudinea above mentioned, he adduces the following main anatomical resemblances. (1) Hatschek's contention that in *Polygordius* the adult nephridia develop as outgrowths from a continuous longitudinal canal; the error of this observation has since been pointed out by Fraipont, Meyer, and Woltereck. (2) The presence of net-like nephridia (plectonephridia) in the Annelids; I have entered into the question of the homologies of these in the descriptive section upon the Oligochæta, and here need only recall that Vejdovský's embryological studies have shown that the plectonephric condition is secondary, derived from the meganephric. (3) The similarity in histological structure of the two kinds of nephridia. (4) Occurrence of serial provisory larval nephridia in Polychætes, that closely resemble protonephridia; that these are homologous with larval protonephridia as well as with the definitive ones, accordingly, that the protonephridia are homologous with segmental organs. Thus Lang derived (1903) "all the segmental nephridia of the Annelids from the segmental portions of the water vascular system that open externally, on the premise that in the Annelids those canals have not persisted which joined the successive segments of the water vascular system. Such a nephridial segment would have consisted in the ancestors of the Annelids of a pair of water vascular trees with excretory ciliated cells on the terminal ends of the capillary branches, and of a trunk opening outward.

. . . Since in the development of the Annelids the head end of the body precedes and the trunk with its successive segments first later comes to formation, so develops first the first nephridial tree pair, the head kidney adapted to the larval body, whose homology with the water vascular system is not contended even by the opponents of the unit theory, later perhaps a second and possibly still a third similar pair with reduced branching. This most anterior pair of nephridial trees that functions during the earliest larval life, at a time when there is still no secondary body cavity developed in the regions concerned, became in the phylogeny a transitory provisory structure, as can be demonstrated on so many larval organs, while the succeeding nephridial pairs of the trunk segments changed to segmental organs."

The other main view is that represented by Bergh (1885). According to him the larval nephridia of the Cœlomata are homologous with the protonephridia, while the adult nephridia of the Annelids are homologous with the gonadal ducts of the Platodes but not homologous with the protonephridia. Thus he concluded (as Williams did long before) that the segmental organs of Annelids were originally genital ducts and later changed into excretory organs; while the protonephridia do not communicate with the cœlom and never serve as genital ducts.

Goodrich has recently represented a view that in the main supports Lang's. To him there are " nephridia " proper that never serve as genital ducts; he considers all of these ectoblastic invaginations and essentially homologous. Then, adding materially to the discoveries of Eisig and E. Meyer, amplifying them, he find that upon such a nephridium a cœlomostome (peritoneal funnel, genital funnel) may become grafted, giving rise then to a complex " nephromixium." To Goodrich all nephridia are essentially homologous, they differ only in being combined or not combined with a cœlomostome.[15] His argument like Lang's is rather anatomical than embryological. Both of these investigators also lay great stress upon the presence in Annelid nephridia of the solenocytes, cells similar to the flame cells of protonephridia; Goodrich argues that such com-

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[15] In the descriptive part under the caption of Polychæta, Goodrich's ideas are given more *in extenso*.

plex cells could not have arisen independently in the two groups, rather that their presence in them means homology of the organs concerned.

It will be seen that my views do not coincide exactly with any of the preceding. I agree entirely with Meyer and Goodrich that the cœlomostome is an organ of origin independent from the nephridium, one that in some cases may connect with the latter. This cœlomostome is equivalent to the genital duct of a lower metazoan, as shown by Bergh. I agree also with Lang that the excretory ducts of the protonephridia have maintained themselves in part in the higher Metazoa, and that the longitudinal canals have disappeared. But I have tried to show that while sometimes such an excretory duct joins directly with a cœlomostome, forming what I call a cœlonephridium, in other cases it joins with retroperitoneal mesentoblastic tissue and the latter may secondarily join with a cœlomostome (metanephridium). In other words, we have to reckon with a retroperitoneal element that frequently forms the greater portion of the nephridium, and this is what Lang and Goodrich have failed to take into account. And I differ from Bergh in concluding that the metanephridium is not in its entirety equivalent to a genital duct, but that only a portion of it (the cœlomostome) is. Goodrich's mistake, if my interpretation is correct, is in assuming that there are only two elements, ectoblastic tube and peritoneal cœlomostome; he entirely neglects the retroperitoneal tissue, and yet this is just what shows the dyshomology of protonephridium and metanephridium. It is a mistake that has resulted from too exclusive reliance upon phenomena of adult structure with neglect of comparative embryology. And the arguments from histological similarity, intracellular cavity, similarity of solenocytes to flame cells, etc., can have little weight now that we are acquainted with still more striking cases of histological convergence as notably the case of the Malpighian vessels of Insects and those of Arachnids. Goodrich has excellently analyzed the history of the cœlomostome and has thereby greatly clarified our knowledge of nephridia. But he has omitted entirely from his general conclusions the retroperitoneal element which has come to supplant the protonephridium almost entirely thus excluding the homology of the protonephridium and metanephridium.

It will be noted that in my considerations I have entirely excluded the argument from the side of the recapitulation theory, for I have maintained (1906) that this theory is fundamentally erroneous. I have compared corresponding stages, adult or embryonic, of the different groups, have stressed embryological resemblances, but have not compared an adult stage of one organ with an embryonic one of another.

It might be expected that I should now enter upon the question of the phylogenetic significance of the cœlom, because this space has so often a close anatomical connection with nephridia. But I have nothing new to add to the discussion, and for a good representation of it would refer to the treatments by E. Meyer (1901) and Lang (1903). I need only state that there are three main theories in explanation of the origin of the cœlom. The oldest was founded by Sedgwick, and is to the effect that the cœlom is an enterocœlic diverticulum, referable to a gastral pocket of an anthozoan. This has deservedly received little support. Next came the gonocœl theory, foreshadowed by Hatschek, elaborated particularly by Bergh and E. Meyer, and more recently supported by Lang and Goodrich; it concludes that the cœlomic sac of a higher metazoan is the amplified derivative of the genital pouch (gonad) of such a form as a Platode, therefore that the mesentoblast is referable to germ cells The third view is the nephrocœl theory, founded by Faussek (1901) and Ziegler (1898), that the cœlom was originally an excretory organ and that the germ cells have associated themselves secondarily with it. Of these three theories the gonocœl theory seems to me to receive the fullest support from the facts of anatomy and embryology.

## LITERATURE LIST.

**Ahting, K.**

**1901.** Untersuchungen über die Entwickelung des Bojanusschen Organs und des Herzens der Lamellibranchier. *Jena. Zeit.*, 36.

**Allen, E. J.**

**1904.** The Anatomy of Pœcilochætus, Claparède. *Quart. Journ. Micr. Sci.* (2), 48.

**Anglas, J.**

**1901.** Observations sur les métamorphoses internes de la Guêpe et de l'Abeille. *Bull. Sc. France et Belg.*, 34.

**Balfour, F. M.**

**1880.** Notes on the Development of the Araneina. *Quart. Journ. Micr. Sci.* (2), 20.

**1881.** A Treatise on Comparative Embryology, London.

**1883.** The Anatomy and Development of Peripatus capensis. *Quart. Journ. Micr. Sci.* (2).

**Balfour, F. M., and Parker, W. N.**

**1882.** On the Structure and Development of Lepidosteus. *Phil. Trans. R. Soc. London,* 173.

**Basse, L.**

**1905.** Beiträge zur Kenntnis des Baues der Tardigraden. *Zeit. w. Zool.,* 80.

**Bateson, W.**

**1884.** Note on the later stages in the development of Balanoglossus Kowalevskii (Agassiz), etc. *Proc. R. Soc. London.*

**1886.** Continued account of the later stages in the development of Balanoglossus Kowalevskii, etc. *Quart. Journ. Micr. Sci.* (2), 26.

**Beard, J.**

**1887.** The origin of the segmental duct in Elasmobranchs. *Anat. Anz.,* 2.

**1889.** On the early development of Lepidosteus. *Proc. Roy. Soc. London,* 46.

**1894.** The Nature of the Hermaphroditism of Myzostoma. *Zool. Anz.,* 17.

**Beddard, F. E.**

**1888a.** On the occurrence of numerous nephridia in the same segment in certain Earthworms, etc. *Quart. Journ. Micr. Sci.* (2), 28.

**1888b.** On certain points in the structure of Urochæta E. P., and Dichogaster n. g., etc. *Ibid.,* 29.

**1889.** On the possible origin of the Malpighian tubules in the Arthropoda. *Ann. Mag. Nat. Hist.* (6), 4.

**1890.** On the structure of a new genus of Oligochæta (Deodrilus) and on the presence of anal nephidia in Acanthodrilus. *Quart. Journ. Micr. Sci.* (2), 31.

**1891a.** On the homology between genital ducts and nephridia in the Oligochæta. *Proc. R. Soc. London,* 48.

**1891b.** On the structure of an Earthworm allied to Nemertodrilus Mich., etc. *Quart. Journ. Micr. Sci.* (2), 32.

**1892.** On certain points in the development of Acanthodrilus multiporus. *Ibid.,* 33.

**1902.** A note upon the Gonad Ducts and Nephridia of Earthworms of the Genus Eudrilus. *Proc. R. Soc. London.*

**Bemmelen, J. F. Van.**

**1883.** Untersuchungen über den anatomischen und histologischen Bau der Brachiopoda Testicardinia. *Jena. Zeit.,* 16.

**Beneden, E. Van et Julin, C.**

**1886.** Recherches sur la morphologie des Tuniciers. *Arch. de Biol.,* 6.

**Benham, W. B.**

**1886.** Studies on Earthworms. *Quart. Journ. Micr. Sci.* (2), 26, 27.

**1888.** Note on a new Earthworm. *Zool. Anz.,* 11.

**1889.** The Anatomy of Phoronis Australis. *Quart. Journ. Micr. Sci.* (2), 30.

**1890a.** An attempt to classify Earthworms. *Ibid.,* 31.

**1890b.** Report on an earthworm collected for the Natural History Department of the British Museum, etc. *Journ. R. Micr. Soc. London.*

**1891.** The nephridium of Lumbricus and its blood-supply; with remarks on the nephridia in other Chætopoda. *Quart. Journ. Micr. Sci.* (2), 32.

**1904.** On a new species of the genus Haplotaxis; with some remarks on the genital ducts in the Oligochæta. *Ibid.,* 48.

**Bergh, R. S.**

**1884.** Ueber die Metamorphose von Nephelis. *Zeit. w. Zool.,* 41.

**1885.** Die Excretionsorgane der Würmer. *Kosmos,* 17.

**1886.** Untersuchungen über den Bau und die Entwickelung der Geschlechtsorgane der Regenwürmer. *Zeit. w. Zool.,* 44.

**1888.** Zur Bildungsgeschichte der Excretionsorgane bei Criodrilus. *Arb. Zool. Inst. Würzburg,* 8.

**1890.** Neue Beiträge zur Embryologie der Anneliden. I. Zur Entwickelung und Differenzirung des Keimstreifen von Lumbricus. *Zeit. w. Zool.,* 50.

**1891.** Die Schichtenbildung im Keimstreifen der Hirudineen. *Ibid.,* 52.

**1899.** Nochmals über die Entwickelung der Segmentalorgane. *Ibid.,* 66.

**1901.** Kleinere histologische Mittheilungen. *Ibid.,* 69.

**Bernard, H. M.**

**1893.** The Coxal Glands of Scorpio. *Ann. Mag. Nat. Hist.* (6), 11.

**1896.** The Comparative Morphology of the Galeodidæ. *Trans. Linn. Soc. London* (2), 6.

**Berndt, W.**

**1903.** Zur Biologie und Anatomie von Alcippe lampas Hancock. *Zeit. w Zool.,* 74.

**Bertkau, P.**

**1885.** Ueber die Coxaldrüsen. *Verh. Nat. Ver. Bonn,* 41.

**1888.** Ueber die Chernetiden oder Pseudoskorpione. *Ibid.,* 44.

**Blochmann, F.**

**1900.** Untersuchungen über den Bau der Brachiopoda. II ter Theil. Jena.

**Bobretzky, N.**

**1877.** Studien über die embryonale Entwicklung der Gasteropoden. *Arch. mikr. Anat.,* 13.

**Böhmig, L.**

**1893.** Zur feineren Anatomie von Rhodope Veranii Kölliker. *Arb. zool. Inst. Graz,* 5.

**1898.** Beiträge zur Anatomie und Histologie der Nemertinen. *Ibid.,* 6.

**1906.** Tricladenstudien, I. *Ibid.,* 7.

**Bolsius, H.**
1892. Les organes ciliés des Hirudineés. *La Cellule,* 7.

**Bonnier, J.**
1891. La glande antennale chez les Amphipodes de la famille des Orchestidæ. *C. R. Acad. Sci. Paris,* 113.

**Börner, C.**
1904. Beiträge zur Morphologie der Arthropoden, 1. Ein Beitrag zur Kenntniss der Pedipalpen. *Zoologica,* 42.

**Bourne, A. G.**
1884. Contributions to the Anatomy of the Hirudinea. *Quart. Journ. Mier. Sci.* (2), 24.
1894. On certain Points in the Development and Anatomy of some Earthworms. *Ibid.,* 36.

**Boutan, L.**
1885. Recherches sur l'anatomie et la développement de la Fissurella. *Arch. Zool. expér. gén. 3, supplement.*

**Boveri, T.**
1892. Die Nierencanälchen des Amphioxus. *Zool. Jahrb.,* 5.
1904. Bemerkungen über den Bau der Nierencanälchen des Amphioxus. *Anat. Anz.,* 25.

**Brandes, G.**
1901. Die Parasiten des Menschen (Leuckart). 2te Aufl. Leipzig.

**Brauer, A.**
1895. Beiträge zur Kenntnis der Entwickelungsgeschichte des Skorpions, 2. *Zeit. wiss. Zool.,* 59.
1902. Beiträge zur Kenntnis der Entwickelung und Anatomie der Gymnophionen, 3. Die Entwickelung der Excretionsorgane. *Zool. Jahrb.,* 16.

**Braun, M.**
1893. Trematodes. Bronn's Klassen und Ordnungen des Thierreichs, 4, Leipzig.

**Bruntz, L.**
1903a. Contribution à l'étude de l'excrétion chez les Arthropodes. *Arch. de Biol.,* 20.
1903b. Excrétion et phagocytose chez les Onychophores. *C. R. Acad. Sci. Paris,* 136.

**Bugge, G.**
1902. Zur Kenntnis der Exkretionsgefässsystems der Trematoden und Cestoden. *Zool. Jahrb.,* 16.

**Bürger, O.**
1891. Beiträge zur Entwickelungsgeschichte der Hirudineen. Zur Embryologie von Nephelis. *Ibid.,* 4.
1894. Neue Beiträge zur Entwickelungsgeschichte der Hirudineen. Zur Embryologie von Hirudo medicinalis und Aulastomum gulo. *Zeit. wiss. Zool.,* 58.

1895. Nemertinen. Fauna u. Flora d. Golfes v. Neapel, 22.

1902. Weitere Beiträge zur Entwickelungsgeschichte der Hirudineen. Zur Embryologie von Clepsine. *Zeit. wiss. Zool.,* 72.

**Bütschli, O.**

1870. Zur Entwickelungsgeschichte der Biene. *Ibid.*

1877. Entwicklungsgeschichtliche Beiträge. Ueber Paludina vivipara. *Ibid.,* 29.

**Caldwell, E. H.**

1882. Preliminary Note on the Structure, Development and Affinities of Phoronis. *Proc. R. Soc. London,* 34.

**Casteel, D. B.**

1904. The Cell-lineage and early larval Development of Fiona marina, a Nudibranchiate Mollusk. *Proc. Acad. Nat. Sci. Philadelphia.*

**Chun, C.**

1880. Die Ctenophoren des Golfes von Neapel. Fauna u. Flora d. Golfes v. Neapel, 1.

**Claus, C.**

1875. Die Schalendrüse der Daphnien. *Zeit. wiss. Zool.,* 25.

1877. Die Schalendrüse der Copepoden. *Sitzber. Akad. Wiss. Wien,* 74.

1890. Ueber die Organisation der Cypriden. *Anz. Akad. Wiss. Wien,* 27.

1895. Beiträge zur Kenntnis der Süsswasser-Ostracoden. *Arb. zool. Inst. Wien,* 11.

**Coe, W. R.**

1896. Notizen über den Bau des Embryos von Distomum hepaticum. *Zool. Jahrb.,* 9.

1906. A peculiar Type of Nephridia in Nemerteans. *Biol. Bull.,* 11.

**Conklin, E. G.**

1897. The Embryology of Crepidula. *Journ. Morph.,* 13.

1905. The Organization and Cell-Lineage of the Ascidian Egg. *Journ. Acad. Nat. Sci. Philadelphia* (2), 13.

**Conte, A.**

1902. Contributions à l'embryologie des Nématodes. *Ann. Univ. Lyon* (2), 1.

**Cori, C. J.**

1890. Untersuchungen über die Anatomie und Histologie der Gattung Phoronis. *Zeit. wiss. Zool.,* 51.

1893. Die Nephriden der Cristatella. *Ibid.,* 55.

**Cosmovici, L. C.**

1880. Glandes génitales et organes segmentaires des Annélides polychètes. *Arch. Zool. expér. gén.,* 8.

**Cowles, R. P.**

1905. Phoronis architecta. *Mem. National Acad. Sci. Washington,* 10.

**Croneberg, A.**

1879. Ueber den Bau von Trombidium. *Bull. Soc. Imp. Nat. Moscou,* 2.

**Cuénot, L.**
1888. Études anatomiques et morphologiques sur les Ophiures. *Arch. Zool. expér. gén.* (2), 5 *bis.*
1895. Études physiologiques sur les Orthopterès. *Arch. de Biol.,* 14.
1897. Études physiologiques sur les Oligochètes. *Ibid.,* 15.
1899. L'excrétion chez les Mollusques. *Ibid.,* 16.
1901. Études physiologiques sur les Astéries. *Arch. Zool. expér. gén.* (3), 9.
1902. Organes agglutinants et organes cilio-phagocytaires. *Ibid.,* 10.

**Daday, E. v.**
1895. Die anatomischen Verhältnisse der Cyprois dispar (Chyz.). *Termész. Füzetek.,* 18.

**Dahlgrün, W.**
1901. Untersuchungen über den Bau der Excretionsorgane der Tunicaten. *Arch. mikr. Anat.,* 58.

**Danielssen, D. C. and Koren, J.**
1881. Gephyrea. Norske Nordhavs-Expedition. 1876–1878, 4, Christiania.

**Darboux, J. G.**
1900. Recherches sur les Aphrodities, Lille.

**Davenport, C. B.**
1893. On Urnatella gracilis. *Bull. Mus. Zool. Harvard,* 24.

**Dawydoff, C.**
1907. Sur le développement du nephridium de la trompe chez les Entéropneustes. *Zool. Anz.,* 31.

**Della Valle, A.**
1893. Gammarini. Fauna u. Flora d. Golfes v. Neapel, 20.

**Dohrn, A.**
1870. Untersuchungen über Bau und Entwicklung der Arthropoden, Leipzig.
1881. Die Pantopoden. Fauna u. Flora d. Golfes v. Neapel, 3.

**Doncaster, L.**
1902. On the Development of Sagitta; with Notes on the Anatomy of the Adult. *Quart. Journ. Micr. Sci.* (2), 46.

**Drasche, R. v.**
1884. Beiträge zur Entwicklung der Polychæten, 1, Wien.

**Drummond, I. M.**
1902. Notes on the Development of Paludina vivipara, with special reference to the Urino-genital Organs and Theories of Gasteropod Torsion. *Quart. Journ. Micr. Sci.* (2), 46.

**Dufour, L.**
1833. Recherches anatomiques et physiologiques sur les Hemiptères. *Mém. Acad. Sci. Paris,* 4.
1841. Recherches anatomiques et physiologiques sur les Orthoptères, les Hyménoptères et les Néuroptères. *Ibid.,* 7.
1851. Recherches anatomiques et physiologiques sur les Diptères. *Ibid.,* 11.
1854. Histoire anatomique et physiologique des Scorpions. *Ibid.,* 14.

**Ehlers, E.**

**1890.** Zur Kenntniss der Pedicellineen. *Abh. Ges. Wiss. Göttingen,* 36.

**Eisig, H.**

**1887.** Monographie der Capitelliden. Fauna u. Flora d. Golfes v. Neapel.

**Emery, C.**

**1883.** Ricerche embriologiche sul rene dei Mammiferi. *Mem. Accad. Lincei.* 15.

**Erlanger, R. v.**

**1891a.** Zur Entwicklung der Paludina vivipara. *Morph. Jahrb.,* 17.

**1891b.** Zur Entwicklung von Paludina vivipara. II Theil. *Ibid.*

**1892a.** Mittheilungen über Bau und Entwicklung einiger marinen Prosobranchier, I. Ueber Capulus hungaricus. *Zool. Anz.,* 15.

**1892b.** Beiträge zur Entwicklungsgeschichte der Gastropoden. Erster Theil. Zur Entwicklung von Bythinia tentaculata. *Mittheil. zool. Stat. Neapel,* 10.

**1893.** Bemerkungen zur Embryologie der Gasteropoden, 1. Ueber die sogenannten Urnieren der Gasteropoden. *Biol. Centralbl.,* 13.

**1894.** Bemerkungen zur Embryologie der Gasteropoden, II. *Ibid.,* 14.

**Evans, R.**

**1901.** On the Malayan Species of Onychophora, Part 2. *Quart. Journ. Micr. Sci.* (2), 45.

**Faussek, V.**

**1892.** Zur Anatomie und Embryologie der Phalangiden. *Biol. Centralbl.,* 12.

**1900.** Untersuchungen über die Entwicklung der Cephalopoden. *Mittheil. zool. Stat. Neapel,* 14.

**Felix, W.**

**1891.** Die erste Anlage des Excretionssystems des Hühnchens. Festschr. f. Nägeli u. Kölliker, Zürich.

**1897.** Beiträge zur Entwickelungsgeschichte der Salmoniden. *Anat. Hefte,* 8.

**Field, G. W.**

**1892.** The Larva of Asterias vulgaris. *Quart. Journ. Micr. Sci.* (2), 34.

**Field, H. H.**

**1891.** The development of the pronephros and segmental duct in Amphibia. *Bull. Mus. Zool. Harvard,* 21.

**Flemming, W.**

**1886.** Die ektoblastische Anlage des Urogenital-systems beim Kaninchen. *Arch. Anat. Physiol.*

**Foettinger, A.**

**1887.** Sur l'anatomie des Pédicellines de la côte d'Ostende. *Arch. de Biol.,* 7.

**Fol, H.**

**1875.** Études sur le développement des Ptéropodes. *Arch. Zool. expér. gén.,* 4.

**1880.** Études sur le développement des Gastéropodes pulmonés. *Ibid.,* 8.

**Folsom, J. W. and Welles, M. U.**

1906. Epithelial Degeneration, Regeneration, and Secretion in the Mid-Intestine of Collembola. *Univ. Illinois Bull.* 4.

**Fraipont, J.**

1888. Le genre Polygordius. Une monographie. Fauna u. Flora d. Golfes v. Neapel, 14.

**Fürbringer, M.**

1878. Zur vergleichenden Anatomie und Entwicklungsgeschichte der Excretionsorgane der Vertebraten. *Morph. Jahrb.*, 4.

**Gast, R.**

1900. Beiträge zur Kenntniss von Apsilus vorax (Leidy). *Zeit. wiss. Zool.*, 67.

**Georgevitch, J.**

1898. Die Segmentaldrüsen von Ocypus. *Zool. Anz.*, 21.

**Georgevitch, P. M.**

1900. Zur Entwickelungsgeschichte von Aplysia depilans L. *Anat Anz.*, 18.

**Gerould, J. H.**

1896. The Anatomy and Histology of Caudina arenata. Gould. *Bull. Mus. Zool. Harvard,* 29.

1906. The Development of Phascolosoma. *Zool. Jahrb.*, 23.

**Gilson, G.**

1894. The Nephridial Duct of Owenia. *Anat. Anz.*, 10.

**Glaser, O. C.**

1905. Ueber den Kannibalismus bei Fasciolaria tulipa (var. distans) und deren larvale Exkretionsorgane. *Zeit. wiss. Zool.*, 80.

**Goldschmidt, R.**

1906. Mittheilungen zur Histologie von Ascaris. *Zool. Anz.*, 29.

**Goodrich, E. S.**

1895. On the Cœlom, Genital Ducts, and Nephridia. *Quart. Journ. Micr. Sci.* (2), 37.

1897a. Notes on the Anatomy of Sternaspis. *Ibid.*, 40.

1897b. On the Nephridia of the Polychæta, Part I. On Hesione, Tyrrhena, and Nephthys. *Ibid.*, 40.

1898. On the Nephridia of the Polychæta, Part II. Glycera and Goniada. *Ibid.*, 41.

1900. On the Nephridia of the Polychæta, Part III. The Phyllodocidæ, Syllidæ, Amphinomidæ, etc., with Summary and Conclusions. *Ibid.*, 43.

1902. On the Structure of the Excretory Organs of Amphioxus. *Ibid.*, 45.

1903. On the Body Cavities and Nephridia of the Actinotrocha larva. *Ibid.*, 47.

**Graf, A.**

1893. Beiträge zur Kenntniss der Exkretionsorgane von Nephelis vulgaris. *Jena. Zeit.*, 28.

1899. Hirudineen-studien. Nova Acta Acad. Leop. Carol. 72.

**Graff, L. v.**

1882. Monographie der Turbellarien, 1. Rhabdocœlidea. Leipzig.

**Grassi, G. B.**

1883. I Chetognati. Fauna u. Flora d. Golfes v. Neapel, 5.
1885. Intorno allo sviluppo delle api nell' uovo. *Atti. Accad. Gioenia,* 18.
1886. Intorno ad un nuovo aracnide artrogastro. *Boll. Soc. entom. ital.,* 18.
1888. Anatomia comparata dei Tisanuri. Reale Accad. de Lincei (4), 4.

**Greef, R.**

1879. Die Echiuren (Gephyrea armata). Nova Acta Leop. carol. Akad. Halle, 41.

**Gregory, E. R.**

1900. Observations on the Development of the Excretory System in Turtles. *Zool. Jahrb.,* 13.

**Grobben, C.**

1879. Die Entwickelungsgeschichte der Moina rectirostris. *Arb. zool. Inst. Wien,* 2.
1881. Die Antennendrüse der Crustaceen. *Ibid.,* 3.
1888. Die Pericardialdrüse der chætopoden Anneliden, nebst Bemerkungen über die perienterische Flüssikkeit derselben. *Sitzber. Akad. Wiss. Wien,* 97.

**Gruvel, A.**

1894. Contribution à l'étude des Cirrhipèdes. *Arch. Zool. expér. gén.* (3), 1.

**Guiart, J.**

1901. Contribution à l'étude des Gastéropodes opisthobranches et en particulier des Céphalaspides. *Mém. Soc. Zool. France,* 14.

**Haase, E.**

1889. Die Abdominalanhänge der Insekten mit Berücksichtigung der Myriopoden. *Morph. Jahrb.,* 15.

**Haddon, A. C.**

1886. Suggestion respecting the epiblastic origin of the Segmental Duct. *Proc. R. Soc. Dublin* (2), 5.

**Hall, R. W.**

1904. The Development of the Mesonephros and the Müllerian Duct in Amphibia. *Bull. Mus. Zool. Harvard,* 45.

**Haller, G.**

1880. Zur Kenntnis der Tyroglyphen und Verwandten. *Zeit. wiss. Zool.,* 34.

**Hamann, O.**

1887. Beiträge zur Histologie der Echinodermen. *Heft* 3. *Jena. Zeit.,* 21.

**Hansen and Sörensen.**

1904. On two Orders of Arachnids, etc. Cambridge.

**Harmer, S. F.**

1885. On the structure and development of Loxosoma. *Quart. Journ. Micr. Sci.* (2), 25.

1889. Notes on the Anatomy of Dinophilus. *Journ. Marine Biol. Assoc. London* (2), 1.

1891. On the Nature of the Excretory Processes in Marine Polyzoa. *Quart. Journ. Micr. Sci.* (2), 33.

**Hatschek, B.**

1877a. Embryonalentwicklung und Knospung der Pedicellina echinata. *Zeit. wiss. Zool.,* 29.

1877b. Beiträge zur Entwickelungsgeschichte der Lepidopteren. *Jena. Zeit.,* 11.

1878. Studien über Entwicklungsgeschichte der Anneliden. *Arb. zool. Inst. Wien,* 1.

1880a. Ueber Entwicklungsgeschichte von Teredo. *Ibid.,* 3.

1880b. Ueber Entwicklungsgeschichte von Echiurus und die systematische Stellung der Echiuridæ (Gephyrei Chætiferi). *Ibid.,* 3.

1883. Ueber Entwicklung von Sipunculus nudus. *Ibid.,* 5.

1885. Entwicklung der Trochophora von Eupomatus uncinatus Philippi (Serpula uncinata). *Ibid.,* 6.

1888. Lehrbuch der Zoologie, Jena.

**Heathcote, F. G.**

1888. The Post-embryonic Development of Julus terrestris. *Proc. R. Soc. London,* 43.

**Hempelmann, F.**

1906. Zur Morphologie von Polygordius lacteus Schn. und Polygordius triestinus Woltereck, nov. spec. *Zeit. wiss. Zool.,* 84.

**Henking, H.**

1882. Beiträge zur Anatomie, Entwicklungsgeschichte und Biologie von Trombidium fuliginosum Herm. *Ibid.,* 37.

**Henneguy, F.**

1888. Recherches sur le développement des Poissons osseux. Embryogénie de la Truite. *Journ. Anat. Physiol.,* 24.

**Henseval, M.**

1896. Étude comparée des glandes de Gilson. Organes métamériques des larves d'Insectes. La Cellule, 12.

**Herbst, C.**

1891. Beiträge zur Kenntnis der Chilopoden. *Bibl. Zool.,* 9.

**Hérouard, E.**

1893. Recherches sur les Holothuries de la mer Rouge. *Arch. Zool. expér. gén.* (3), 1.

**Hertwig, O.**

1880. Die Chætognathen. Eine Monographie. *Jena. Zeit.,* 14.

**Hertwig, O. und R.**

1881. Die Cölomtheorie, Jena.

**Hescheler, K.**

1900. Mollusca. Lang's Lehrbuch der vergleichenden Anatomie der wirbellosen Thiere. 2te Aufl. Jena.

**Heymons, R.**

**1893.** Zur Entwicklungsgeschichte von Umbrella mediterranea Lam. *Zeit. wiss. Zool.*

**1896.** Grundzüge der Entwickelung und des Körperbaues von Odonaten und Ephemeriden. *Anh. Abh. Akad. Wiss. Berlin.*

**1898.** Entwickelungsgeschichte der Chilopoden. *Sitz. Ber. Akad. Wiss Berlin.*

**1901.** Die Entwickelungsgeschichte der Scolopender. *Zoologica,* 33.

**Hincks, T.**

**1880.** A History of the British Marine Polyzoa, London.

**Hlava, S.**

**1904.** Einige Bemerkungen über die Exkretionsorgane der Rädertierfamilie Melicertidæ und die Aufstellung eines neuen Genus Conchiloides. *Zool. Anz.,* 27.

**1905.** Ueber die Anatomie von Conchiloides natans (Seligo). *Zeit. wiss. Zool.,* 80.

**Hoffmann, C. K.**

**1886.** Zur Entwickelungsgeschichte der Urogenitalorgane bei den Anamniern. *Ibid.,* 44.

**1889.** Zur Entwicklungsgeschichte der Urogenitalorgane bei den Reptilien. *Ibid.,* 48.

**Hoffmann, R. W.**

**1899.** Beiträge zur Entwickelungsgeschichte der Oligochäten. *Ibid.,* 66.

**Holmes, S. J.**

**1900.** The early Development of Planorbis. *Journ. Morph.,* 16.

**Hudson, C. T. and Gosse, P.**

**1886–9.** The Rotifera; or Wheel-Animalcules, London.

**Ijima, J.**

**1885.** Ueber Bau und Entwickelung der Süsswasserplanarien (Tricladen). *Zeit. wiss. Zool.*

**Ikeda, I.**

**1901.** Observations on the Development, Structure and Metamorphosis of Actinotrocha. *Journ. Coll. Sci. Univ. Tokyo,* 13.

**Ischikawa, C.**

**1885.** On the Development of a freshwater macrourous Crustacean, Atyephyra compressa de Haan. *Quart. Journ. Micr. Sci.* (2), 25.

**Jâgerskiöld, L. A.**

**1898.** Ueber die büschelförmigen Organe bei Ascarisarten. *Centralbl. Bakt. Parasitenk.,* 24.

**Janosik, J.**

**1887.** Zwei junge menschliche Embryonen. *Arch. mikr. Anat.,* 30.

**Johansson, L.**

**1898.** Einige systematisch wichtige Theile der inneren Organisation der Ichthyobdelliden. *Zool. Anz.,* 21.

**Joliet, L.**
1880. Organe segmentaire des Bryozoaires endoproctes. *Arch. Zool. expér. gén.*, 8.

**Joyeux Laffuie.**
1882. Organisation et développement de l'Oncidie. *Ibid.*, 10.

**Kaiser, J.**
1892. Die Nephridien der Acanthocephalen. *Centralbl. Bakt. Parasitenk.*, 11.
1893. Die Acanthocephalen und ihre Entwickelung. *Bibl. Zool.*, 7.

**Karpelles, L.**
1893. Zur Anatomie von Bdella arenaria (Kramer). *Verh. zool.-bot. Ges. Wien*, 43.

**Kennel, J. v.**
1885. Entwicklungsgeschichte von Peripatus edwardsii und P. torquatus. *Arb. zool. Inst. Würzburg*, 7, 8.

**Kenyon, F. C.**
1895. The Morphology and Classification of the Pauropoda, with Notes on the Morphology of the Diplopoda. *Tufts College Studies*, 4.

**Kingsley, J. S.**
1889. The Development of Crangon vulgaris. *Bull. Essex. Inst.*, 21.

**Kishinouye, K.**
1890. On the Development of Araneina. *Journ. Coll. Sci. Univ. Japan*, 4.
1894. Note on the Cœlomic Cavity of the Spider. *Ibid.*, 6.

**Kleinenberg, N.**
1886. Die Entstehung des Annelids aus der Larve von Lopadorhynchus. *Zeit. wiss. Zool.*, 44.

**Koehler, R.**
1890. Recherches sur l'organisation des Cirrhipèdes (Lépadides et Balanes). *Arch. de Biol.*, 10.

**Kofoid, C. A.**
1895. On the early development of Limax. *Bull. Mus. Zool. Harvard*, 27.

**Kölliker, A. v.**
1861. Entwickelungsgeschichte des Menschen und der höheren Thiere, Leipzig.

**Kollman, J.**
1891. Die Rumpfsegmente menschlicher Embryonen von 13 bis 35 Urwirbeln. *Arch. Anat. Physiol.*

**Korschelt, E.**
1882. Ueber Bau und Entwicklung des Dinophilus apatris. *Zeit. wiss. Zool.*, 37.

**Kowalevsky, A.**
1871. Embryologische Studien an Würmern und Arthropoden. *Mém. Acad. Sci. St. Pétersbourg.*

**1889.** Ein Beitrag zur Kenntnis der Excretionsorgane. *Biol. Centralbl.*, 9.

**1892.** Beitrag zur Kenntniss der Excretionsorgane der Pantopoden. *Mém. Acad. Sci. St. Pétersbourg* (7), 38.

**1896.** Étude des glandes lymphatiques de quelques Myriapodes. *Arch. Zool. expér. gén.* (2), 3.

**Kramer, P.**

**1885.** Ueber Halarachne Halichoeri Allm. *Zeit. Naturw. Halle,* 58.

**Lacaze-Duthiers, H. et Pruvot, G.**

**1887.** Sur un œil anale larvaire des Gastéropodes opisthobranches. *C. R. Acad. Sci. Paris,* 105.

**Lang, A.**

**1881.** Der Bau von Gunda segmentata. *Mittheil. zool. Stat. Neapel,* 3.

**1884.** Die Polycladen (Seeplanarien) des Golfes von Neapel. Fauna u. Flora d. Golfes v. Neapel, 11.

**1888.** Lehrbuch der vergleichenden Anatomie, Jena.

**1903.** Beiträge zu einer Trophocöltheorie, Jena.

**Langerhans, P.**

**1873.** Zur Entwicklung der Gastropoda Opisthobranchia. *Zeit. wiss. Zool.,* 23.

**Lankester, E. R.**

**1865.** The Anatomy of the Earthworm. *Quart. Journ. Micr. Sci.*

**1877.** Notes on the Embryology and Classification of the Animal Kingdom, etc. *Ibid.,* 17.

**Latter, O. H.**

**1897.** The Prothoracic Gland of Dicranura vinula, and other Notes. *Trans. Ent. Soc. London.*

**Laurie, M.**

**1894.** On the Morphology of the Pedipalpi. *Journ. Linn. Soc. London,* 25.

**Lebedinsky, J.**

**1891.** Die Entwicklung der Daphnia aus dem Sommereie. *Zool. Anz.,* 14.

**1892.** Die Entwicklung der Coxaldrüse bei Phalangium. *Ibid.,* 15.

**Lehmann, O.**

**1887.** Beiträge zur Frage von der Homologie der Segmentalorgane und Ausführgange der Geschlechtsproducte bei den Oligochæten. *Jena. Zeit.,* 21.

**Leipoldt, F.**

**1893.** Das angebliche Excretionsorgan der Seeigel, untersucht an Sphaerechinus granularis und Dorocidaris papillata. *Zeit. wiss. Zool.,* 55.

**Leuckart, R.**

**1894.** Die Parasiten des Menschen. 2te Aufl., Leipzig.

**Leydig, F.**

**1860.** Naturgeschichte der Daphniden, Tübingen.

**Locy, W. A.**

**1886.** Observations on the Development of Agelena naevia. *Bull. Mus. Zool. Harvard,* 12.

**Loman, J. C. C.**

1887. Ueber die morphologische Bedeutung der sogenannten Malpighischen Gefässe der echten Spinnen. *Tijdschr. Nederl. Dierk. Ver.* (2), 1.

1888. Altes und Neues uber das Nephridium (die Coxaldrüse) der Arachniden. Bijd. Dierk. Amsterdam, 14.

**Longchamps, de Selys.**

1902. Recherches sur le développement des Phoronis. *Arch. de Biol.,* 18.

**Looss, A.**

1894. Die Distomen unserer Fische und Frösche. *Bibl. Zool.,* 16.

**Ludwig, H.**

1889–94. Echinodermen (Stachelhäuter), Bronn's Klassen u. Ordnungen d. Thierreichs. 2, Leipzig.

**Luther, A.**

1904. Die Eumesostominen. *Zeit. wiss. Zool.,* 77.

**Maas, O.**

1897. Ueber Entwicklungsstadien der Vorniere und Urniere bei Myxine. *Zool. Jahrb.,* 10.

**McKim, W. D.**

1895. Ueber den nephridialen Trichterapparat von Hirudo. *Zeit. wiss. Zool.,* 59.

**McMurrich, J. P.**

1886. A Contribution to the Embryology of the Prosobranch Gastropods. *Stud. Biol. Lab. Johns Hopkins Univ.,* 3.

**Marchal, P.**

1889. L'acide urique et la fonction rénale chez les Invertébrés. *Mém. Soc. zool. France,* 3.

1892a. La glande coxale du Scorpion et ses rapports morphologiques avec les organes excréteurs des Crustacés. *C. R. Acad. Sci. Paris,* 115.

1892b. Recherches anatomiques et physiologiques sur l'appareil excréteur des Crustacés décapodes. *Arch. Zool. expér. gén.* (2), 10.

**Martin, E.**

1888. Ueber die Anlage der Urniere beim Kaninchen. *Arch. Anat. Physiol.*

**Masterman, A. T.**

1897. On the Diplochorda. *Quart. Journ. Micr. Sci.* (2), 40.

**Mayer, P.**

1875. Ueber Ontogenie und Phylogenie der Insekten. *Jena. Zeit.,* 10.

**Mazzarelli, G.**

1892. Intorno al preteso occhio anale delle larve degli Opisthobranchi. *Rend. Accad. Lincei,* 1.

1898. Bemerkungen über die Analniere der freilebenden Larven der Opisthobranchier. *Biol. Centralbl.,* 18.

1904. I reni primitivi dei Molluschi. *Monit. Zool. Ital.,* 14.

**Meisenheimer, J.**

**1898.** Entwicklungsgeschichte von Limax maximus. *Zeit wiss. Zool.,* 63.

**1899.** Zur Morphologie der Urniere der Pulmonaten. *Ibid.,* 65.

**1901a.** Entwickelungsgeschichte von Dreissensia polymorpha Pall. *Ibid.,* 69.

**1901b.** Die Entwickelung von Herz. Pericard, Niere und Genitalzellen bei Cyclas im Verhältniss zu den übrigen Mollusken. *Ibid.,* 69.

**Metalnikoff, S.**

**1900.** Sipunculus nudus. *Ibid.,* 68.

**Meyer, E.**

**1887.** Studien über den Körperbau der Anneliden. *Mittheil. zool. Stat. Neapel,* 7.

**1888.** Studien über den Körperbau der Anneliden, IV, *Ibid.,* 8.

**1890.** Ueber die Nephridien und Geschlechtsorgane von Lopadorhynchus. *Biol. Centralbl.,* 10.

**1901.** Studien über den Körperbau der Anneliden. *Mittheil. zool. Stat. Neapel,* 14.

**Meyer, H.**

**1890.** Die Entwickelung der Urniere beim Menschen. *Arch. mikr. Anat.,* 36.

**Michael, A. D.**

**1883.** Observations on the Anatomy of the Oribatidæ. *Journ. R. Micr. Soc.* (2), 3.

**1892.** On the Variations in the Internal Anatomy of the Gamasinæ, etc. *Trans. Linn. Soc. London,* 5.

**1895.** A Study of the Internal Anatomy of Thyas petrophilus, an unrecorded Hydrachnid found in Cornwall. *Proc. R. Soc. London.*

**Mihalkovics, G. v.**

**1885.** Untersuchungen über die Entwickelung der Harn- und Geschlechtsapparates der Amnioten. Internat. *Monatschr. Anat. Physiol,* 2.

**Minchin, E. A.**

**1892.** Notes on the Cuvierian Organs of Holothuria nigra. *Ann. Mag. Nat Hist.*

**Mollier, S.**

**1890.** Ueber die Entstehung des Vornierensystems bei Amphibien. *Arch. Anat. Physiol.*

**Montgomery, T. H. Jr.**

**1897.** On the Structure of the Nephridia of Stichostemma. *Zool. Jahrb.,* 10.

**1903a.** The adult Organisation of Paragordius varius (Leidy). *Ibid.,* 18.

**1903b.** On the Morphology of the Rotatorian Family Flosculariidæ. *Proc. Acad. Nat. Sci. Philadelphia.*

**1904.** The Development and Structure of the Larva of Paragordius. *Ibid.*

**1906.** The Analysis of Racial Descent in Animals, New York.

**Moore, J. P.**

**1897.** On the Structure of the Discodrilid Nephridium. *Journ. Morph.,* 13.

**Morgan, T. H.**

**1894.** The Development of Balanoglossus. *Ibid.,* 9.

**Morin, J.**

1888. Studien über die Entwicklung der Spinnen. (In Russian.) Abh. neuruss. Naturf. Odessa, 13.

**Morse, E. S.**

1902. Observations on Living Brachiopoda. *Mem. Boston Soc. Nat. Hist.*, 5.

**Müller, G. W.**

1894. Die Ostracoden des Golfes von Neapel. Fauna u. Flora d. Golfes v. Neapel, 21.

**Müller, W.**

1875. Has Urogenitalsystem des Amphioxus und der Cyclostomen. *Jena. Zeit.*, 9.

**Nalepa, A.**

1884. Die Anatomie der Tyroglyphen, 2. *Sitz. Ber. Akad. Wiss. Wien*, 90.
1885. Die Anatomie der Tyroglyphen, 2. *Ibid.*, 92.
1888. Die Anatomie der Phytopoden. *Ibid.*, 96.

**Nansen, F.**

1885. Bidrag til Myzostomernes Anatomie og Histologi, Bergen.

**Nassonow, N.**

1886. Welche Insectenorgane dürften homolog den Segmentalorganen der Würmer zu halten sein? *Biol. Centralbl.*, 6.
1900. Zur Kenntniss der phagocytären Organe bei den parasitischen Nematoden. *Arch. mikr. Anat.*, 55.

**Nelson, J. A.**

1904. The early Development of Dinophilus. *Proc. Acad. Nat. Sci. Philadelphia.*
1907. The Morphology of Dinophilus Conklini. *Ibid.*, 59.

**Nemec, B.**

1896. Ueber Excretionsorgane und Geschlechtsverhältnisse einiger Isopoden. *Zool. Anz.*, 19.

**Nettovich, L. v.**

1900. Neue Beiträge zur Kenntnis der Arguliden. *Arb. zool. Inst. Wien*, 13.

**Nowikoff, M.**

1905. Untersuchungen über den Bau der Limnadia lenticularis. *Zeit. wiss. Zool.*, 78.

**Nusbaum, J.**

1885. Zur Entwickelungsgeschichte der Geschlechtsorgane der Hirudineen (Clepsine complanata Sav.). *Zool. Anz.*, 8.
1901. Dybowscella baicalensis nov. gen. spec. *Biol. Centralbl.*, 21.

**Ostroumoff, A. A.**

1886. Contribution à l'étude zoologique et morphologique des Bryozoaires du Golfe de Sébastopol. *Arch. Slav. de Biol.*, 2.

**Oudemans, J. T.**

1887. Bijdrage tot de kennis der Thysanura en Collembola, Amsterdam.

**Packard, A. S.**

**1898.** A Text-Book of Entomology, New York.

**Palmén, J. A.**

**1877.** Zur Morphologie des Tracheensystems, Helsingfors.

**Patten, W. and Hazen, A. P.**

**1900.** The Development of the Coxal Gland, Branchial Cartilages, and Genital Ducts of Limulus polyphemus. *Journ. Morph.*, 16.

**Pedaschenko, D. D.**

**1899.** Embryonalentwickelung und Metamorphose von Lernaea branchialis L. *Trav. Soc. Nat. Pétersbourg,* 26.

**Pelseneer, P.**

**1885.** On the Coxal Glands of Mygale. *Proc. Zool. Soc. London,* 2.

**1901.** Études sur des Gastropodes pulmonés. *Mém. Acad. Sci. Belg.*, 54.

**Pintner, T.**

**1896.** Studien über Tetrarhynchen, II. *Sitzber. Akad. Wiss. Wien,* 105.

**Plate, L. H.**

**1888.** Beiträge zur Naturgeschichte der Tardigraden. *Zool. Jahrb.*, 3.

**1889.** Ueber die Rotatorienfauna des bottanischen Meerbusens, etc. *Zeit. wiss. Zool.*, 49.

**Price, G. C.**

**1897.** Development of the Excretory Organs of a Myxinoid (Bdellostoma stouti Lockington). *Zool. Jahrb.*, 10.

**Prouho, H.**

**1890.** Contributions à l'histoire des Loxosomes. *Arch. Zool. expér. gén.* (2), 9.

**1892.** Contribution à l'histoire des Bryozoaires. *Ibid.*, 10.

**Punnett, R. C.**

**1900.** On a Collection of Nemerteans from Singapore. *Quart. Journ. Micr. Sci.* (2), 44.

The Enteropneusta. Fauna and Geography of the Maldive and Laccadive Archipelagoes.

**Purcell, W. F.**

**1895.** Note on the Development of the Lungs, Entapophyses, Tracheæ and Genital Ducts in Spiders. *Zool. Anz.*

**1900.** On the Anatomy of Opisthopatus cinctipes, Purc., with Notes on other, principally South African, Onychophora. *Ann. South African Mus.*, 2.

**Rabl, C.**

**1879.** Ueber die Entwicklung der Tellerschnecke. *Morph. Jahrb.*, 5.

**1896.** Ueber die Entwicklung des Urogenitalsystems der Selachier. *Ibid.*, 24.

**Reichenbach, H.**

**1886.** Studien zur Entwicklungsgeschichte des Flusskrebses. *Abh. Senckenb. Nat. Ges.*, 14.

**Reinhard, W.**

1887. Kinorhyncha (Echinoderes) ihr anatomischer Bau und ihre Stellung im System. *Zeit. wiss. Zool.,* 45.

**Renson, G.**

1883. Contributions à l'embryologie des organes d'excrétion des oiseaux et des Mammifères, Bruxelles.

**Rho, F.**

1888. Studii sullo sviluppo della Chromodoris elegans. *Atti Acad. Sci. Napoli,* 1.

**Richard, J.**

1892. Recherches sur le système glandulaire et sur le système nerveux des Copépodes libres d'eau douce, etc. *Ann. Sci. Nat. Paris* (7), 12.

**Rosa, D.**

1903a. Il cloragogo tipico degli Oligocheti. *Mem. Accad. Sci. Torino* (2), 52.

1903b. Nefridii di Rotifero in giovani Lombrichi. *Boll. Mus. Zool. Anat. Comp. Torino,* 18.

**Roule, L.**

1889. Études sur développement des Annélides et en particulier d'un oligochæte limicole marin (Enchytræoides Marioni). *Ann. Sci. Nat.* (7), 7.

**Rousselet, C.**

1891. On the vibratile tags of Asplanchna amphora. *Journ. Quekett Micr. Club,* 4.

**Rucker, A.**

1901. The Texan Kœnenia. *Amer. Nat.,* 35.

**Rückert, J.**

1888. Ueber die Entstehung der Excretionsorgane bei Selachiern. *Arch. Anat. Physiol.*

1892. Entwicklung der Excretionsorgane. *Ergebn. Anat. Entw.,* 1.

**Russo, A.**

1889. Sul valore morfologice e funzionale degli organi di Cuvier delle Oloturie. *Monit. Zool. Ital.,* 10.

**Salensky, W.**

1872. Beiträge zur Entwicklung der Prosobranchiaten und Referat. *Zeit. wiss. Zool.,* 12.

1885. Études sur le développement du Vermet. *Arch. de Biol.,* 6.

**Sarasin, C. F. und P. B.**

1888. Ueber die Niere der Seeigel. *Zool. Anz.,* 11.

**Sarasin, P.**

1882. Die Entwicklungsgeschichte der Bythynia tentaculata, Wiesbaden.

**Schaeppi, T.**

1894. Das Chloragogen von Ophelia radiata. *Jena. Zeit.,* 28.

**Schaub, R. v.**

**1888.** Ueber die Anatomie von Hydrodroma (C. L. Koch). *Sitz. Ber. Akad. Wiss. Wien,* 97.

**Schauinsland, H.**

**1886.** Die Excretions- und Geschlechtsorgane der Priapuliden. *Zool. Anz.,* 9

**Schimkéwitsch, W.**

**1884.** Ueber die exkretorische Thätigkeit des Mittelarmes der Würmer. *Biol. Centralbl.,* 14.

**1888.** Ueber Balanoglossus Mereschkovskii. *Zool. Anz.,* 11.

**1895.** Zur Kenntnis des Baues und der Entwicklung des Dinophilus vom Weissen Meere. *Zeit. wiss. Zool.,* 59.

**1897.** Ueber die Entwickelung des Darmcanals bei einigen Arachniden. *Trav. Soc. Natural. Pétersbourg,* 29.

**Schmidt, P.**

**1895.** Beiträge zur Kenntnis der niederen Myriopoden. *Zeit. wiss. Zool.,* 59.

**Schneider, A.**

**1866.** Monographie der Nematoden, Berlin.

**Schultz, E.**

**1895.** Ueber den Process der Excretion bei den Holothurien. *Biol. Centralbl.,* 15.

**1903a.** Aus dem Gebiete der Regeneration, III. *Zeit. wiss. Zool.,* 75.

**1903b.** Aus dem Gebiete der Regeneration, IV. *Ibid.*

**Schultze, M.**

**1854.** Bericht über einige in Herbst 1853 an der Küste des Mittelmeeres angestellte zootomische Untersuchungen. *Verh. phys. med. Ges. Würzburg,* 4.

**Schultze, O.**

**1883.** Beiträge zur Anatomie des Excretionsapparates (Schleifencanäle) der Hirudineen. *Arch. mikr. Anat.,* 22.

**Sedgwick, A.**

**1880.** Development of the Kidney in relation to the Wolffian Body in the Chick. *Quart. Journ. Micr. Sci.,* 20.

**1881.** On the early Development of the anterior Part of Wolffian Duct and Body in the Chick, etc. *Ibid.,* 21.

**1885–8.** Development of the Cape Species of Peripatus. *Ibid.,* 25–28.

**Seeliger, O.**

**1893.** Tunicata (Mantelthiere). Bronn's Klassen u. Ordnungen d. Thierreichs, 3. Suppl. Leipzig.

**Semon, R.**

**1891.** Studien über den Bauplan des Urogenitalsystems der Wirbelthiere. Dargelegt an der Entwicklung dieses Organsystems bei Ichthyophis glutinosus. *Jena. Zeit.,* 26.

**Semper, C.**

**1874.** Die Stammesverwandtschaft der Wirbelthiere und Wirbellosten. *Arb. zool. Inst. Wien,* 2.

**Shearer, C.**

1906a. On the Structure of the Nephridia of Dinophilus. *Quart. Journ. Micr. Sci.* (2).

1906b. Studies on the Development of Larval Nephridia, Part 1. Phoronis. *Mittheil. zool. Stat. Neapel.* 17.

**Shipley, A. E.**

1890. On Phymosoma varians. *Quart. Journ. Micr. Sci.* (2), 31.

1892. On Onchesoma Steenstrupii. *Ibid.*, 33.

**Sluiter, C. P.**

1882a. Beiträge zu der Kenntnis der Gephyreen aus dem Malayschen Archipel, 1. *Nat. Tijdschr. Nederl. Indie*, 14.

1882b. *Idem.*, 2. *Ibid.*

1884. *Idem.*, 3. *Ibid.*, 43.

**Sograf, N.**

1883. Materialien zur Kenntnis der Embryonalentwicklung von Geophilus ferrugineus L. K. und Geophilus proximus L. K. *Nachschr. Ges. Fr. Naturw. Moskau, 43.*

**Spee, F.**

1884. Ueber direkte Betheiligung des Ektoderms an der Bildung der Urnierenanlage des Meerschweinchens. *Arch. Anat. Physiol.*

**Spencer, W. B.**

1889. The giant Earthworm of Gippsland. *Nature*, 39.

**Spengel, J. W.**

1876. Das Urogenitalsystem der Amphibien, I. Theil. *Arb. zool.-zoot. Inst. Würzburg*, 3.

1880. Beiträge zur Kenntnis der Gephyreen. *Mittheil. zool. Stat. Neapel*, 1.

1893. Enteropneusta. Fauna u. Flora d. Golfes v. Neapel, 18.

**Stauffacher, H.**

1898. Die Urniere bei Cyclas cornea (Lam.). *Zeit. wiss. Zool.*, 63.

**Stecker, A.**

1876. Anatomisches und Histologisches über Gibocellum, eine neue Arachnide. *Arch. Naturg.*, 42.

**Stummer-Traunfels, R. v.**

1903. Beiträge zur Anatomie und Histologie der Myzostomen, 1. *Zeit. wiss Zool.*, 75.

**Sturany, R.**

1891. Die Coxaldrüsen der Arachnoiden. *Arb. zool. Inst. Wien*, 9.

**Sukatschoff, B.**

1900. Beiträge zur Entwickelungsgeschichte der Hirudineen, 1. Zur Kenntnis der Urnieren von Nephelis vulgaris Moqu. Tand. und Aulastomum gulo Moqu. Tand. *Zeit. wiss. Zool.*, 67.

**Swaen, A. et Brachet, A.**

1901. Études sur les premières phases du développement des organes dérivés du mésoblaste chez les Poissons Téléosteens, 2me partie. *Arch. de Biol.*, 18.

**Thon, K.**

1905. Neue Exkretionsorgane bei der Hydrachniden-familie Limnocharidae Kramer. *Zeit. wiss. Zool.,* 79.

**Thor, S.**

1904. Recherches sur l'anatomie comparée des Acariens prostigmatiques. *Ann. Sci. Nat.* (8), 19.

**Todaro, F.**

1902a. Sopra gli organi escretori delle Salpidi. *Rend. Accad Lincei* (5), 11.

1902b. Sur les organes excréteurs des Salpidés (Salpidæ Forbes). *Arch. Ital. Biol.,* 38.

**Torrey, J. C.**

1903. The early Embryology of Thalassema mellita (Conn). *Ann. New York Acad. Sci.,* 14.

**Trinchese, S.**

1881. Par la fauna marittima italiana. Aeolididæ e Familie affini. *Atti R. Accad. Lincei,* 11.

**Vejdovský, F.**

1885. System und Morphologie der Oligochæten Prag.

1886. Zur Morphologie der Gordiiden. *Zeit wiss. Zool.,* 43.

1890. Entwickelungsgeschichtliche Untersuchungen. *Heft 2.* Die Entwickelungsgeschichte von Rhynchelmis und der Lumbriciden, Prag.

1892a. *Idem., Hefte 3 und 4.* Die Organogenie der Oligochæten. *Ibid.*

1892b. Zur Entwickelungsgeschichte des Nephridial-Apparates von Megascolides australis. *Arch. mikr. Anat.,* 40.

1894. Organogenie der Gordiiden. *Zeit. wiss. Zool.,* 57.

1895. Zur vergleichenden Anatomie der Turbellarien, 2. *Ibid.,* 60.

1900. Noch ein Wort über die Entwicklung der Nephridien. *Ibid.,* 67.

1901. Zur Morphologie der Antennen- und Schalendrüse der Crustaceen. *Ibid.,* 69.

**Verhoeff, C.**

1902. Myriopoda. Bronn's Klassen u. Ordnungen d. Thierreichs, 5, Leipzig.

**Villot, A.**

1874. Monographie des Dragonneaux. *Arch. Zool. expér. gén.,* 3.

**Voinov, D. N.**

1896. Les néphridies de Branchiobdella varians (V. astaci). *Mém. Soc. Zool. France,* 14.

**Wagner, J.**

1894. Die Embryonalentwickelung von Ixodes calcaratus Bir. *Arb. zoot. Lab. Univ. Pétersbourg, 5.*

**Waite, F. C.**

1899. The Structure and Development of the Antennal Glands in Homarus americanus Milne-Edwards. *Bull. Mus. Zool. Harvard,* 35.

**Waldeyer, W.**

1870. Eierstock und Ei. Leipzig.

**Weber, E. F.**

1898. Faune rotatorienne du bassin du Leman. *Rev. suisse Zool.*, 5.

**Weber, M.**

1886. Die Abdominalporen der Salmoniden nebst Bemerkungen über die Geschlechtsorgane der Fische. *Morph. Jahrb.*, 12.

1889. Ueber Temnocephala Blanch. Zool. Ergebn. einer Reise in Ostindien, 1. Leiden.

**Weismann, A.**

1874. Ueber Bau und Lebenserscheinungen von Leptodora hyalina, Lilljeborg. *Zeit. wiss. Zool.*, 24.

**Weiss, E.**

1890. Excretory Tubules in Amphioxus. *Quart. Journ. Micr. Sci.* (2), 31.

**Weldon, W. F. R.**

1887. On Dinophilus gigas. *Ibid.*, 27.

**Wheeler, W. M.**

1893a. The primitive number of Malpighian vessels in Insects. *Psyche*, 6.

1893b. A Contribution to Insect Embryology. *Journ. Morph.*, 8.

1896. The Sexual Phases of Myzostoma. *Mittheil. zool. Stat. Neapel*, 12.

1899. The Development of the Urinogenital Organs of the Lamprey. *Zool. Jahrb.*, 13.

**Whitman, C. O.**

1887. A Contribution to the History of the Germ-layers in Clepsine. *Journ. Morph.*, 1.

**Wiedersheim, R.**

1890. Ueber die Entwicklung des Urogenitalapparates bei Crocodilen und Schildkröten. *Arch. mikr. Anat.*, 36.

**Wierzejski, A.**

1893. Atrochus tentaculatus nov. gen. et spec. *Zeit. wiss. Zool.*, 55.

**Wilhelmi, J.**

1906. Untersuchungen über die Excretionsorgane der Süsswassertricladen. *Ibid.*, 80.

**Willem, V.**

1899. Observations sur l'excrétion chez l'Arénicole. *Trav. Stat. zool. Wimereux*, 7.

**Willey, A.**

1899. Enteropneusta from the South Pacific, with Notes on the West Indian Species. Zoological Results, Cambridge.

**Williams, T.**

1858. Researches on the Structure and Homology of the Reproductive Organs of the Annelids. *Phil. Trans. R. Soc. London.*

**Wilson, E. B.**

1889. The Embryology of the Earthworm. *Journ. Morph.*, 3.

1890. The Origin of the Mesoblast-bands in Annelids. *Ibid.*, 4.

**Wilson, H. V.**
1891. The Embryology of the Sea Bass (Serranus atrarius). *Bull. U. S. Fish Comm.*, 9.

**Winkler, W.**
1888. Anatomie der Gamasiden. *Arb. zool. Inst. Wien.*, 7.

**With, C. J.**
1904. The Notostigmata, a new suborder of Acari. *Vid. Medel. Nat. For. Kjöbenhabn* (6), 6.

**Witlaczil, E.**
1882. Zur Anatomie der Aphiden. *Arb. zool. Inst. Wien,* 4.

**Wolfson, W.**
1880. Die embryonale Entwicklung des Limnæus stagnalis. *Bull. Acad. Sci. Pétersbourg,* 26.

**Woltereck, R.**
1902. Trochophora-Studien. 1. Ueber die Histologie der Larve und die Entstehung des Annelids bei den Polygordius-Arten der Nordsee. *Zoologica,* 34.
1905. Zur Kopffrage der Anneliden. Verh. deutsch. zool. Ges.

**Wyhe, J. W. Van.**
1889. Ueber die Mesodermsegmente des Rumpfes und die Entwicklung des Excretionssystems bei Selachiern. *Arch. mikr. Anat.,* 33.

**Zelinka, C.**
1886. Studien über Räderthiere, 1. *Arb. zool. Inst. Graz,* 1.
1888. *Idem.,* 2. *Ibid.,* 2.
1889. Die Gastrotrichen. *Ibid.,* 3.
1891. Studien über Räderthiere, 3. *Ibid.,* 3.

**Ziegler, H. E.**
1898. Ueber den derzeitigen Stand der Cölomfrage. *Verh. deutsch. Zool Ges.*

**Zur Strassen, O.**
1892. Bradynema rigidum v. Sieb. *Zeit. wiss. Zool.* 54.

# MEDIÆVAL GERMAN SCULPTURE IN THE GERMANIC MUSEUM OF HARVARD UNIVERSITY.

By KUNO FRANCKE.

(*Read April 25, 1908.*)

There is a curious anomaly in the equipment of German universities, an anomaly accounted for partly by the traditional cosmopolitanism of German scholarship, partly by the somewhat belated development of Germany into a united and powerful nation.

Whereas for sudents of classical archæology there is provided in nearly every university of the fatherland a well-planned and systematically arranged museum of casts of Greek sculptures, the student of German history would not find at a single one of these universities any collection which would offer to him a fairly accurate representation of the artistic development of his own country. Even in the German capital with its wealth of ethnological and archæological exhibits from Troas and Pergamon, from Egypt and Assyria, from India and South America, no attempt has as yet been made to bring together, in reproductions, the great artistic landmarks of Germany herself. It has been reserved to an American university to make at least a beginning of such an undertaking, but it is interesting to note that the Germanic Museum of Harvard University could not have achieved whatever success it has had thus far, had it not been for the generous interest bestowed upon it by His Majesty the German Emperor. So that this museum, although established on non-German soil, is after all in its way another symptom of the long strides which modern Germany has made toward national greatness and international influence.

The bulk of the collections of the Germanic Museum at Cambridge is devoted to German sculpture of the Middle Ages and the Renaissance, and particular stress is laid upon a good representation of the thirteenth century.

It is not as generally acknowledged as it should be that the thirteenth century marks a truly classic epoch in the development of German plastic act. German sculpture between 1220 and 1250 is fully on a level with the great creations of the lyric and epic poetry of chivalry; and no one who is susceptible to the peculiar beauty of Walther von der Vogelweide's minne-song or is impressed with the heroic figures of the Nibelungenlied, of Kudrun, of Parzival, or Tristan, can fail to observe their affinity of spirit with the plastic monuments of Wechselburg and Freiberg, of Naumburg and Halberstadt, of Bamberg and Strassburg. Here as well as there we find a high degree of refinement and measure; a strenuous insistence on courteous decorum; intense moral earnestness linked to a strange fancifulness of imagination; a curious combination of scrupulous attention to certain conventional forms of dress, gesture, and expression, on the one hand, and a free sweep in the delineation of character, on the other. Here as well as there we find a happy union of the universally human with the distinctively mediæval; a wonderful blending of the ideal human type with the characteristic features of the portrait. As the art of Phidias and Praxiteles is an indispensable supplement to the art of Æschylus and Sophocles, for our understanding of Attic culture in its prime, so these works of German sculpture of the thirteenth century stand to us (or should stand to us) by the side of the great productions of the chivalric poets, as incontrovertible proofs of the free and noble conception of humanity reached by mediæval culture at its height.

A brief review of a few at least of these sculptures may serve to elucidate this statement somewhat more fully.

Among the earliest plastic monuments of the thirteenth century are the pulpit and the Crucifixion group of the Church of Wechselburg in Saxony, executed probably between 1210 and 1220. In both monuments it seems as though the artist was still grappling with the problem of form. In the relief from the front of the pulpit—Christ seated on the throne as Judge of the world, surrounded by the symbols of the Evangelists—mastery of form, classic solemnity, exalted repose have indeed been attained. In the more animated scenes of the side reliefs—the sacrifice of Isaac and the healing of the Jews by the brazen serpent—there is a curious contrast between grandeur and awkwardness, sweetness of feeling and naive naturalism. And a similar contrast is found in the Crucifixion group. The figures of Mary and John standing under the Cross, as well as that of Joseph of Arimathea holding out the cup to receive the blood of the Saviour, are remarkable for nobility of outline, depth of feeling, and measured beauty of expression. There is a fine sweep of movement in the two angels on the cross-beam, gentle sadness in the figure of Christ, and a mild tenderness in the attitude of God the Father appearing above. The symbolical figures, however—probably Jewdom and Pagandom—on which John and Mary are standing, are tortuous and forced. Apparently, here is an artist who looks at life about him with a keen, penetrating, and receptive eye, but who at the same time is impelled to subject reality to certain canons of measure and proportion which he has not yet made fully his own.

A decided step in advance is made in the sculptures of the Golden Gate of the Cathedral of Freiberg, likewise in Saxony. In the arrangement of plastic figures, both on the sides of the portal and on the archivolts, French influence is clearly seen. But these plastic figures seem here much more independent of the architectural framework than is common in the French sculptures, *e. g.*, those of Chartres Cathedral, which served as models to the German artist; and the human type and bodily proportions are unmistakably original.

A thoroughly satisfactory interpretation of all the figures, human, animal and fantastic, which cover the sides of the portal, the tympanum and the archivolts, and of the fundamental conception underlying them, has not yet been given, although Anton Springer has done a great deal for the identification of individual personages. Springer thinks that the fundamental conception of the whole is the mystic marriage between Christ and the Church, and that all the scenes and figures of the portal may be interpreted as symbolic of this mystic idea. Simpler and more plausible it seems to me to find in this portal a plastic counterpart to dramatic scenes from the cycle of the Christmas plays, the popularity of which in the thirteenth century is proved, for Germany, by a particularly complete example, the Benediktbeuren Christmas Play. Clearly a scene from the Christmas cycle is the one represented in the tympanum of the portal: the Adoration of the Magi, the three kings approaching from the left, Mary with the child enthroned in the middle, the archangel Gabriel and Joseph at the right. And no less plausibly than this scene may the eight somewhat under life-size figures which flank both sides of the portal be connected with the subject of the Christmas plays. Prophet and Sibyl scenes were very frequently used as introducing the Nativity play proper, one prophet or Sibyl after another entering to testify to the coming of the Saviour. While retaining most of the names suggested by Springer for these eight figures,—John the Baptist and John the Evangelist, David and Solomon, the Queen of Sheba and Bathseba, David and Aaron,—we may call them collectively witnesses to Christ's Nativity.

As to the plastic representations on the four archivolts encircling the tympanum, they are, to be sure, not taken from any actual scene of a Christmas play; but they are entirely in keeping with the joyous, idyllic character of these plays. On the innermost archivolt, nearest to the Adoration of the Magi, there are at the sides the four archangels, in worshipful attitude; in the middle, the Coronation of Mary by Christ. The next archivolt contains six apostles, three at each side, and in the center Abraham with a soul of the blessed in his lap, while an angel reaches out another soul toward him. The third archivolt shows eight figures of apostles and in the center the dove of the Holy Ghost surrounded by angels. On the outermost archivolt, finally, the resurrection of the flesh is represented by ten figures rising from their graves with manifoldly varying expressions of faith, hope and exultation; while the central group, an angel receiving by either hand a saved soul, fittingly symbolizes the last and highest stage of human redemption. All these sculptures, as well as those of the tympanum and the sides of the portal, are distinguished by a remarkable symmetry and adjustment to architectural demands, and by a wonderful mellowness and purity of form and an exquisite sweetness and serenity of expression, making an artistic whole of extraordinary beauty and perfection.

The climax, however, of North German art of the thirteenth century is reached in the Portrait Statues of Founders and Patrons of Naumburg Cathedral from the west choir of that church, a series of works which may be definitely assigned to the middle of the thirteenth century. These statues, together with that of a young ecclesiastic from the same church, are a striking refutation of what since Jacob Burckhardt's "Kultur der Renaissance in Italien" has come to be a popular axiom, the assumption, namely, that modern individualism had its origin in the era of the *rinascimento;* they show conclusively that Burckhardt's phrase of "the discovery of the individual" by the great Italians of the quatro-cento is misleading, that, in other words, the Middle Ages themselves contain the germs of modern individualism. There is nothing in the art of the Renaissance which surpasses these Naumburg statues in fulness, distinctness, and vigor of individual life. Every one of these figures is a type by itself, a fully rounded personality. The two pairs of princely husband and wife, one of the men full of power and determination, the other of youthfully sanguine appearance, one of the women broadly smiling, the other, with a gesture full of reserved dignity, drawing her garment to her face; the canoness standing erect, but with slightly inclined head, thoughtfully gazing down upon a book which she supports with one hand while the other turns over its leaves; the princess drawing her mantle about her; the young ecclesiastic with his carefully arranged hair flowing from his tonsure, holding the missal in front of him; the various knights, one looking out from behind his shield, another supporting his left on the shield and shouldering the sword with his right hand, a third resting both shield and sword in front of him on the ground, while with his right hand he gathers his mantle about his neck, others in still different postures and moods,—there is not a figure among them which did not represent a particular individual at a particular moment, and which did not, without losing itself in capricious imitation of accidental trifles, reproduce life as it is. It is impossible in the face of such works of sculpture as these not to feel that they proceeded from artists deeply versed in the study of human character, fully alive to the problems of human conduct, keenly sensitive to impressions of any sort—in other words, fully developed, highly organized, complicated individuals. One feels that here are seen the mature artistic fruits of the great Hohenstaufen epoch—an epoch rent by tremendous conflicts in church and state, and convulsed by the throes of a new intellectual and spiritual birth.

Almost contemporary with these statues, though probably somewhat younger, is the Naumburg Rood Screen separating the west choir of the Cathedral from the nave. The sculptures of this rood screen form an interesting contrast to the sculptures of the Freiberg Golden Gate, analyzed before. While the Freiberg sculptures present a plastic counterpart to the mediæval Christmas plays, we have in the Naumburg rood screen a plastic counterpart to the Passion plays. On the middle beam of the door leading through the screen, which has the shape of a cross, the figure of the dying Saviour is suspended, while on each side of the door there stand in niches the over life-size figures of Mary and John. The other scenes of the Passion, from the Last Supper to the Bearing of the Cross, are brought to view in high reliefs which as a continuous frieze, crowned by a Gothic canopy, give to the whole structure a most impressive attic-like top. These sculptures seem to mark a stage of development somewhat beyond that reached by the Naumburg portrait statues. They are signalized by intense dramatic power. Some of the scenes of the frieze in particular impress one as direct transpositions into stone of scenes from the Passion Play stage. They excel even the portrait statues in freedom and sweep of movement and in keenness of realistic characterization. On the other hand. they show a tendency toward exaggeration, which occasionally (as in John and Mary) leads to a strained and distorted expression of feeling; and, in the portrayal of the vulgar and the commonplace, they occasionally (as in the representatives of the Jewish rabble) diverge into caricature. They are, then, clear anticipations of the ultra-naturalistic, and therefore unnatural tendency of later Gothic sculpture.

We may properly close our review by selecting at least one group of South German sculptures affording a striking example of the strong influence exerted by French Gothic art upon this part of Germany: I mean the "Death of Mary" and the "Ecclesia and Synagoga" from the Romanesque portal of Strassburg Cathedral. The Death of Mary is one of the noblest creations in the whole history of art. The Virgin is represented reclining on a couch, wrapped in a garment which reveals with rare delicacy the lines of her body. Her face is majestic, Juno-like. Although the moment represented is after her death, her eyes are still open and have a look of heavenly exaltation. Behind her couch, in the middle of the tympanum, stands Christ, holding Mary's soul (in the form of an infant) in his left hand, his right hand raised in blessing. Mary Magdalen cowers in front of the couch, wringing her hands, her face expressing deepest sorrow. The space at the sides and back of the death-bed is filled with the figures of the Disciples, some of them giving way to grief, others contemplative, others transfigured, all of them filled with holy awe and deep religious feeling. The graceful vine which runs along the edge of the Romanesque arch of the tympanum gives to the whole composition a fitting enclosure. In this monument the French sense of form and German feeling seem most happily blended.

Of no less refinement are the statues of Ecclesia and Synagoga. To contrast the Church triumphant and the Synagogue defeated was a very common conception both in the religious sculpture and in the religious drama of the Middle Ages. Noteworthy instances of their occurrence in sculpture are the statues of Rheims Cathedral, the north portal of Bamberg Cathedral, and the vestibule of the Cathedral of Freiburg im Breisgau; of their introduction into the drama, the part played by them in the Ludus de Antichristo and the Alsfeld Play. Of all plastic representations, these Strassburg statues are the most exquisite. The Church, with wide-flowing mantle, the crown on her head, her right hand holding the standard of the cross, her left bearing the communion chalice, stands erect and dignified at the left side of the portal, looking with pride and disdain at her adversary on the opposite side. The Synagogue wears neither crown nor mantle; in her left hand she holds the table of the Mosaic law turned downward, in the right a standard, the shaft of which is broken in many places; her eyes are bandaged (to indicate that she does not see the true light), and her face is turned away from the Church and is bent slightly down. In spite of her humiliation, she appears more human and lovable than her victorious rival. Both figures together are perhaps unsurpassed in mediæval sculpture for grace and delicacy of outline; only in the somewhat coquettish twist of the hips there is observable a slight indication that the highest point in the classic epoch of plastic art has already been passed and that the age of extravagant emotion and artificiality is setting in.

When, in November, 1903, these and other precious gifts of the German Emperor were temporarily installed in the insignificant little building which Harvard University could spare for them as a scanty shelter, it was hoped that only a short time would elapse before a new and worthy museum building would have been erected through the liberality of American friends of German culture. These hopes have not yet been fulfilled. Here is the opportunity for our fellow citizens of German origin to prove to the world that they do not leave their ideals at home when they leave the fatherland; and here is a chance for all Americans to show their appreciation of what German culture has given to this country.

CAMBRIDGE, MASS.

### *Stated Meeting October 2, 1908.*

Secretary HOLLAND in the Chair.

Dr. E. A. Spitzka, a newly elected member, was presented to the chair and took his seat in the Society.

Letters accepting membership were read from:

Prof. Richard Hawley Tucker.
Prof. Albrecht F. K. Penck.
Prof. Herbert Weir Smyth.

Letters were received

From the City of Faenza inviting the Society to be represented at the Torricelli tercentenary.

From the University of Cambridge inviting the Society to participate in the commemoration of the centenary of Charles Darwin's birth in June, 1909, and Prof. Henry F. Osborn was appointed to represent the Society on the occasion.

From the Physico-Medical Society at Erlangen, thanking the Society for its congratulatory address on the occasion of its centenary celebration.

The decease was announced of:

Hon. Grover Cleveland, at Princeton, N. J., on June 25, 1908, æt. 71.
Prof. F. L. Otto Röhrig, at Pasadena, Cal., on July 14, 1908, æt. 89.
Dr. Ainsworth Rand Spofford, at Holderness, N. H., on August 12, 1908, æt. 83.
Prof. Antoine Henri Becquerel, at Croisic, in Brittany, on August 25, 1908, æt. 56.
Prof. E. Mascart, at Paris, on August 26, 1908, æt. 71.
Prof. Dr. Hugo von Meltzel, of Koloszvar, Hungary.

The following papers were read:

"The Humming Telephone," by Prof. A. E. Kennelly and Walter L. Upson. (See page 329.)

"On the After-images of Subliminally Colored Stimuli," by Edward Bradford Titchener and William Henry Pyle. (See page 366.)

### *Stated Meeting October 16, 1908.*

President KEEN in the Chair.

The decease was announced of President Daniel Coit Gilman, at Norwich, Conn., on October 15, 1908, æt. 77.

Dr. Edward O. Hovey read a paper entitled "A contribution to the History of Mont Pelée, Martinique."

### *Stated Meeting November 6, 1908.*

President KEEN in the Chair.

A letter was received from the Board of Curators and Faculty of the University of Missouri, inviting the Society to be represented at the inauguration of Albert Ross Hill, LL.D., as president of the University, at Columbia, Mo., on December 10 and 11, 1908, and Dr. William Trelease was appointed to represent the Society on the occasion.

The decease was announced of Prof. Otis T. Mason, at Washington, D. C., on November 5, 1908, æt. 70.

Dr. Alexis Carrel read a paper entitled "Recent Studies in Transplantation of Organs in Animals" (see page 677), which was discussed by President Keen, Dr. Coplin, Dr. Eshner and Dr. Carrel.

# HEPATOSCOPY AND ASTROLOGY IN BABYLONIA AND ASSYRIA.

By MORRIS JASTROW, Jr.

(*Read December 4, 1908.*)

In any general study of the subject of divination we must distinguish between two forms which for want of a better designation we may distinguish as voluntary and involuntary. Under voluntary divination is meant the act of deliberately seeking out some object or means through which one may hope to pierce the unknown future, hidden from the ordinary gaze. The placing of marked arrows before the image of a deity, and according to the ones drawn by lot, to determine what the god may have in mind or what his pleasure may be is an illustration of voluntary divination as practiced among the ancient Arabs.[1] Sending out birds selected for the purpose and noting the direction and manner of their flight[2] may be instanced as another procedure of direct divination. Among the Babylonians and Assyrians, the common method of voluntary divination was the examination of the liver of the sacrificial animal—invariably for this purpose a sheep—and, according to signs noted in the various parts of that organ, to diagnose the intentions of the gods as the arbiters of human fate and as the powers presiding over all occurrences on earth.

Involuntary divination, on the other hand, rests on the interpretation of all manner of signs and phenomena that without being sought out force themselves on our notice. Preeminent among such signs is the observation of the phenomena of the heavens, primarily the movements and aspects of the sun, moon and planets with the gradual extension to the observation of clouds, of constellations and of single particularly prominent stars—as practiced by the cultural

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[1] Wellhausen, "Reste Arabischen Heidenthums," p. 126.

[2] Wissowa, "Religion der Römer," p. 457, note 3.

nations of antiquity.[3] In addition to this branch of involuntary divination, we have the significance attached to diverse occurrences that by their more or less unusual or striking character attract attention or that for any other reason were regarded as fraught with some special importance. The interpretation of dreams falls within this category. Monstrosities among human beings and animals form another subdivision, while peculiar actions among animals—snakes, dogs, ravens, locusts and the like—further extend the scope of involuntary divination until it becomes practically boundless. All the little mishaps and accidents of daily life were looked upon as signs, indicative of the disposition of the gods towards men, and in a still larger sense, as affecting the general welfare, were storms, floods, swollen streams, climatic disturbances and more the like.

In order to differentiate between these two methods of divination we may designate the signs derived from voluntary divination as omens, and those obtained from involuntary divination as portents, while within the field of involuntary divination two broad divisions may be recognized, the one represented by portents connected with the phenomena of the heavens, including clouds, storms and rains, and such as are connected with terrestrial phenomena. In grouping the portents derived from the observation of the phenomena of nature under the general heading of astrology, it must therefore be borne in mind that the term includes more than the mere study of the stars, but so far at least as Babylonia and Assyria are concerned, there is no distinction between the character of the interpretations offered for the phenomena of the heavens in the narrower sense, and such phenomena as are merely associated with the heavens. For the Babylonians and Assyrians, as for the nations of antiquity in general, heaven is not very far removed from the earth.[4] It was supposed to begin where the solid earth came to an end and indeed the tops of mountains so frequently enveloped in clouds appear to have been regarded as bordering on the domain of heaven if not

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[3] Dr. J. G. Frazer calls my attention to the fact that astrology in any proper sense is not found among peoples of primitive culture.

[4] This view underlies the Biblical story of the building of the Tower of Babel (Genesis, chapter XI.), as is shown by the circumstance that the task of building a tower which should reach to heaven is not looked upon as an impossible task but as a wicked one.

actually a part of it. Hence to place the seat of the gods on the tops of mountains, as was so frequently done by nations of antiquity, was equivalent to assigning them to the heavens.

Confining ourselves to Babylonia and Assyria, we find that although divination through the interpretation of terrestrial phenomena—dreams, monstrosities, actions of animals, mishaps, swollen streams, etc., etc.—also play a prominent role and that within the field of voluntary divination we have by the side of hepatoscopy (or divination through the liver), other procedures such as the interpretation of the action of oil bubbles in a basin of water,[5] the two chief methods of divination, forming part of the official cult, are Hepatoscopy and Astrology.[6] Both forms were developed into elaborate systems marked by definite rules of interpretation, consistently and logically applied. Extensive collections of omens and portents were compiled by Babylonian and Assyrian priests attached to the temples, in which all signs noted on the liver of sheep and all manner of phenomena observed in connection with sun, moon, planets, constellations and stars on the one hand, and with clouds, storms, rains and floods on the other, were entered together with the interpretation of the signs. The evident endeavor of the compilers was to make the collections as comprehensive as possible so as to provide for all contingencies, since the purpose of the collections was to serve as guides and handbooks for the priests in their practical labors as well as text-books in instructing the pupils of the temple schools. As a consequence, considerable skill and ingenuity were displayed in arranging the omens and portents systematically so as to facilitate their use. On the other hand, while the signs noted were primarily based on actual cases, the theoretical factor enters largely into play. This led to many signs being entered in both classes of divination

[5] See Hunger, "Becherwahrsagung bei den Babyloniern" (Leipzig, 1903).

[6] For details with copious translations of texts see the writer's "Religion Babyloniens und Assyriens," parts 10 to 14, as well as various articles on special points such as "The Signs and Names for the Liver in Babylonian" (*Zeitschrift für Assyriologie,* XX., pp. 105–129); "The Liver in Antiquity and the Beginnings of Anatomy" (*University of Pennsylvania Medical Bulletin,* January, 1908, and Trans. of the Phila. College of Physicians, 3d Series, XXIX., pp. 117–138); "Sign and Name for Planet in Babylonian" (PROCEEDINGS OF THE AMER. PHILOS. SOCIETY, XLVII., pp. 141–156).

which represent such as in the opinion of the priests *might* occur. Certain rules of interpretation having been devised, based on actual occurrences following upon the signs noted, these rules were applied to contingent cases which might occur; and often in astrological texts, signs are even entered which have no practical significance at all but purely a theoretical interest as illustrations of the extremes to which the system of interpretation was pushed.

In the case of both methods the interpretations have reference almost exclusively to the general welfare and not to the individual, to crops, war, pestilence, victory, defeat, famine, plenty, favorable or unfavorable climatic conditions and the like. The individual plays a very minor role, and when he is introduced, in most cases it is the king who is directly mentioned or indirectly referred to. Even the welfare of the king is bound up with the welfare of the country under the view of kingship which continues to hold good till the end of the Babylonian-Assyrian control and according to which the king's welfare, because of his peculiar relationship to the gods, conditions the general prosperity and happiness;[7] and this applies also to signs connected with a member of the royal household. It is because of this bearing of both forms of divination on the general welfare that they form integral parts of the official cult. Especially is this the case with the rites of hepatoscopy which, as texts from the days of the Assyrian empire show, formed part of a regular ritual.[8]

More important, however, than this aspect of hepatoscopy and astrology in Babylonia and Assyria is the circumstance that both methods rest upon a well-defined theory and are therefore not to be viewed as merely arbitrarily chosen devices. In the case of hepatoscopy the underlying theory may be summed up as follows. The sacrificial animal on being accepted by the deity to whom it is offered is assimilated to the deity. The deity becomes one with it, much in the same way as the one who partakes of an animal becomes part of that animal, or the animal part of him. The soul of the animal is thus put in harmonious accord with the soul of the god.

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[7] See J. G. Frazer, "Lectures on the Early History of Kingship."

[8] See Jastrow, "Religion Babyloniens und Assyriens," II., pp. 174 seq. and 300 seq.

The two agree as two watches regulated to be in perfect unison. If, therefore, one can read the soul of the animal, one enters at the same time into the inner being of the god. Now according to a view widespread still among people living in a state of primitive culture, the seat of life is in the liver, which is not only the organ of emotional activity but of intellectual functions as well, the source of all emotions high and low, of thought, will and all manifestations of what we ordinarily call soul life.[9] From this point of view the liver is the seat of life and of the soul, as the ancients conceived vitality and its inward and outward phenomena.

The combination of these two conceptions (1) of the liver as the seat of the soul and (2) of the assimilation of the soul of the sacrificial animal to the soul of the deity to whom it is offered and who accepts it, leads to the conclusion that if one is able to read the soul of the animal as revealed in the condition of the liver and of the signs thereon, the soul including, therefore, the will and intention of the deity is revealed. Through the liver of the sacrificial animal one enters as it were into the workshop of the gods. The mind of the god is reflected in the liver of the sacrificial animal like an image in a mirror—to use the figure introduced by Plato in an interesting passage of the Timaeus[10] bearing on divination through the liver.

As for the system of interpretation of the signs noted it revolves largely around a more or less natural association of ideas. The chief parts of the liver to which attention was directed being the right and left lower lobes, the upper lobe with its two appendices, the larger one known as the *processus pyramidalis* and the smaller

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[9] For further details regarding this view of the liver which also underlies hepatoscopy among the Etruscans, Greeks and Romans see Jastrow, "Religion Babyloniens und Assyriens," II., pp. 213 seq. In a special article (shortly to be published) on "The Liver as the Seat of the Soul" I have set forth the historical development of the location of the soul in the liver, in the heart and in the head successively. The second stage, though reached by the Babylonians and Assyrians, never found expression in Hepatoscopy, whereas among the Romans from a certain period on, the heart and occasionally the lungs and even the milt were also examined. The third stage was reached too late for incorporation into the divination rites, but in phrenology as an extra-official pseudo-scientific form of divination we have the outward expression of the belief which placed the soul in the brain.

[10] § 71 C.

one as the *processus papillaris,* the gall-bladder, the cystic duct, the hepatic duct, the common bile-duct, the hepatic vein and the "liver gate" (*porta hepatis*). A swollen gall-bladder was interpreted as pointing to an enlargement or increase of power, a long cystic duct to a long reign, a depression in the liver gate to a decrease in power and so forth. Through the further distinction between right and left, the former representing the favorable side, the latter the unfavorable side, the signs in question referred to the king's side or to the enemy's side, as the case might be. Besides the parts of the liver, markings on the liver—holes, lines, and depressions—due largely to the traces on the liver surface of the subsidiary ducts and veins, were accorded a special significance. According to the shape of these markings, frequently fantastically pictured as weapons of the gods, an interpretation, likewise based on association of ideas, was offered and in this way the field of hepatoscopy was further extended. No two livers were ever exactly alike, and it will readily be seen how in the course of time the collections of signs with their interpretation would grow to huge proportions, and the opportunity thus given for the imagination and fancy of the divining priest—the *bârû* or "inspector"[11] as he was called, to roam over a boundless territory. To the credit of the Babylonian and Assyrian priests be it said that so far as the evidence goes, they applied the elaborate and complicated system devised by them logically and consistently. They did not hesitate to announce to the kings an unfavorable result of the examination of the signs. Grouping all the signs noted together, if the unfavorable signs predominated, a second sheep was offered and the liver examined, and if the result of this diagnosis was also unfavorable, the omens were taken for a third time. The frequency with which in official reports to the kings unfavorable prognostications are set forth[12] warrants the con-

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[11] The underlying stem is the common term for "to see." The *bârû* as "the seer" was the one who by means of an "inspection" foretold the future. The term was extended also to the "inspector" of the heavens or the astrologer. In Hebrew we have as an equivalent *rô'ēh* and in an article "*Rô'ēh* and *Ḥôzēh*" (*Journal of Biblical Literature,* Vol. XXVIII., part I) I have tried to show that the *rô'ēh* like the *bârû* was originally an "inspector" of some object through which the future was divined.

[12] Jastrow, *o. c.,* II., p. 287 seq. for examples.

clusion that the diviners were far removed from resorting to deception and to tricky devices such as are reported of augurs among Greeks and Romans.[13] Indeed the mere circumstance that hepatoscopy prevailed uninterruptedly from the earliest to the latest periods, and that on all important occasions it was resorted to as the official means of ascertaining the will and intentions of the gods, is a testimony to the conscientious manner in which the priests must have carried out their tasks.

In passing from hepatoscopy to astrology—the term always used in the larger sense above pointed out[15]—we pass also from the domain of popular and to a large extent primitive beliefs to a domain of speculation that in comparison justly merits the designation scientific. Astrology in Babylonia and Assyria rests on the identification of the heavenly bodies with the gods of the pantheon. While in the case of the personification of the sun and moon as deities we are still within the province of popular and primitive conceptions, we pass beyond this province in the extension of such personification to the planets and stars. It lies in the nature of animism, which is certainly to be regarded as a stage in the development of religious beliefs, even if it is not admitted to be the starting-point of such development, not to distinguish sharply between the manifestation of a personified power and the seat of that power. The sun is at once the sun-god and the seat of that god; and the same applies to the moon. Both, accordingly, have their places in the heavens. Storms, rains, thunder and lightning likewise come from the heavens and hence the gods representing the personification of these powers also have their seats in the heavens. Such conceptions are a direct outcome of popular and primitive methods of thought, and we may perhaps go a step farther and assume that by analogy other powers whose manifestations proceeded from a hidden source were assigned to the heavens, but this step is far removed from the identification of *all* the stars with deities and still farther from projecting

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[13] See, *e. g.*, the anecdotes related by Polyænus, "Strategicon," IV., 20, and Frontinus, "Strategematicon," I., XI., 15. Compare also Hippolytus, Refutatio, IV., 40.

[14] The earliest reference occurs in the inscriptions of Gudea (c. 2500 B. C.), the latest in the inscriptions of Nabonidus, the last king of Babylonia. See Jastrow, *o. c.*, II., p. 273 and 247 seq.

[15] See above, p. 647.

the seats of *all* gods and goddesses on to the heavens. Again, the influence of moon and sun, as well as storms with their accompanying phenomena, on the fate, welfare and happiness of mankind was so apparent as to force itself upon the notice even of people living in a state of primitive culture; and when we pass to the higher stages of nomadic, semi-nomadic and agricultural life, the dependence of the country's prosperity and of the individual's welfare upon sun, moon and climatic conditions would be correspondingly increased. The observation of the movements and aspects of sun and moon would follow as a natural consequence, and we may suppose that at a comparatively early stage in cultural development crude and sporadic attempts might be made on the basis of empirical observations to select the favorable moment for such actions as the undertaking of a journey, for hunting or war, for the planting of seeds, for the gathering of the harvest or even for the pairing of domesticated animals. The influence of the planets and stars, however, would be less obvious and indeed until a comparatively advanced stage of intellectual development would not be recognized at all. Astrology in the proper sense, therefore, is not found among peoples of primitive culture[16] who at the most are guided by certain empirical considerations in their enterprises.

The projection of the seats of all the gods on the heavens can only have arisen in people's minds as the outcome of theoretical speculation. This, to be sure, represents merely the extension by analogy of the primitive conception of sun, moon and storms, but an extension which for the very reason that it is neither obvious nor the result of actual experience, lies outside of the range of early thought. The views of Cumont[17] and Boll[18] may, therefore, be unhesitatingly accepted that astrology everywhere represents a *scientific* view of the universe—scientific of course in a relative sense, and in comparison with the conceptions that underlie hepatoscopy or with the significance attached to universal occurrences on earth or to the

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[16] See above, p. 647, note 3.

[17] Les Religions Orientales dans le Paganisme Romain" (Paris, 1907), pp. 197 seq.

[18] "Die Erforschung der antiken Astrologie" (*Neue Jahrbücher für das Klassische Altertum,* I., Abt., Bd. XXI.), p. 108 seq.

mishaps and accidents of daily life. Indeed, one may safely go a step further and set up a contrast between hepatoscopy and astrology corresponding to the difference nowadays between the popular views of the universe which are still so largely controlled by superstitious beliefs and crude speculations—instance the hold that astrology, phrenology, chiromancy, clairovoyance, dreams and belief in the power of ghosts still have upon the masses,—and those held by scientific thinkers. The astrological system of Babylonia and Assyria, which is the earliest known to us, might be described as taking the place in antiquity that in modern times is taken by the "Darwinian" theory of evolution in so far as it is the product of the schools and not of popular conceptions.

It may reasonably be supposed that the recognition of the regular movements of the planets and that within certain periods they pass through a well-defined course as do the sun and moon, was the decisive step which led to the departure from along the lines of popular conceptions. With the planets thus placed on a par with sun and moon, it was a natural sequence to regard them also as gods, or, what amounted to the same thing, as the seats of gods, and to endow them with the power to control occurrences on earth. In the oldest astrological texts, as a matter of fact, we find the five planets already identified with the chief gods of the Babylonian-Assyrian pantheon, Jupiter being known as Marduk, Venus as Ishtar, Saturn as Ninib, Mercury as Nebo and Mars as Nergal.[19] This identification in itself is sufficient to establish the advanced character of the entire astrological lore, for the gods in question, according to the popular conceptions and even in the official cult, stand in no connection with the stars. Marduk, Ninib and Nergal are originally solar deities. Nebo appears originally to have been a water deity,[20] while Ishtar is the earth goddess, the symbol and personification of fertility in general. In thus being identified with the planets, the original character of the deities in question is entirely lost sight of. The identification, therefore, represents a break with popular conceptions and with the traditions that had

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[19] Kugler, "Sternkunde und Sterndienst in Babel," I., p. 8 with the corrections on pp. 221 and 286.

[20] Jastrow, *o. c.*, I., p. 118.

gathered around these deities. In view of this, it is clear that in dealing with Babylonian-Assyrian astrology we have to do with the theories of the theologians or priests as the representatives of advanced and abstract thought, and not with popular notions. Moreover, the choice of the deities in question and the order in which they are enumerated when introduced as equivalents of the planets are further indications of the speculative spirit which led to their identification with the planets, and also of the time when this identification took its rise. Jupiter-Marduk is always mentioned first and this precedence is evidently a reflection of the period when Marduk was regarded as the head of the pantheon, *i. e.,* the period after Hammurabi with whom as the unifier of the Euphratean states, the city of Babylon as the capital of the empire assumes the definite position it continued to hold till the destruction of the neo-Babylonian kingdom by Cyrus in 539 B. C. The pantheon as constituted during or after the days of Hammurabi assigns to Marduk as the patron deity of Babylon the first position. Marduk takes the place held by Enlil of Nippur and subsequently, as would appear, by Ninib.[21] The other great gods of the pantheon, as found in the Hammurabi period, are precisely the ones identified with the remaining four planets, Ishtar, Ninib, Nebo and Nergal together with Sin the moon-god, Shamash the sun-god and Adad-Ramman the storm-god. The basis upon which Babylonian-Assyrian astrology rests thus assumes the definite formation of a pantheon and moreover the particular form of the pantheon that marks the Hammurabi period, *i. e.,* after 2000 B. C. This does not necessarily mean that astrology dates in Babylonia from this period, for it is possible that there was an earlier series of identification of gods with planets, but that the astrological texts known to us do not revert to originals older than the days of Hammurabi. There are indeed references in the inscriptions of Gudea which would point to the practice of interpreting the signs of the heavens at this earlier period[22] and it may well be therefore that the priests long before Hammurabi had started on the course of speculation which culminated in placing the seats of *all* the gods in the starry firmament. But whatever the age of Babylonian-Assyrian

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[21] See Jastrow, *o. c.,* I., p. 452 seq.

[22] See Jastrow, *o. c.,* II., p. 423.

astrology may be, it must have involved the dissociation of the gods identified with planets and stars from their original character as solar, agricultural, water or chthonic deities, and it is also reasonable to assume that it is subsequent to the period when, by a process of selection, certain deities, though originally local in character, were differentiated from the many other local gods and became members of a definitely constituted pantheon consisting of a limited number of great gods and of a larger number of minor deities.

Before passing on to another phase of the subject, it may be proper to point out the more specific factors involved in the identification of the planets with certain gods—all confirmatory of the general thesis that astrology represents a system devised in the schools, and that its very artificial character is indicative of its being a "scientific" and not a "popular" product. Marduk was identified with Jupiter by the natural association which led to assigning the head of the pantheon to the most striking of the planets known to the ancients.[23] In the case of Venus it was probably her double character as morning and evening star that suggested the identification with Ishtar, who as the goddess of fertility likewise presents two aspects in the two divisions of the year—the producer of life and vegetation in the spring and summer, and the one who withdraws her favors in the fall and winter.[24] The dark-red color of Mars appears to have been the factor which prompted the identification with Nergal, the god of the burning summer solstice, of pestilence and death. Nebo becoming in the pantheon of Hammurabi the son of Marduk,[25] a natural association of ideas would lead to assigning him to the smallest of the planets. There would

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[23] See Kugler, *o. c.*, p. 14, note 1.

[24] This double character of Ishtar underlies the famous myth commonly known as Ishtar's descent into the lower regions. See Jensen, "Keilinschriftliche Bibliothek," VI., 1, pp. 80–91. The destructive character of Ishtar appears also in the myth of the slaying of Tammuz and in the other capacity of Ishtar as a goddess of war. See Jastrow, *o. c.*, I., pp. 82 seq.

[25] See Jastrow, *o. c.*, I., p. 120. As a concession to the predominance of the Nebo cult in the days of the neo-Babylonian dynasty, we find in the astronomical texts of the latest period (after 400 B. C.) a change in the order of the planets, Nebo-Mercury assuming the third place, *i. e.*, after Marduk and Ishtar, instead of Ninib-Saturn who is assigned to the fourth place. See Kugler, *o. c.*, p. 13.

thus remain for Ninib the planet Saturn whose large size would have been regarded as appropriate for a solar deity once occupying the position that afterwards was assumed by Marduk.

The planets thus representing the great gods of the pantheon, the prominent fixed stars were associated with the minor deities and while in the case of many of the stars occurring in the purely astronomical texts which belong to the later and latest periods of Babylonian culture,[26] no definite association with specific deities was worked out, yet it is to be borne in mind that all the stars were regarded as gods in a logical and consistent extension of the principle which gave rise to astrology as a system of divination. It is one of the many merits of Hugo Winckler[27] to have demonstrated as one of the tenets of the Babylonian-Assyrian conception of the universe a perfect correspondence between occurrences on earth and phenomena in heaven.[27a] Earth and heaven stand related to each other as a reflection in a mirror to the original which is reflected. Since all that happens is due to the gods, it follows from the speculative view which places the gods in the heavens that occurrences on earth are prepared in the heavens. What one sees in the heavens is therefore the activity of the gods preparing the events on earth. The constantly changing aspect of the starry universe thus finds a natural explanation. The movements of sun, moon and planets as well as the ever-varying aspects of clouds and all other phenomena of a striking character were the external symptoms of the never-

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[26] See Kugler, "Sternkunde," p. 2 and elsewhere whose views have been accepted by Boll, Eduard Meyer, Schmidt and many others. See Jastrow, II., p. 432, note 1, where I have set forth my own position on the important question as to the age of astronomy in Babylonia and Assyria with an endeavor to do justice to both sides of the burning problem.

[27] "Himmels und Weltenbild der Babylonier" (Leipzig, 1893, 2te Auflage) and numerous other monographs of this scholar. See Jastrow, *o. c.*, II., p. 418, note 2.

[27a] The same view prevails among the Indians of Mexico according to Preuss "Die Astralreligion in Mexico in vorspanischer Zeit und in der Gegenwart" (Transactions of the 3d International Congress for the History of Religions I., p. 36 seq.). It is to be noted that also among the Mexican Indians the astral cult included the worship of storm and rain deities (*l. c.*, p. 38 seq.). Preuss is mistaken, however, in regarding this astral religion as "primitive." On the contrary, it betrays all the earmarks of a cult devised by priests on the basis of elaborate cosmical speculations.

ceasing divine activity. The theory of the correspondence between heaven and earth was carried by the theologians of the Euphrates Valley to its logical consequences. Myths and legends were so shaped under the influence of the theory as to admit of a double interpretation, the one having reference to the movements and aspects of the heavenly bodies, the other to occurrences whose scene is placed on earth. A series of acts of creation on earth is counterbalanced by a corresponding series in the heavens.[28] The heavens were divided off into districts with mountains, rivers and cities corresponding to those on earth. The famous Gilgamesh Epic—a composite tale with almost equal proportions of nature myth, legendary lore and dimned historical traditions—admits likewise of a double interpretation, the scenes applying equally to the movements of heavenly bodies and to events on this globe;[28a] and the same holds good for such tales as the story of Etana and the Adapa myth which, besides betraying the work of theological schools in making the tales the medium of conveying doctrinal teaching,[29] are so constructed as to conform with the fundamental principle of a correspondence between heaven and earth.

Corresponding, therefore, to the theory underlying Babylonian-Assyrian hepatoscopy as above set forth, we have in the case of astrology likewise a theory which lifts the endeavor to divine the future through the observation of the planets and stars beyond mere caprice and arbitrary guesswork. Granted the underlying assumption that there is a perfect correspondence between heaven and earth, it follows that if one can grasp the meaning of the aspects and movements of the heavenly bodies one can recognize clearly what the gods are doing, and hence what the future is to be, which, since it is in the hands of the gods, is merely the outcome of their activity as revealed in the heavens. Astrology is, therefore, like hepatoscopy a means of entering into the workshop of the divine

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[28] See Zimmern, "Biblische und Babylonische Urgeschichte" (3$^{te}$ Auflage, Leipzig, 1903).

[28a] See Kugler, die Sternenfahrt des Gilgamesch (Stimmen aus Maria-Laach, 1904. Heft. 4).

[29] See Jastrow, "Religion of Babylonia and Assyria" (Boston, 1898), pp. 519–555, and in greater detail in the writer's next volume. "Temples, Myths and Cults of Babylonia and Assyria."

will and intention. Through the planets and stars or rather in the planets and stars one sees the gods at work and if one knows what they are contriving, one knows what occurrences will take place on earth. Again, as in the case of hepatoscopy, past experience and association of ideas are the two main factors involved in the system of interpretation gradually devised by the Babylonian-Assyrian *bârû* priests or "inspectors" in their capacity as astrologers or "inspectors" of the heavens. A favorable event or a favorable outcome of a crisis following upon certain aspects of the heavenly bodies would be made the basis of a favorable prognostication on another occasion when the same conditions presented themselves; and the prognostication would be made without reference to the particular event following upon the original observation. It was not the event that was of importance but merely the circumstance whether it was favorable or unfavorable. On the basis of this experience phenomena were entered as pointing to favorable or unfavorable occurrences, and these entries served as a guide to the priests in the task imposed upon them of divining the future. But while the principle of *post hoc propter hoc* entered largely into the formation of collections of astrological omens—as it did in the collections of hepatoscopical omens[30]—the natural or artificial association of ideas was even a more prominent factor. Normal conditions as a rule were interpreted as favorable. Thus, if the moon and sun appeared in conjunction at the proper time, a favorable prognostication was indicated. If the conjunction took place at a time earlier or later than the expected moment it forboded disaster of some kind. Again, by a perfectly logical association, in case the new moon was seen on the first day of the month, *i. e.*, was not obscured by clouds, the omen was of a favorable character; if, however, clouds obscured it so that the new moon was not visible, difficulties of some kind might be expected. Days were entered as favorable or unfavorable according to these and numerous other indications and though in the case of a specific inquiry of the gods recourse was had to hepatoscopy in order to ascertain what a deity had in mind with regard to the particular situation in question, the signs

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[30] See Jastrow, "Religion Babyloniens und Assyriens," II., p. 251 seq., for examples.

involuntarily forced on one's notice by conditions prevailing in the heavens were not and could not be neglected. A few examples from astrological texts will suffice for our purposes. Thus we read in an official report of the Assyrian period:[31]

> "If the moon is seen on the first day, good faith and stable conditions in the land. If the first day is abnormally long, the king will have a long reign."

The prognostication is clearly based on a natural association of ideas. From the fact that the new moon is visible on the day set for it, the conclusion is drawn that as the moon kept good faith, as it were, so the king may expect those entrusted with any mission to be faithful and that his subjects in general will be loyal. By a still clearer association long days point to a long reign.

Another report states:[32]

> "If the moon is seen out of the expected time, prices will be low.[33] The moon was seen with the sun on the twelfth day. If moon and sun are seen together at an abnormal time, a strong enemy will oppress the land, but the king of Babylonia will accomplish the overthrow of his enemy."

The normal period when moon and sun should be seen at the same time in the heavens is on the fifteenth day—the moment of opposition. The *bârû*-priest reports, however, that the appearance of moon and sun took place already on the twelfth day—earlier, therefore, than was expected. The abnormal condition points to some misfortune and two omens that are to be regarded as extracts from actual collections are introduced, the one referring to economic conditions, the other to political affairs, and though both are unfavorable, yet in the second instance it is added that ultimately the enemy will be overthrown. In the case of such specific prognostications we are perhaps justified in concluding that they rest on past experience. In other words, on some occasion when sun and moon were seen together in the heavens earlier than the fourteenth or fifteenth day of the month, prices went down or an enemy entered the land but was eventually vanquished. The occurrences were

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[31] Thompson, "Reports of the Magicians and Astrologers of Nineveh and Babylon" (London, 1900), Vol. I., No. 1.

[32] *o. c.*, No. 119.

[33] Low prices were regarded as an unfavorable condition in Babylonia and Assyria.

accordingly entered as unfavorable in the collections, and when the same conditions again took place, the fact was reported to the king who would thus be warned either against undertaking an expedition or at least would be prepared for some disaster or discomfiture.

To even partially enumerate the phenomena noted in the astrological collections would carry us too far, and it will easily be seen how in the course of time the collections would grow to huge proportions.[34] Halos around the moon or sun, moon and sun eclipses, thunder in certain months or on certain days, one planet or the other standing within the halo around the moon, the appearance of Venus or some other planet at the heliacal rising or at some other point in its course, the appearance of the moon's horns or crescent, the position or appearance of a certain planet or of a certain star are among the phenomena entered and here the prognostications vary according to the season of the year, according to the month or day of the month.[35]

Without losing sight of the purely artificial character of the system of interpretation devised by the Babylonian theologians, one should not withhold one's meed of praise for the consistency with which the elaborate system was carried out for a long stretch of centuries, as well as for the patience displayed in the compilation of the extensive collections of omens of which only portions have come down to us. Moreover, the Babylonian-Assyrian astrology shows that even a superstition can harbor an exalted idea, for the result of the continuous observation of the movements and aspects of planets and stars must have been to impress at all events the priests with the realization of the reign of law in the universe; and it is, assuredly, a decided gain to realize that even the activity of the gods is under the sway of a fixed order. In striking contrast to hepatoscopy which rests upon the arbitrary nature of the gods and merely aims to fathom their caprice, astrology starts with the recognition of the

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[34] The best known of such astrological collections in Ashurbanapal's famous library is a series known from the opening words as "When Anu and Enlil" and comprising more than seventy tablets. See Jastrow, *o. c.*, II., p. 424, notes 3 and 4, and copious examples beginning p. 458.

[35] In their ambition to make the collections as complete as possible, the *bârû*-priests even enter phenomena that never occurred, and some that never could have occurred.

fact that the gods as represented by the planets and stars act in concert. The phenomena of the heavens suggest *united* action in place of individual caprice, and the general regularity of the movements of heavenly bodies must soon have suggested to the priests the view that divine government of the universe rests at least to a large extent upon law and order. We may properly assume that this aspect of astrology by which, through constant observation, the permanent impression of awe and reverence for the grandeur of heavenly phenomena was deepened, was an important factor in maintaining the faith in the stars as manifestations of the divine will and of the intentions of the gods towards mankind. The Babylonian *bârû*-priest could reëcho the sentiment of the Psalmist (19, 1–2) who, carried away by the sight that greeted him in the heavens, exclaimed, " The heavens declare the glory of God and the firmanent sheweth his handywork. Day unto day uttereth speech and night unto night sheweth knowledge." To the *bârû*-priest the heavens spoke by day and night, and it was his privilege to interpret to others the knowledge revealed to him.

Attention has already been directed[36] to the fact that in the case of both hepatoscopy and astrology the interpretations of the omens have reference exclusively to the public welfare, to the condition of the crops, to pestilence, to war or victory and that the introduction of the king likewise falls within this category. More than this, the interpretations in both systems are substantially the same, so that a dependence of one system upon the other becomes at least a probable hypothesis. A detailed study of the two systems leads indeed to a confirmation of this thesis and since hepatoscopy, as has been shown, is an outcome of popular conceptions and exists in full force in the earliest period of Babylonian history, it is reasonable to suppose that it was the first to be developed and that the astrological system represents an adaptation of the principles underlying the interpretation of signs on the liver to signs noted in the heavenly bodies. The " scientific " view of the universe that is closely bound up in the astrological system represents, as is obvious, a later stage in cultural development than the " popular " conception upon which hepatoscopy rests. In

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[36] See above, p. 649.

the name given to the planets in Babylonia we have, I venture to think, a direct proof of this dependence of astrology upon hepatoscopy. It has always been a puzzle to scholars that the common designation for planet should have been a compound ideograph,[37] the two elements of which signify "sheep" and "dead." Attempts to furnish a satisfactory explanation have failed and the interpretation offered by Babylonian scribes as "causing the death of cattle,"[38] while confirming the division of the sign into the two elements in question, is purely fanciful and is of value chiefly as showing that the real origin of the designation had already in ancient times become obscured. Through a syllabary (II. Rawlinson, Pl. 6, 4 c–d) we learn that the compound sign (Lu-Bat) is to be read *bi-ib-bu* and the context in which the word occurs[39] is sufficient to show that it is one of the names for "sheep." This, moreover, is confirmed by the fact that the first element, Lu, with or without the addition of the sign for "male" designates the "sheep." Now, the second element (Bat) has also the force of *têrtu,* "omen,"[40] the explanation

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[37] Lu-Bat. For a full discussion see a special article by the writer "The Sign and Name for Planet in Babylonian" in the PROCEEDINGS OF THE AMERICAN PHILOSOPHICAL SOCIETY, Vol. XLVII., pp. 141–155. It is also to be noted that while all the planets are designated as Lu-Bat or *bibbu,* there are two, Mercury and Saturn, to whom the designation is specially applied. On the reason for this as well as for the explanation of the Babylonian names for Mercury (Lu-Bat Gu-Ud) and Saturn (Lu-Bat Sag-Uš) see the article just referred to, in which on p. 142 a reference should have been added to Zimmern, "Keilinschriften u. das alte Testament," p. 622, seq.

[38] *muš-mit bu-lim* (V. Rawlinson, Pl. 46, Nr. 1 (rev.), 41), in which equation Lu is entered as the equivalent of *bulu* "cattle" and Bat as III., 1 of *mâtu* "cause the death" or "kill." The artifical character of the explanation is revealed by the unwarranted extension of Lu in the general sense of "cattle," nor can Bat without some further qualifying prefix mean "cause to die" but merely "to die" or "to be dead." Lu-Bat could have the force of "sheep that is dead" or "sheep that is killed," but never "sheep (or 'cattle') that kill."

[39] It is followed by *a-tu-du* "goat" and *sap-pa-ru* "mountain goat." Note also that l. 1, a-b Lu = *kir-ru*—a common term for "lamb." Dr. Rudolf Eisler finds in the double sense of the Semitic stem *āmār* "word" and "sheep" a further support for the thesis here set forth ("Origin of the Eucharist," p. 10—an address before the Third International Congress for the History of Religions at Oxford, Sept. 18, 1908.)

[40] See II., Rawlinson, Pl. 27, No. 2, 46 obv. c-d. Ur-Bat = *ter-tum ša ḫa-se-e, i. e.,* "omen of the liver," the first element (Ur) being the common

for which is to be sought in the circumstance that through the sacrificial animal, killed for the purpose, an omen was secured. The combination Lu-Bat, " dead sheep," is therefore intended to convey the notion of a " sacrificial sheep," offered to the deity as a means of securing an " omen." So prominent is the part played by hepatoscopy in the Babylonian-Assyrian religion as shown not merely by the extensive omen texts, dealing specifically with divination through the liver,[41] but by the frequent allusions to the rite in historical inscriptions that one is tempted to set up the thesis that the original purpose of sacrifice among the inhabitants of the Euphrates Valley was to ascertain through the sacrificial animal what the future had in store or what the gods had in mind,—this purpose taking precedence of other views of sacrifice such as tribute or alliance with the deity.[42] However this may be, the animal, so far as the evidence goes, invariably chosen for purposes of divination was the " sheep,"[43] and there is one instance[44] in which the combination Lu and Bat occurs in a " liver " divination text to designate the " sacrificial sheep " the liver of which is to be examined as a means of divination. It is with this use of the term that I propose to connect the designation Lu-Bat for " planet." The sheep being the common animal of divination, the term acquired the general force of an " omen " precisely as in Latin we have *auspicium,* originally an augury through " bird observation," *i. e.,* the noting of the flight of birds, becoming the generic term for any kind of an augury, because of the prominence of " bird observation " as a means of divination. Still

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ideograph for "liver" (see Jastrow, "Signs and Names for the Liver in Babylonian," in *Zeits. für Assyr.,* XX., p. 105, seq. and p. 127) and the combination thus having the force of " liver omen." The association leading from " dead " to " omen " thus becomes intelligible, since the " dead " or " sacrificed " animal is the medium for procuring an omen.

[41] Over 1,000 of the circa 30,000 fragments of the royal Library of Ninevah are " liver " divination texts. See Jastrow, " Religion Babyloniens und Assyriens," II., p. 211, note 1, and p. 222, note 2.

[42] See Jastrow, *o. c.,* II., p. 217.

[43] So, *e. g.,* in the case of the official reports to Assyrian Kings, in the prayers connected with the divination rite as well as in the omen collections. See Jastrow, *o. c.,* II., pp. 281, 289, 301, 307, 308, etc.; " Cun. Texts," XX., Pl. 1, 1; Boissier, " Documents assyriens relatifs aux Présages," p. 97, 11.

[44] Boissier, *l. c.,* p. 212, 27. Lu(Nita) Bat (u) = *immêru mîtu.*

more striking is the analogy offered by the usage in Greek where the word for bird, ὄρνις or ὀιωνός, has acquired the force of "omen."[45] The planets, accordingly, were called "sheep" because the purpose for which they were observed was to serve as "omens," and this view is confirmed by a statement of Diodorus (Bibl. Hist. II., 30) that the Babylonians (or "Chaldeans" as he calls them) called the planets ἡρμενεῖς, "interpreters," because "they reveal (or "interpret) the intention of the gods to men." The term used by Diodorus accurately reproduces the force of Lu-Bat in the sense of an "omen" or "interpretation" of the will and purpose of the gods. If this explanation be admitted, we would thus have a direct evidence of the dependence of astrology upon hepatoscopy, in accord with the reasonable assumption on *a priori* grounds of the rise of astrology subsequent to hepatoscopy. The justification for thus assuming a bond uniting astrology and hepatoscopy is furnished by the evidence for an analogous condition among the Etruscans whose method of hepatoscopy has many points in common with the Babylonian-Assyrian rite.[46] On the famous bronze model of a liver found near Piacenza[47] and which, dating from about the third century B. C., was used as an object lesson for instruction in hepatoscopy, precisely as the clay model of a liver dating from the Hammurabi period was used in a Babylonian temple school,[48] we find the edge of the liver divided into sixteen regions with the names of the deities inhabiting them, corresponding to divisions of the heavens in which the gods have their seats, while on the reverse side there is a line dividing

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[45] See the passage in the Birds of Aristophanes ll. 719–22 to which my colleague Prof. Lamberton directed my attention and Xenophon, Anabasis, III., 2, 9, which Dr. R. G. Kent, of the University of Pennsylvania, kindly pointed out to me.

[46] See Thulin, "Die Etruskische Disciplin," I. (Göteborg, 1905), p. xii, seq.

[47] It is sufficient for our purposes to refer to two recent treatises on this remarkable object (a) Thulin, "die Götter des Martianus Capella und der Bronzeleber von Piacenza" (Giessen, 1906), and Körte, "die Bronzeleber von Piacenza," in *Mitt. d. Kais. Deutsch. Arch. Instituts* (Römische Abteilung), XX., pp. 349–379.

[48] Published in "Cun. Texts," VI., Pls. 1 and 2 (with photograph). See Boissier's first attempt at an interpretation, "Note sur un Monument babylonien se rapportant à l'Extispicine" (Genève, 1899). I hope ere long to publish the results of my study of the inscription on this object.

[49] See Körte, *l. c.*, p. 356.

the liver into "day" and "night."[49] Professor Körte, in a study of this remarkable object, summing up the results of many years of research, explains this by showing that the liver was regarded as a microcosm reflecting the macrocosm,[50] or, in other words, the liver of the sacrificial animal from being originally a reflection of the soul or mind of the god to whom the animal was offered, was brought into connection with the observation of the heavenly bodies revealing the intention of the gods acting in concert. This combination of hepatoscopy with astrology likewise points to the latter system of divination as the later one, dependent in some measure upon the earlier method of divining through the liver.

This leads us to the last two points to be considered here, the relationship of Babylonian-Assyrian astrology to astronomy and the spread of astrology from the Euphrates Valley to other peoples. While astrology even in its most primitive phases assumes some knowledge of astronomy, it stands to reason that since the sole purpose for which the planets and stars were observed was as a means of securing omens, there could be no genuine interest in astronomical lore, pure and simple. As the scope of astrology increased, more stars were added to the field of observation, with each succeeding ages further details of the movements of the planets were noted, and groups of stars were combined into constellations of a more or less fanciful character. It became necessary for purposes of instruction in astrology to systematize and synthesize the knowledge thus acquired from empirical observation. In the course of time a considerable body of "school" literature thus took shape in the form of lists of stars, with attempts to locate them and to set forth some of the phenomena connected with them.[51] For the practical purpose of regulating the calendar further pedagogical aids were devised, and

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[50] Körte (p. 362) expresses himself as follows "Die Leber, der Sitz des Lebens nach antiker Auffassung, erscheint als ein Abbild des Weltganzen im kleinen. Wie dieses ist sie in eine rechte und in eine linke Hälfte, eine Tages—und Nachtseite geteilt. Die Trennungslinie entspricht der Ost-Westlinie des Weltalls. Wie das Himmelsgewölbe ist ihr Rand in 16 Regionen geteilt, in denen Götter walten und Zeichen geben können."

[51] As examples of such lists see II. Rawlinson, Pl. 49, Nos. 1, 3, 4; III. Rawlinson, Pl. 57, No. 6, and the texts entered in the Index to Bezold's "Catalogue of the Cuneiform Tablets of the Kouyunjik Collection," p. 2096. These lists in the royal library of Nineveh revert to older Babylonian originals.

thus at a comparatively early age the seeds for a genuine science of astronomy were planted. The fact, however, is significant that, with perhaps some exceptions, we have in the library of Ashurbanapal, representing to a large extent copies from older originals, no texts that can properly be called astronomical.[52] For this reason a reaction has set in among Assyriologists against the view formerly held that astronomy was cultivated at an early period in Babylonia and Assyria.[53] It is certainly significant that the astronomical tablets so far found belong to the latest period and in fact to the age following upon the fall of the Babylonian empire.[54] While we must be warned against pressing the argument *ex silentio* too far, still there is sufficient evidence to warrant the conclusion that the most glorious period of Babylonian astronomy falls in the fourth to the second centuries before this era, that is to say, within the period of the Greek occupation of the Euphrates Valley. According to Kugler,[55] the oldest dated genuinely astronomical tablet belongs to the seventh year of Cambyses, *i. e.*, 522 B. C., although it shows evidence of having been revised on the basis of an older original. We also find evidence of changes both in the astronomical terminology and in the order of the planets after c. 400 B. C.,[56] so that while we are justified in going back to the neo-Babylonian dynasty as the point of departure for the beginnings of a genuine astronomical science, it would be rash to go much farther back than this. At all events,

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[52] K. 9794 appears to be purely astronomical. See Bezold, *o. c.*, Vol. V., p. xxv. and iii., p. 1039; also Jeremias, "das Alter der babylonischen Astronomie" (Leipzig, 1908), p. 21.

[53] For a fuller discussion of the recent literature on the subject see Jastrow, *o, c.*, II., pp. 232–434. Kugler, in "Kulturhistorische Bedeutung der Babylonischen Astronomie" (*Vereinsschriften der Görres-Gesellschaft,* 1907, III., pp. 38–50), maintains the late origin of Babylonian astronomy. His views have been accepted by Boll, "die Erforschung der Antiken Astrologie" in *Neue Jahrbücher für das Klassische Altertum,* I. Abteilung, Bd. XXI., pp. 103–126) and others, while Jeremias ("das Alter der babylonischen Astronomie") and the adherents of the Winckler school cling to the view that astronomy took its rise in the early period of Babylonian history. For a general summary of our present knowledge of Babylonian astronomy, on the basis chiefly of Kugler's researches, see the two articles by Schiaparelli in the *Rivista di Scienza,* III., pp. 213–259, and IV., pp. 24–54.

[54] See Kugler, "Sternkunde und Sterndienst in Babel," I., p. 2.

[55] Sternkunde, p. 61.

[56] *o. c.*, pp. 12, 13, 22, 62, etc.

it is not until we reach the days of the Seleucidian and Arsacidian dynasties that we find astronomical calculations of the movements and of the position of the moon and planets in full swing.

It can hardly be regarded as accidental that the flourishing period of Babylonian astronomy should thus be coincident with the time when, according to definite evidence, Babylonian astrology passed over into Greece. "The conquest of Alexander," as Bouché-Leclercq tersely puts it, "threw down the barriers hitherto separating races and civilizations."[57] To Berosus, the "Chaldaean" priest who wrote in Greek a history of Babylonia and Assyria, the Greeks themselves ascribe the introduction of astrology into their midst. Settling in the island of Cos, the home of Hippocrates, Berosus himself taught the Babylonian system to the students whom the fame of the great physician had attracted to that place.[58] The fragments preserved of the writings of Berosus,[59] few as they are, suffice to show that he gathered his material direct from the sources, and there is therefore no reason to question that he followed conscientiously the methods laid down in the Babylonian collections of astrological omens. While it is of course possible and indeed probable that through the contact with the Persians the Greeks may have heard of the Babylonian system of divining the future through the stars, it is certain that astrology did not take a definite hold on the Greeks and become part of their intellectual outfit until the days of Berosus, *i. e.,* till about the beginning of the third century B. C. A few centuries sufficed to transform Babylonian astrology under the influence of the Greek spirit from the character of an "oriental religion" which as Bouché-Leclercq[60] recognized it had at the time of its adoption, into the appearance of a science. Already advanced students of astronomy, the Greek physicists combined astrology with the principles and speculations of mathematics and brought it into accord with the current systems of philosophy until it became a genuine expression of the Greek spirit and an integral part of Greek culture. A feature which the Greeks introduced and which

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[57] L'Astrologie Grecque," p. 35.

[58] Vitruvius, de Architectura, IX., 6. See also Bouché-Leclercq, *o. c.,* pp. 2 and 37.

[59] Cory, "Ancient Fragments," pp. 51–69.

[60] *o. c.,* p. 1.

of itself served to change the aspect of the Babylonian system was the perfection of a method whereby the fate of the individual was brought into connection with the stars. The science of genethlialogy[61] or the casting of the individual horoscope from the position of the stars at the time of an individual's birth is a *distinctly* Greek contribution. The insignificant role that the individual plays in all phases of divination, except in the case of the accidents and unusual incidents that happen to him and which were therefore looked upon as signs sent by the gods to the individual as such, prevented the rise of the thought that the activity of the gods as shown in the heavens had any bearing on the fate of the individual. As we have seen, astrology, just as hepatoscopy, concerned itself in Babylonia and Assyria with the general welfare and the public state. There was no place in either of the two great systems of divination for the individual and we may go a step farther and assert that it was contrary to the entire spirit of the Babylonian-Assyrian religion to suppose that the gods concerned themselves with the individual sufficiently to give him as such, through the stars or through the liver of a sacrificial animal, an indication of what they purposed doing.[62] It was different in Greece where long before the time that Babylonian astrology was assimilated to Greek culture, the individual had asserted himself to an extent undreamed of in the Euphrates Valley. Instead of an intellectual oligarchy with all learning confined to priestly circles, corresponding to the concentration of all political power in the hands of a few privileged families, we have in Greece a republic of letters with an independence of thought only surpassed by the strength of individualism in the political sphere. Religion had long ceased to be the controlling factor or at least the predominant

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[61] Bouché Leclercq, *l. c.*, p. 49, while noting that there is no trace of the application of the astrology to the individual horoscope in cuneiform texts, is disposed to attribute this to the dearth of material. Since he wrote his great work that material has largely increased, and it is perfectly safe to conclude that this phase of astrology *never* existed in the Euphrates Valley.

[62] If in a few very late texts (cf. Bouché-Leclercq, *l. c.*, p. 50) we find entries of the birth of a child with the mention of the aspect of the moon, planets and constellations, this is to be ascribed to Greek influence as Bouché-Leclercq himself suggests. Some Greek astrologers even went so far, according to Vitruvius (*l. c.*), as to cast the horoscope of an individual from the time of conception.

factor in Greek civilization. One science after the other had freed itself from the thraldom of religious tradition and, accordingly, astrology, when introduced into Greece, did not become a part of the Greek religion but an element of Greek *science.* Passing on to the Romans[63] as an integral part of Greek culture, and becoming with the spread of Roman authority the general possession of the ancient world, astrology, because of its indissoluble association with astronomy, mathematics, and the philosophical systems of Greece, became part of the heritage of Greece to the world and took on in time the aspects of a religious cult.[63a] With the revival of Greek influence through the intellectual movement following upon the rise and spread of Islamism, astrology took a firm hold on the choice minds of mediaeval Europe by the side of such a force as Aristotelianism,[64] and continued to sway men's minds till the threshold of modern scientific thought, when it was swept away with so many other cherished traditions from the broad highway of science into the byways where it still flourishes at the present time and will no doubt continue to do so for a long time to come. Though somewhat more complicated in its processes, mediaeval and modern astrology is practically identical with the form it took on in Greece.[65] Not only did Greek astrology make its way throughout the West but it spread also to the East, for it has been definitely ascertained that what we find of it in India and even in China is due to the spread of the sphere of Greek influence;[66] and the same holds good for Egypt, where it begins to flourish with the rise of Hellenistic culture.[67]

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[63] Bouché-Leclercq, *l. c.,* Chap. XVI., "L'Astrologie dans le Monde Romain" and "Cumont," "Les Religions Orientales dans le Paganisme Romain" (Paris, 1907), Chap VII.

[63a] See Cumont, l'Influence religieuse de l'Astrologie dans le Monde Romain (Transactions of the 3d International Congress for the History of Religions, II., pp. 197–198).

[64] Bouché-Leclercq, pp. 624 seq.

[65] Compare for example the ideas associated with the planets in a modern manual of astrology like Ellen H. Bennett's "Astrology" (New York, 1897), pp. 93–100, with Bouché-Leclercq's statement of the Greek views ("L'Astrologie Grecque," pp. 93–101 and 311–326).

[66] Thibaut, "Astronomie, Astrologie und Mathematik," in Bühler-Kielhorn, "Grundriss der Indo-Arischen Philologie," III., 9, p. 15, and Kugler, "Kulturhistorische Bedeutung der babylonischen Astronomie," p. 49.

[67] It is one of the many merits of Bouché-Leclercq to have demonstrated

We thus find the source of all astrology in the ancient world in the system that arose in the Euphrates-Valley; and in view of this it will be admitted that the thorough study of Babylonian-Assyrian astrology is a factor of considerable importance in tracing the intellectual development of mankind. Coming back, therefore, to our immediate subject we have the curious phenomenon that about coincident with the period when a genuine science of astronomy takes a firm footing in Babylonia, astrology begins its triumphant march throughout the world. It is tempting to suppose that we have in this phenomenon the symptom of an "exchange" of influences that, while on the one hand Babylonia gave astrology to Greece, the contact with the scientific spirit of Greece resulted in giving an impetus to astronomical investigations in Babylonia. The possibility, indeed, of Greek influence on Babylonian astronomy was suggested by Bouché-Leclercq and is favored by Kugler.[68] Since, as now appears, the credit for the discovery of the precession of the equinoxes rests with the Greek astronomer, Hipparch, who announced it c. 130 B. C., and since it would indeed appear that in the second century B. C. the Babylonians, according to Kugler, were still ignorant of this principle, there is certainly every reason to suppose that the Babylonians were in this instance the pupils, and the Greeks the teachers. On the other hand, the Greek astronomers seem to have obtained from the Babylonians the names for the constellations of the ecliptic which we still use at the present time. Certainly, for the beginnings of their astronomy the Babylonians are not indebted to the Greeks since those beginnings reach back beyond the contact of Orient with

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in his great work on Greek astrology the worthlessness of the traditions which ascribe Greek astronomy and astrology to an Egyptian origin. See especially the important note ("L'Astrologie Grecque," pp. 51–52) from which it appears that "Chaldean" and "Egyptian" are used almost interchangeably by uncritical Greek and Roman writers who hand down more or less fanciful traditions. Since Boll ("Sphæra," p. 159 seq.) and others have demonstrated the late origin of the zodiac of Denderah, the chief evidence for the early introduction of astronomy in Egypt has fallen away; and there is no reason for assuming that astrology flourished in Egypt before the Ptolemaic period.

[68] Bouché-Leclercq, *o. c.*, p. 50 and Kugler, "Kulturhistorische Bedeutung der babylonischen Astronomie," p. 48.

Occident, but that would not preclude the possibility of influences from the side of Greece at a later stage in the development of astronomical lore.

To account for the point of departure for the unfolding of a genuine science as astronomy, independent of merely empirical observations in the interest of astrology, and which as we saw[69] dates from the sixth century B. C., we have another factor entering into Babylonia about this time that must have exerted a profound influence—the appearance of Persia on the scene and with it the advanced form of faith known as Zoroastrianism and which by comparison with the emphatically polytheistic conceptions of the Babylonian religion was superlatively rationalistic. Contact with a strange culture is always attended by an intellectual stimulus, and this takes place whether the contest be friendly or hostile. Though the Persian rulers even after Darius with whom the full sway of Zoroastrianism may be said to begin, maintained a conciliatory attitude towards the gods of Babylonia, Cyrus going so far as to claim that his conquest of the country was in the interest of Marduk,[70] nevertheless, the presence of a totally different religion, recognized as the official one by the Persian rulers from the days of Darius on, must have acted as a disintegrating element that led to a decline in the belief in the Babylonian gods and to a corresponding weakening of the hold that the official rites had on the people. I venture to think that the influence of Zoroastrianism, bringing in its wake—as did Christianity and as did Islamism—a wave of intellectual advance, is the factor which accounts for the definite separation of the study of the heavenly phenomena from being merely an adjunct to a system of divination, to take its position as a genuine and independent science. A further impetus to the new science was given by the contact with Greek culture with the further possibility of a direct influence of Greek astronomical theories and methods on the investigations of the Babylonian priests.

The advance of astronomy must, however, have reacted also on the basic principle which we have seen underlay Babylonian-Assyrian astrology. Though even the *bârû*-priests, while still com-

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[69] See above, p. 667.

[70] Hagen, Cyrus-Texte in "Beiträge zur Assyriologie," II., p. 229.

pletely enthralled by astrology, must have been impressed with the domain of law in the movements and phenomena of the heavens, there remained enough scope for caprice in the more unusual phenomena which the imperfect knowledge placed outside of the sphere of regularly working law. With the gradual reduction of this scope until through astronomical calculations even such phenomena as eclipses came within the range of recognized law, the belief in astrology must have suffered a decline, at all events in the minds of the better informed priests. Astronomy and astrology presented a contrast not unlike that which in modern times is frequently represented by science and religion and though no open conflict ensued, the growth of astronomy must have involved the decline of astrology. If the data of astrology are all due to the workings of inevitable and clearly recognized eternal laws, there is no room for any spontaneity on the part of the gods, so far at least as the stars manifest divine activity. Every advance in astronomy, therefore, removed a stone from the foundation on which the structure of astrology was reared, until the stability of the entire structure was endangered. The last three centuries before our era represent in general a period of declining faith in the gods both in Babylonia as well as in Greece and elsewhere. The old order throughout the ancient world of cultural development was passing away, and the growing strength of astronomy is in itself symptomatic of the new order destined to take the place of the old. It is no unusual phenomenon to find a great civilization handing over to posterity as a legacy at the period of its decay—a superstition instead of a real achievement. "The evil that men do lives after them; the good is oft interred with their bones" applies to nations as to individuals, and so it happens that while the wholesome fruits of the Babylonian-Assyrian civilization were not entirely lost, the overripe products with the odor of decay pervading them were the first to be exported to other climes. What became proverbial among Greeks and Romans as "Chaldaean wisdom" is not the astronomy of Babylonia but the astrology which, after having spent its force in the soil in which it arose, takes root elsewhere and soon flourishes more luxuriantly than it ever did in its native heath. We have, however, also seen that in the care of others the original plant was modified through the transfer from the Orient to the Occident. Astrology in Babylonia declines as astronomy grows, for the very reason that astronomy is an outgrowth of astrology, representing the evolution of a science, by the breaking away from attachment to a religion and a cult. In Greece astronomy arises as do other sciences through the growth of the spirit of investigation. There was so far as we can see no religious tradition out of which or in opposition to which astronomy took its rise. There is no antecedent astrology from which astronomy emerges as the butterfly from the chrysalis. Therefore, astrology coming to the Greeks as a novel conception, with all the force of an apparently practical application of a scientific theory, suggesting the possibility of a direct communion with the arbiters of human fate—the conscious goal or unconscious hope of all religions—it was capable of being assimilated to the already firmly established astronomy. Astrology as further developed by the Greeks became merely one of the phases of astronomy, as is shown by the synonymity of the two terms, ἀστρολογία and αστρονομία[71]—a condition which persisted till mediaeval scholasticism, which distinguishes merely as a matter of definition between " natural astrology " or theoretical astronomy and " judicial astrology " or divination through the stars as the application of the theory to human life.

Lastly, if another suggestion be permitted, the " Chaldaeans " whom we encounter so frequently in Greek and Roman writers acting as " diviners " on such various occasions, appear to be indeed Babylonian *bârû*-priests or the disciples of these priests who, because of the decline of faith in astrology in the centers in which it arose, left their homes to seek their fortunes elsewhere. As with the growth of astronomical lore, the hold of the old system of astrology was loosened, the occupation of the *bârû*-priests was gone. Their condition was not unlike that of the Levites who, as the priests of the local sanctuaries in Palestine, were deprived of their standing and livelihood with the decline of these sanctuaries through the gradual concentration of Jahweh worship in the central sanctuary of Jerusalem. These Levites wandered to Jerusalem where, according to the Priestly Code, provision was made for them by assigning them to posts as assistants to the *kôhanim*—the legitimate priests of the cen-

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[71] See Bouché-Leclercq, *o. c.*, p. 3, note 2.

tral sanctuary.[72] The *bârû*-priests of Babylonia in their capacity as astrologers wandered to the West, there to ply their trade for which a market was no longer forthcoming in their own homes. Babylonian astrology, enjoying the popularity in Greece and in the Roman empire frequently granted to a foreign importation in preference to a home industry, became the fashion of the Occident during the centuries that marked the decline of belief in the gods of Greece and Rome and that offered a hospitable welcome to all kinds of strange faith and mystic cults, until the term "Chaldaean" became synonymous with "astrologer." In time it was no doubt applied to the one who divined through the stars irrespective of his origin.[72a] Besides astrology, hepatoscopy was also practiced by these "Chaldaeans,"[73] but both forms of divination, being derived from an official cult and practiced purely as a profession that was presumably not without profit suffered, as was inevitable, a degeneration, with the result that a measure of reproach became attached to the term "Chaldaean," which acquired almost the force of trickster and deceiver. It was nevertheless fortunate that the term survived as a fingerpost, directing us to the land in which the system of divination arose that after strange vicissitudes has survived in the form as modified under Greek influences and with some additions in the mediaeval period, to our own days, still finding many devotees in circles where one would hardly expect to encounter them.[74]

The degenerating process through which the term "Chaldaean"

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[72] See *e. g.*, Baudissin, Geschichte des Altestamentlichen Priesterhums (Leipzig, 1889), p. 287.

[72a] So, *e. g.*, Teukros, the author of a Greek treatise on astrology, is called "the Babylonian" evidently in the sense of "astrologer." See the fragments of this treatise published by Boll ("Sphæra," pp. 16–21) who places Teukros in the first century of this era.

[73] See the story told by Polyænus, "Strategicon," IV., 20, of the deception practised upon the army of Attalus I. of Pergamon by Soudinos "a Chaldæan augur" who writing the words "victory of the king" (*βασιλέως νίκη*) backwards on the palm of his hand, pressed the smooth side of the liver of a sacrificial animal on his hand, and then held the liver with the significant words inscribed on it to the gaze of the army, who regarded it as a sign sent by the gods. See also, above, p. 650, note 13.

[74] The late Richard Garnett is only one of many examples of men otherwise abreast with modern thought who cling to the faith in the revelations of the stars.

passed must not, however, lead us to the conclusion, which would be decidedly false, that astrology when it passed over to the West became wholly at the mercy of professional tricksters. This is but one phase of the subject which, seriously cultivated by Greek physicists, became bound up as we have seen with advanced forms of astronomy, mathematics and philosophical speculation. It is the old Babylonian astrology directly imported by "Chaldaeans" as professional astrologers that degenerated into a dishonest trade, whereas the modification of the Babylonian system under the influence of the Greek scientific spirit was raised to the dignity of a genuine science; and belief in it remained an integral part of science throughout the middle ages. In our days when the new scientific spirit has definitely broken with astrology, we are witnessing a process not unlike that which set in when faith in the Babylonian system declined in the land of its birth. Whatever justifiable basis (if any) it may have had is entirely obscured by those who exploit it as a profession. The modern "astrologers" are not the Greek astronomers attaching to their science a divinatory aspect, but the old *bârû*-priests in a new garb, plying a trade that flourishes through the readiness of people to be deceived—a readiness that amounts almost to willingness. Why then, it may be asked, search out the follies and superstitions of the past? Bouché-Leclercq[75] supplies us with the answer when he says "that it is not a waste of time to find out how other people wasted theirs."

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[75] "L'Astrologie Grecque," p. ix.

# FURTHER STUDIES ON TRANSPLANTATION OF VESSELS AND ORGANS.[1]

### By ALEXIS CARREL.

*(Read, November 6, 1908.)*

It is known that tissues can be removed from an animal, transplanted into another animal and live normally in the body of their new owner. The transplantation of anatomical structures has already been, and will be again in the future, used in human surgery. For instance, an excellent method of treating an aneurism of the femoral artery would be the extirpation of the diseased part and its replacement by a piece of artery of same caliber. This new artery cannot be taken from an animal and grafted on man, for the serum of an animal is toxic for the cells of an animal of different species. A dog's vessel transplanted on man could possibly perform its arterial functions, but the histological structure of its wall would be deeply modified and accidents could occur. It is probable that arteries from anthropoid ape would be of safer use, because man and ape are closely related from a zoölogical standpoint. But this would be exceedingly expensive and not practical. It will be safer and simpler to graft on man vessels taken from another man. The vessels can be extirpated from an amputated limb or from the body of a criminal or of a man killed by accident. But it is sure that these cases will not present themselves at the time convenient for the surgeon and his patient. Therefore, it is important to find a method to store human vessels during the period which will elapse between their extirpation and their graft on the patient. With this view, I have attempted to preserve arteries in a condition of latent life, in order that, after having spent several days or several weeks outside of the body, they can be transplanted successfully.

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[1] From the Laboratories of the Rockefeller Institute for Medical Research.

Before describing the method which renders possible the preservation of arteries, I shall briefly summarize some of the results obtained at the Rockefeller Institute in the transplantation of blood vessels and organs. These operations became possible as soon as a practical method of uniting blood vessels was found. Success in transplanting organs is direct function of the circulation. The circulation cannot be immediately reëstablished but by the sewing of the vessels of the organ to those of the host. The sewing of vessels is today a very easy operation. Some years ago, while I was working at the University of Lyons, I found a method of uniting severed arteries or veins, which gave excellent results. This method was progressively improved in such a manner that it is practically always successful. The vessels heal very quickly and no coagulation of the blood occurs when the operation is aseptic and the union of the vascular ends accurate. The scar of the severed vessels is, in many cases, so small that after a few months it is hardly discernible. On a renal vein examined a little over two months after the sewing, it was impossible to localize exactly the position of the anastomosis. The anastomosis of the renal artery was represented only by an indistinct line crossing the intima. Twelve months after the anastomosis of a carotid artery, the anatomical specimen was removed and examined. After longitudinal incision of the wall, no scar was seen on the intima, there was no modification of the caliber. But, in one small point, the vessel had lost part of its elasticity and it permitted to localize approximately the anastomosis. The results are permanent. Two and three years after the operation, the circulation through the anastomosis remains normal. It must be known also that, if the method is not correctly applied, or a fault of technique, even very slight, is made, thrombosis may occur. Success depends much less on the way of handling the needles or passing the threads than on the knowledge of the causes which are able to produce thrombosis and their removal. On human beings, this method has already been successfully used by American and European surgeons, and on animals, it has permitted to perform the transplantation of blood vessels, organs and limbs.

The graft of a segment of artery on an artery of another animal of the same species is ordinarily successful when the vessels are of sufficient caliber. After a few months, the transplanted segment assumes exactly the same appearance as the normal vessel. The carotid of a dog was examined three months after the graft of an arterial segment. The transplanted segment was exactly similar to the other parts of the artery. There was no modification of caliber. The elasticity was normal. The only evidence of the operation was two whitish transverse lines on the intima. The remote results are excellent. A dog, into whose aorta a segment of aorta from another dog had been transplanted, was living and in good health nine months after the operation and the femoral pulse was normal. The transplantation of arteries has already been attempted in human surgery by Pierre Delbet in the treatment of aneurism. When a large artery is wounded and partially destroyed, or when a tumor adherent to the main vessels of a limb renders necessary the extirpation of these vessels, the substitution of a new piece of artery to the removed part would prevent the occurrence of gangrene.

The graft of an artery of an animal into an animal of different species is often successful if the animals are closely related. I transplanted several times segments of dog's carotid arteries on the abdominal aorta of cats with excellent functional results. Nevertheless, these results cannot be compared with those obtained in transplantation between animals of same species. Sometimes the lumen becomes dilated, or even a fusiform aneurism can be found. Even when the functions of the transplanted segment are perfect, its wall undergoes marked histological changes. The elastic framework disappears and progressively the muscular fibers are resorbed. After a few months, they have practically disappeared. The vessel is then composed mainly of connective tissue.

Veins can easily be grafted on arteries. I performed several times the transplantation of the vena cava on the aorta, on dogs and on cats, with excellent results. A segment of vein transplanted into an artery undergoes immediately very marked changes. The wall, which is very thin, becomes thicker and stronger. The lumen is often dilated, but no aneurism has ever been observed. On the contrary, the vein reacts against the increased blood pressure by thickening its wall. The thickening is due to an hyperplasy of the muscular cells and an hypertrophy of the adventitia. There is also a very large increase of the interstitial connective tissue of the media. The venous wall becomes as strong as the arterial wall. The function has created the organ. Therefore, veins can act as a substitute for arteries. This is of practical importance in human surgery, for on the patient himself an abundant supply of vein can always be found.

The organs, kidneys, spleen, or thyroid gland, for instance, can be transplanted from an animal to another animal and their circulation immediately reëstablished by suture of the blood vessels to those of their host. Two methods are used—the simple transplantation, and the transplantation in mass. The simple transplantation consists of dissecting the organ, cutting its vessels, and uniting these vessels directly to those of the host. In the transplantation in mass, the organ is extirpated, together with the surrounding tissues and organs, its nerves, vessels and the main vessels of the region. After transplantation, the anastomoses are not made on the vessels of the organ themselves, but on the main vessels of the anatomical region. The transplantation in mass of the kidneys has been performed on cats. It consists of extirpating from a first animal both kidneys, their vessels and the corresponding segments of the aorta and vena cava, their nerves and nervous ganglia, their ureters and the corresponding part of the bladder; of placing these anatomic specimens into the abdominal cavity of a second animal whose kidneys have been previously resected and the aorta and vena cava cut transversely; and of suturing the vascular segments between the ends of the aorta and vena cava, and of grafting the flap of bladder onto the bladder of the host. In every case the reëstablishment of the renal functions was observed. These functions were determined by the character of the urine and the general condition of the animals.

The secretion of urine often begins as soon as the arterial circulation is reëstablished. In some cases the amount of urine during the first twenty-four hours was more than 100 c.c. However, a cat urinated only 25 c.c. during the first twenty-four hours; the second day the amount of urine passed was only 16 c.c.; this urine was highly concentrated and contained much urea. Every cat urinated abundantly every day, but the animals presented sooner or later some complication, which modified in some measure the renal functions. As is to be expected after an operation as complex as the transplantation in mass, various accidents occurred; hydronephrosis, intestinal compression by peritoneal adhesions, volvulus, phlegmon, puerperal infection, compression of the renal veins by organized hematoma of the connective tissue, which were the direct or indirect causes of death in these animals. However, in two experiments the functions of the kidneys seem to have been for a certain time almost completely normal. The color of the urine was yellow, generally, or often less dark than the normal urine of the cat. Its reaction was acid. Its quantity for twenty-four hours oscillated between 120 and 160 c.c., but it might be, exceptionally, 25 and even 15 c.c., or in another case, 215 or 255 c.c. for twenty-four hours. The density was very far from constant; generally it oscillated between 1.018 and 1.030, going sometimes as high as 1.035 and 1.051. Among the abnormal constituents of the urine the presence of albumin only has been looked for. In some cases there was a little albumin during the first days, ranging from 0.50 to 0.25 for 1,000 c.c. In other cases the albumin disappeared about one week after the operation.

The general condition of the animal can be used, in some measure, to indicate the perfection of the urinary elimination. As long as no complications were present the animals lived as normal cats do, without presenting any symptoms which could be considered as produced by renal insufficiency. When general complications occurred the cats reacted against them in normal ways. In one case, the animal was in apparently normal condition four days after the operation. She walked about the room, played and ate a great deal of raw meat. Her condition remained excellent for several weeks. Twenty days after the operation she was in good health, had glossy hair, was very fat, ate with appetite all kinds of food and urinated normally. There was, however, albumin in the urine, and slow and progressive enlargement of the kidneys took place, which showed that she was not in an entirely normal condition. It remained in excellent health until the twenty-ninth day after the operation. Then gastro-intestinal symptoms appeared, and death occurred on the thirty-first day after the operation.

In another experiment the animal was a female cat which had lived in the laboratory for several months. She was in excellent condition when she was operated on and recovered very quickly from the operation. Her life went on just the same as before. The kidneys were movable and small. She looked in excellent health and lived as a normal cat. On the eighteenth day after the transplantation albumin appeared in the urine and a direct examination of the kidneys was made to ascertain the cause. The general condition was little affected by the operation and the albumin disappeared on the twenty-first day, but reappeared again a little later. On the thirty-fifth day the animal was very weak and emaciated. She died on the thirty-sixth day of acute calcification of the arteries.

These results show that the functions of the kidneys reëstablished themselves after the transplantation. Since an animal can live in an apparently prosperous condition of health fifteen or twenty-five days and more, after a double nephrectomy, and eliminate each twenty-four hours from 120 to 160 c.c. of urine through the new kidneys, it is certain that the functions of the transplanted organs are efficient.

The "simple transplantation" of the kidneys consists of dissecting a kidney, cutting the renal vessels and ureter a few centimeters below the hilus, implanting the organ on the same or another animal, and of anastomosing its vessels to the renal vessels of the host. I performed the double nephrectomy and the replantation of one kidney in five dogs. The secretion of the urine remained normal as long as no ureteral complication occurred. The conditions of the kidneys were excellent. A little more than two months after the operation, the location of the anastomoses of the renal vein could not be detected. The anastomosis of the renal artery was seen as a small and indistinct line on the intima.

The remote results of this operation are excellent. On February 6, 1908, the left kidney of a middle-sized bitch was extirpated, perfused with Locke's solution and put into a jar of Locke's solution at the temperature of the laboratory. The ends of the vessel were prepared for anastomoses, and afterward the kidney was replaced into the abdominal cavity. The circulation was reëstablished after suture of the vessels and the ends of the ureter united. The animal made an uneventful recovery. Fifteen days afterward the right kidney was extirpated. The animal remained in perfect health. The urine did not contain any albumin. It is generally of low density. Today the animal is in perfect condition. (Fig. 1.)

FIG. 1. The dog, who is jumping, underwent nine months ago a double nephrectomy and replantation of one kidney.

This observation demonstrated definitely that an animal can live in normal condition after both kidneys have been extirpated and one replaced. It removes also, without need of further discussion, the objections of the experimenters who claim that the section of the renal nerves, the temporary suppression of the renal circulation or the perfusion of the kidneys produce necessarily dangerous and even fatal lesions of this organ.

By using the method of transplantation in mass it becomes possible to perform the transplantation of a whole anatomic region, with its main artery and vein. From a first dog, the right part of the scalp and the auricle were extirpated in one mass wtih the cartilaginous portion of the auditory canal cut close to the skull, the connective tissue and the glands of the retro-maxillaris space, the tissues of the carotid region, and the upper portions of the external jugular vein and of the common carotid artery. On a second dog the auricle and a portion of the scalp was extirpated and the right part of the neck opened through a longitudinal incision. The anatomic specimen was then placed close to the wound, and the peripheral end of the carotid artery and of the jugular vein united to the central end of the corresponding vessels of the host, at the level of the middle part of the neck. The circulation was then reëstablished. Then the neck was closed by two rows of suture. A few minutes after the establishment of the circulation the ear and the scalp assumed their normal appearance. The new ear was fixed by circular suture of its cartilaginous canal to the cartilaginous canal of the host. The auricular muscles were sutured and the operation completed by continuous catgut suture of the skin without drainage.

Three weeks after the operation the auricle and the transplanted tissues were in normal condition. The temperature of both auricles, normal and transplanted, were about the same. The transplanted ear was as thin and glossy as the normal one. Except for the difference of color, it could not have been seen that the ear did not belong to the dog.

The transplantation of a limb from one animal to another of the same species is a problem very much simpler than the transplantation of a gland. In April, 1907, I found that a thigh, extirpated from the fresh cadaver of a dog, and transplanted onto another dog, could begin to heal in a very satisfactory manner. One year after, by using more careful asepsis in the transplantation of the leg from one fox terrier to another, I observed union by first intention of the new leg to its host.

A white, middle-aged male fox terrier was etherized and the left leg cut just below the knee. The limb was perfused with Locke's solution, wrapped in a greased silk towel and kept on a table at the temperature of the laboratory. A white, young female fox terrier was etherized. She was of the same size and shape as the first dog. Her nails and bones were very slightly smaller. The leg was amputated circularly just below the knee. The new leg was immediately fixed to the central end of the tibia of the host by an Elsberg's aluminum splint. The muscles, nerves and femoral vessels were united to the corresponding parts of the host, and the circulation reëstablished. A small exploratory incision was made between the second and third toes. Hemorrhage of red blood occurred. The animal recovered quickly and remained in normal condition. The temperature of the new foot was at first higher than that of the normal one. It was also edematous. After a few days the edema disappeared and the foot had exactly the same appearance as the normal one. The temperature went slightly down. There was only a difference of one tenth of a degree centigrade between the normal and the new foot.

Fifteen days after the operation the new leg was perfectly healed by first intention, but the bones were not very strongly united. The Elsberg splint had broken and the tibia was a little incurved. The exploratory incision of the foot, although having been slightly infected, was completely cicatrized. The new leg had the same appearance as the normal one. The animal was in good condition, but coughed a little. At this time several other dogs died of broncho-pneumonia. The animal became sick. Twenty days after the operation her condition became worse and a marked dyspnea appeared. The dog died on the twenty-second day after the operation. Postmortem examination showed a double diffuse broncho-pneumonia. The new leg was perfectly healed; with linear cutaneous scars. Its appearance was exactly the same as the normal leg. The bones were strongly united by a fibrous callus. The exploratory incision of the foot had healed without visible scar.

This experiment is the first example of successful grafting of a new limb on an animal. It demonstrates that the leg, in spite of the change of owner, remains normal. If further experiments show that the functions of the transplanted limb are normally reëstablished, it will be permissible to try on man the transplantation of limbs, or segments of limbs, taken from an amputated limb, or from the body of a man killed by accident.

All these experiments show that the remote results of the transplantation of fresh vessels can be perfect, that transplanted kidneys functionate, that an animal having undergone a double nephrectomy and the transplantation of both kidneys from another animal can live normally for a few weeks, and that an animal which has undergone a double nephrectomy and the graft of one of his own kidneys can recover completely and live in perfect health. Finally, it has been demonstrated that a leg extirpated from a dog and substituted for the corresponding leg of another dog heals normally.

Since the experimental transplantation of arteries are permanently successful, it is permissible to use this method in human surgery; for instance, in treating aneurisms as it has been already tried by Delbet in Paris. The era of these operations being opened, the attempt of preserving blood vessels outside of the body in a condition of latent life was made with the view of rendering these operations more practicable.

The length of the period which elapses between the extirpation of a tissue, and the reëstablishment of its circulation after transplantation, is an important factor of success or failure. The result of the graft depends entirely on the condition of the tissues at the time of the reëstablishment of the circulation. They must still be alive; although apparently dead. If the tissues are really dead, the graft is completely unsuccessful. There are two kinds of death, general death or death of the whole organism, and elemental death or death of the tissues and organs. It is impossible to give a definition of general death. Everybody understands what it means. Nevertheless, we are as ignorant about it as about life. General death can occur suddenly, while elemental death is a slow process. A man, for instance, is stabbed through the heart and killed. His personality has disappeared. He is dead. However, all the organs and tissues, which compose the body, are still living. The life of every tissue and organ of the body could go on if a proper circulation was given back to them. If it were possible to transplant immediately after death the tissues and organs, which compose this body, into other human organisms, no elemental death would occur, and all the constituent parts of the body would continue to live. The man, however, would be dead, for his personality would have disappeared. In this case, general death can be defined as the rupture of the contract of association between the tissues and organs of the organism by failure of one of the partners, the heart. Therefore, general death is very different from elemental death. It is merely the starting point of the disintegrative phenomena which lead to elemental death.

Immediately after general death, elemental death begins. It is a complex and slow process which progressively destroys the living matter. We cannot know directly whether or not a tissue is living and by what chemical or physical peculiarities a living being differs from its corpse. There is no reagent of life. Living matter, in a condition of non-manifested life, is apparently similar to non-living matter. We perceive life only through its manifestations. Our ignorance renders for us unmanifested life similar to death. If seeds or microbes are placed in physico-chemical conditions, where manifested life is impossible, living matter canot be distinguished from dead matter. What is the difference between a dead seed and the seed which will produce a large tree? We do not know. Between a vessel which will live normally after transplantation, and another one which will undergo deep microscopical lesions, there is no morphological difference. We know merely that, immediately after general death, the tissues are still alive, because they manifest life if they are given back their normal circulation. We know also that some time after general death they die, because they are not able to manifest life again, even when replaced in normal physiological condition. Between the death of the organism and the elemental death there is a period where the tissues are progressively invaded by cadaveric disintegration. At the beginning, the cadaveric changes are slight, and the tissues can recover if placed back into normal condition. Later, irreversible changes take place and elemental death, that is, destruction of the living matter, occurs.

The duration of this period intermediate between death of the organism and elemental death is longer or shorter, according to the nature of the tissue. The cerebral substance disintegrates so quickly that, after a few minutes of complete anemia, irreparable lesions take place. The spleen, liver and kidneys are also rapidly destroyed. On the contrary, the anatomical structures which compose a limb are very strong and can overcome for a long time the cadaveric processes. The different parts of the same organ do not present similar resistancy to cadaveric disintegration. Among the anatomical components of renal substance, the cells of the secretory tubules are extremely delicate and may present marked morphological changes a short time after death. The cells of the excretory tubuli are stronger. The glomeruli are still more resistant. It may happen that the epithelial cells are already dead, while the glomeruli and the vessels are still living. The vascular endothelium seems to be the "ultimum moriens" of the organ, according to Wells. The vessels, which are the necessary condition of life of organs, are also the part of the organs which resists longer the disintegrative processes. The elements which compose the wall of an artery differ widely in resistancy. The muscular fibers die first. Immediately after the stopping of the circulation, all the elements of the vascular wall are alive. If the transplantation is performed at this moment, the artery lives in the body of its host and keeps its normal constitution. If the transplantation is performed a little later, when the muscular fibers are already dead, the wall of the artery will be composed mainly of connective and elastic tissue, and the muscular fibers will disappear. If the artery is completely dead when the transplantation is made, its wall will be composed of amorphous substance, around which the organism will create an envelope of dense connective tissue.

Elemental death is brought about by microbian and autolytic enzymes. Immediately after general death, the microörganisms from the digestive tract diffuse through the body and their ferments begin to destroy the tissues. At the same time, the autolytic ferments, which are not any longer held in check by the serum, contribute also to the disintegration of the organs. This destructive process is increased or retarded by the causes which activate or retard the enzymotic actions, and the multiplication of the microorganisms. For instance, the rate of cadaveric disintegration, which is very rapid at 35° or 40° C., becomes very slow at + 1° or + 2° C. It is completely stopped by desiccation of the tissues. The preservation of the tissues in the serum of the same animal will also retard very much the organic destruction.

The occurrence of cadaveric changes in tissues, which will be used for transplantation, must be prevented. This can be attained in two different manners: by stopping completely the chemical activities of the tissue, or merely by retarding so much the evolution of autolytic disintegration that, after a few days or a few weeks, the lesions are so small that they are not dangerous.

The first method would be ideal. The tissue, being in a condition of chemical indifference, could be preserved theoretically for an indefinite period. There are many instances of this form of latent life in the animal kingdom. Two centuries ago, Loevenhoeck obtained the resurrection of *Milnesium tardigradum,* which had been completely dried for a long time, by moistening it with water. In 1840, Doyere studied also the peculiarities of latent life of *Milnesium tardigradum.* He dried completely a few of these animals, heated them at a temperature of 100° C., and, after having humidified them, observed that they lived again. These observations are very important because *Milnesium tardigradum* is highly organized and contains muscular fibers, nerves, nervous ganglia, etc. Paul Bert, in several famous experiments, attempted to preserve tissues of mammals in a condition of latent life. One of those experiments consisted of cutting the tail of a rat, drying it in vaccum, and submitting it to a temperature of + 100° C. The tail was afterwards transplanted onto another rat. It was observed that the dimensions of the tail grew larger, that its vessels united to the vessels of the host and that the bone marrow underwent fibrous degeneration. It showed that the heated and dried tail could live again. I attempted to preserve arteries in latent life by a similar method. Carotid arteries from dogs were extirpated and placed in sealed glass tubes, part of which were filled with calcium chloride. Within a few hours, the arteries became yellow brown, shrank and looked like pieces of catgut. One tube was heated for twelve minutes at + 100°. When, after several days, the dried vessels were put into Locke's solution, they took back their water and assumed again their normal color, size and consistency. Two of them were transplanted onto the carotid arteries of dogs. It was found that they could perform normally their functions. Two weeks after the operation, one of the vessels was examined. The circulation was normal. The transplanted segment looked very much like the other parts of the carotid. It was covered by a normal connective tissue sheath. The wall was of same color and thickness as the wall of the normal carotid. Its consistency was a little harder. Nevertheless, it was found, by microscopical examination, that this wall was composed of an elastic framework and amorphous material surrounded by a new wall of connective tissue. The vessel was dead. The death of the vessel was perhaps due more to the way in which the desiccation was done than to the desiccation itself. With a better technique, results similar to those of Paul Bert could possibly be obtained. Actually, this method is dangerous because the artery is not any longer a living structure, but merely a foreign body, as a piece of rubber tubing or an artery preserved in formalin or killed by heating.

The second method of preserving arteries, outside of the body, consists in lowering the power of the microbian and autolytic enzymes, by keeping the tissues at a low temperature. This method cannot suspend, for an indefinite time, the occurrence of elemental death. It increases only the length of the period during which the cadaveric changes are slight and not able to interfere with a complete, or almost complete, recovery of the artery after transplantation. If a vessel is extirpated aseptically, placed in a sterilized sealed tube and kept in a refrigerator just above the freezing point, it can be preserved for a long time in good condition. From a surgical standpoint, it is sufficient that the vessels are kept safely for a few days outside of the body before being transplanted. Nevertheless, it is far from perfect. The ideal method would be certainly to place the tissues in a condition of latent life, as is possible for *Milnesium tardigradum* and other organisms.

The technique that I use is very far from being original. The vessels are merely preserved in cold storage as are commonly eggs, or chickens, or vegetables. They are removed from a living or a dead animal soon after death, perfused and washed with Locke's solution and placed in sterilized glass tubes, the atmosphere of which is moistened with a few drops of water. The tubes are immediately

FIG. I.

FIG. 2.

FIG. I. Segment of artery preserved in a sealed sterilized tube.

FIG. 2. Segment of artery preserved for twenty two days in cold storage. Six months after transplantation.

sealed. (Plate VII, Fig. 1.) Sometimes, the arteries are put in a fluid. A few vessels have been preserved in isotonic sodium chloride solution. The result was unsatisfactory; for the muscular fibers of the artery were killed in twenty-four hours. The results obtained with Locke's solution were much better. However, a still better method would consist in keeping the vessels in serum of an animal of the same species or in inactivated serum of an animal of different species. The serum is more exactly isotonic for the tissues than Locke's solution; it is slightly bactericidal, and it contains antibodies for the autolytic ferments of the cells. I performed once only the transplantation of a segment of dog's carotid, preserved in dog's serum for forty-eight hours. Fifteen days after the transplantation, the vessel was examined and found in a perfect microscopical condition.

The sealed tubes containing the arterial segments are put into a thick-walled ice-box, the temperature of which remains constantly between 0 and + 1° C. The temperature must not go down below 0° C. When the vessels have been frozen, the wall presents soon after the transplantation marked microscopical lesions. If the temperature is too high, and the operation not thoroughly aseptic, microbian colonies may settle in the wall of the vessels. Obliteration or development of fusiform aneurism are the consequence of these faults of technique. When the operation has been correctly performed, the artery keeps its normal appearance for a long time. After several weeks, its color and consistency are generally normal. The wall is a little softer and the vessel flattens itself more easily. After six, seven and even ten months, the macroscopical appearance of the vessel is not markedly modified. Sometimes it looks completely normal. From a microscopical standpoint, the condition of the arteries is very variable. In some cases, the nuclei of the muscular fibers are modified. In other cases they are absolutely normal. A section of a pig's carotid artery, preserved in a sealed tube with a few drops of Locke's solution from April to November, 1908, was entirely normal. It looked as if it had been extirpated from the animal a few moments before being fixed in Zenker's fluid, while it had been preserved for six months outside of the body.

A few minutes before the transplantation, the tube is removed from the ice-box and broken. The vessel is removed from the tube, put in a jar of Locke's solution at the temperature of the laboratory, thoroughly washed and placed in warm vaseline. Afterward, the vaseline is expressed from its lumen, and the segment grafted onto the artery of the host. As soon as the circulation is established through the artery of the host, the transplanted segment, which is white, takes back immediately its normal color and becomes almost similar to the other parts of the artery. Sometimes the small vessels of the adventitia appear neatly injected with blood. In segments of carotid artery, preserved for eight and eleven months in cold storage and grafted on the carotid of a dog, the vasa vasorum were seen full of blood as soon as the circulation was reëstablished.

The results of the transplantation of arteries, preserved in cold storage, are generally excellent from a functional standpoint, even if the vessel has been kept for one or two months outside of the body. But, from an anatomical standpoint, the microscopical constitution of the vessel is markedly modified when it has spent a long time in cold storage. The duration of the period during which a vessel can be preserved without occurrence of any lesion, is not exactly determined. However, it seems that an artery, preserved for more than eight days in cold storage, undergoes always, after transplantation, a degeneration of its muscular fibers, while the other parts of the vessel seem to remain normal. Several times a perfect histological condition of the transplanted artery was observed. A piece of carotid artery from a dog was put in a sealed tube with a few drops of Locke's solution and, two days afterward, transplanted onto the carotid artery of another dog. Two weeks after the operation, the neck of the dog was reopened. The circulation through the carotid was normal. The transplanted segment looked like the other parts of the carotid. It was resected and examined histologically. The adventitia was thickened and contained several small vessels. The media was normal. The nuclei of the muscular fibers were found entirely similar to those of a normal artery. The intima was well preserved and slightly thickened. This observation shows, evidently, that a vessel can be preserevd in cold storage and live again normally when transplanted. It is not a dead, but a living artery, with all its normal anatomical elements.

Thus, the vessel, while in cold storage, was in a condition of unmanifested life.

The behavior of a vessel, transplanted after having been killed, by formalin or by heating at 80° C., is different. Often its appearance is normal, from a gross anatomical standpoint. Nevertheless, a few days after transplantation, its microscopical constitution is deeply modified. Its wall is composed of an amorphous material where no nuclei can be observed, but where the elastic framework still is visible, although very modified in its shape. The wall is surrounded by a layer of connective tissue produced doubtless by the host. A dead vessel is merely a foreign body, which would progressively be resorbed and replaced by connective tissue. Thrombosis frequently occurs after this kind of transplantation and its use is dangerous from a clinical standpoint. On the contrary, a vessel, preserved for a few days in a condition of latent life, is still a living structure when it is transplanted. Its use is as safe as that of a fresh artery.

In all the cases where the vessels spent more than eight days in the ice-box, the muscular fibers of the media disappeared a few days after transplantation. Nevertheless, the anatomical results were often so perfect that, after a few months, the location of the transplanted segment on the artery of the host was hardly discernible. On April 2, 1908, a piece of carotid, preserved for twenty-two days in cold storage, was transplanted on the carotid of a dog. On October 15, 1908, the neck was opened and the carotid dissected. It was not possible to find the location of the transplanted segment. After longitudinal opening of the carotids, the location of the anastomoses could be determined. (Plate VII, Fig. 2.) The result of the graft of a vessel which had spent seventy days in cold storage was as satisfactory. Six months after the operation a section was made through the middle part of the transplanted segment. The adventitia was normal and the intima thickened. The media was composed of elastic fibers which had retained their ordinary wavy appearance. All the muscular fibers had been destroyed.

The actual method failed to give positive results in the transplantation of arteries after several months in cold storage. Graft of arteries which had spent eight months outside of the body was attempted in two cases. Thrombosis occurred. The vessels were dead, and, in spite of their almost normal appearance, markedly disintegrated.

The remote results of the transplantations of preserved vessels are very satisfactory from a clinical standpoint. In November, 1906, a segment of the abdominal aorta of a cat was extirpated and replaced by a piece of dog's carotid preserved in cold storage for twenty days. The animal remained in excellent health. After a few weeks, the abdomen was reopened and the transplanted artery

FIG. 2. Cat in which a segment of the abdominal aorta was replaced by a piece of dog's carotid.

examined. The circulation through the new artery was excellent, and its caliber normal. The abdomen was closed. The cat spent the years 1907 and 1908 at the Rockefeller Institute in excellent health. The femoral pulse was normal. The condition of the femoral pulse is an indication of the condition of the circulation through the abdominal aorta. Partial or complete occlusion of the aorta produces diminution or disappearance of the pulse of the femoral arteries. To-day, twenty-five months have elapsed since the operation, the cat is in good condition (Fig. 2) and the femoral pulse normal.[2]

FIG. 3. Dog in which a segment of the abdominal aorta was replaced by a piece of human popliteal artery.

In May, 1907, a short portion of the abdominal aorta of a small bitch was extirpated. Between its cut ends was grafted a segment of popliteal artery from a young man's leg amputated at the Presbyterian Hospital by Dr. Ellsworth Eliot. Before being transplanted, the popliteal artery had been preserved for twenty-four

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[2] This cat was presented before the American Physiological Society, December 1906.

days in cold storage. The femoral pulse remained normal. A few months after the operation, the abdomen was reopened and the circulation through the new artery found normal. There was no modification of its caliber. The animal remained in good health. During the years 1907 and 1908, no modification of the femoral pulse occurred. It is still normal to-day, one year and a half after the operation, and the animal is in excellent condition (Fig. 3).

These experiments demonstrate that the clinical results of the transplantation of preserved vessels can remain satisfactory for a long time. However, in both cases, the operation was performed under unfavorable circumstances. The grafted arteries belonged to an animal of different species and the method of preservation used in both cases was imperfect. The wall of these vessels underwent certainly marked histological changes. Nevertheless they are still able to perform normally their functions.

## CONCLUSIONS.

The results of the experiments of preservation of arteries in cold storage must be considered from both the anatomical and the practical standpoint.

From an anatomical standpoint, they show that an artery from an animal can be kept outside of the body for two days at least, transplanted onto another animal of the same species, and live again without presenting any change of its constituent elements. The transplantation of vessels killed by drying, heating or fixation in formalin is followed by degeneration of the wall and replacement by connective tissue from the host. When the vessel is kept in cold storage for a longer period of time, all the muscular fibers of the media disappear a few days after transplantation. If the period spent in cold storage is still longer, eight months for instance, thrombosis occurs.

From a practical standpoint, these experiments demonstrate that the preserved vessels, even if their muscular fibers are completely resorbed, are an excellent substitute for arteries and perform normally their functions for months and years.

## *Stated Meeting November 20, 1908.*

President KEEN in the Chair.

The decease was announced of Prof. William Keith Brooks, at Baltimore, on November 12, 1908, æt. 60.

The following papers were read:

"The Early History of the American Philosophical Society," by Mr. Joseph G. Rosengarten.

"The Recapitulation Theory of Embryologists," by Prof. Thomas H. Montgomery, Jr., which was discussed by President Keen, Prof. Kraemer, Prof. Doolittle, Prof. Pratt and Prof. Montgomery.

## *Stated Meeting December 4, 1908.*

President KEEN in the Chair.

Prof. Edwin G. Conklin read an obituary notice of Prof. William Keith Brooks (see page iii).

The following papers were read:

"Astrology in Ancient Babylonia," by Prof. Morris Jastrow, Jr. (see page 646), which was discussed by President Keen and Mr. Goodwin.

"On the Effect of a Radio-Active Mineral on Plant Growth," by Mr. Joseph Willcox.

Dr. John L. Shober exhibited some photographs made by radiations from radium and uraninite.

## *Stated Meeting December 18, 1908.*

PRESIDENT KEEN IN THE CHAIR.

Professor Herbert Weir Smyth, a newly-elected member, was presented to the chair and took his seat in the Society.

A letter was read from the Geological Society of Glasgow stating that it would celebrate its jubilee on January 28, 1909, and inviting the Society to be represented thereat. The invitation was accepted and Sir William Turner, K.C.B., was appointed the Society's representative.

The decease was announced of

Dr. Ernest T. Hamy, at Paris, on November 18, 1908, æt. 65.

Prof. Oliver Wolcott Gibbs, at Newport, R. I., on December 9, 1908, æt. 86.

Professor Herbert Weir Smyth read a paper on "Ancient Greek Conceptions of the Future Life" which was discussed by Professor Lamberton, Professor Newbold and Professor Smyth.

### *Special Meeting December 21, 1908.*

PRESIDENT KEEN IN THE CHAIR.

The President introduced Professor Guglielmo Ferrero, who read a paper on "Antony and Cleopatra."

# INDEX.

# OBITUARY NOTICES

OF

# MEMBERS DECEASED

## WILLIAM KEITH BROOKS.

William Keith Brooks was born at Cleveland, O., March 25, 1848, and died at his home, "Brightside," near Baltimore, November 12, 1908. His parents were born in Vermont, but their ancestors had lived for many generations at or near Concord, Mass., the first of the name having come to America from England prior to 1634. Young Brooks received his early education in the public schools of Cleveland, and he afterward entered Hobart College, Geneva, N. Y., where, he says, "I learned to study, and, I hope, to profit by but not to blindly follow, the writings of that great thinker on the principles of science, George Berkeley." He spent two years at Hobart, where he took high honors, and then entered the junior class at Williams College. Here he distinguished himself as a thorough and independent scholar, and is said to have been one of the most brilliant students in mathematics Williams had ever known. In 1870 he received the degree of bachelor of arts and was elected to Phi Beta Kappa.

After his graduation his father took him into mercantile business with himself, intending that he should become his successor, but such work was distasteful to young Brooks and he soon abandoned it and became a teacher in a boys school at Niagara, N. Y. When he left college he was undecided whether to devote himself to mathematics, to Greek, or to biology, for he was unusually proficient in all of these subjects. He was an enthusiastic naturalist; even as a boy he had given much attention to fresh-water aquaria and to the habits of animals, and he had published some of his observations; with one of his friends he had constructed a microscope and with other associates he had organized a class in natural history; he had also read many books on natural history and was intensely interested in evolution and Darwinism. He finally decided to devote himself to biology, largely influenced, we may imagine, by the philosophical importance of this subject.

At Harvard Louis Agassiz was at the climax of his wonderful career, and thither flocked many young men, who afterward became leaders in biological science, to study under this great master; among these was Brooks. In the summer of 1873 he was a student at Agassiz's laboratory at Penikese, and from that time until his death he remained a student of marine life. The sea with its teeming multitudes of living things always had a particular charm for him, not merely because of the interest and variety of its forms of life, but also because it was the scene of the earliest acts in the drama of evolution.

In 1875 he received the degree of Ph.D. from Harvard University and was appointed assistant in the museum of the Boston Society of Natural History. On the founding of the Johns Hopkins University in 1876 Brooks applied for and obtained one of their twenty famous fellowships, which have done so much to change the character of university work and ideals in this country. Before he entered upon his fellowship his abilities as a teacher were recognized and he was appointed associate in biology. In 1883 he was appointed associate professor of morphology and in 1889 professor in that subject. On the retirement of Professor H. Newell Martin from the headship of the Biological Department in 1894, Professor Brooks became head of the department and continued in that position until his death. His active scientific life was therefore coextensive with that of the Johns Hopkins University, and his love of the Biological Department and his loyalty to his University were among his strong characteristics.

Although his publications were numerous and important I think that his influence was greatest and most far reaching in his work as a teacher and scientific director. To few biologists, perhaps to no other in the history of this country, has it been given to direct the work and shape the scientific ideals of so large and influential a body of young men. Among those who took their doctor's degrees under him are more than a score of the leading zoölogists of this country, while many other distinguished scholars of this and foreign lands were his pupils.

Although Professor Brooks would present a subject in his lectures in a most clear and entertaining manner, he rarely if ever attempted to smooth the path of the investigator; the latter was to a very large extent thrown upon his own resources. He believed so thoroughly in the law of natural selection, as he once told me, that he thought it was best for a student to find out for himself, as soon as possible, whether he was fitted for independent investigation or not, and by this rigid discipline the unfit were weeded out from the fit. This was certainly no school for weaklings, but it afforded magnificent training for those who had ability and determination. For those who endured this ordeal he maintained the warmest regard, and his interest and pride in the work of his students was as marked as it was stimulating.

In connection with his work as teacher and director must be mentioned the establishment by him of the Chesapeake Zoological Laboratory in 1878. This was the second marine laboratory in this country founded for advanced work in pure zoölogy. The first was established by Louis Agassiz on the island of Penikese in Buzzards Bay in 1871. The Chesapeake Laboratory, unlike the one at Penikese, was not limited to one place, it consisted neither of buildings nor equipment, but of men and ideas. For the first few years of its existence it was located at several different points in Chesapeake Bay; afterwards it was located at Beaufort, N. C., then at different places in the Bahama Islands, and finally in Jamaica. In the various expeditions of Brooks and his students to these different places they made not only a thorough biological survey of each region, but they did work of most fundamental and far reaching importance on the various groups of animals found. Out of these expeditions has grown the beautiful and permanent station of the U. S. Fisheries Bureau at Beaufort, N. C., in which Brooks took great interest and pride.

The "Scientific Results of the Sessions of the Chesapeake Zoölogical Laboratory" were at first published as a separate journal of which Brooks was the founder and editor, later this was incorporated in the "Studies from the Biological Laboratory" of which he was joint editor with H. Newell Martin. He subsequently established and edited "Memoirs from the Biological Laboratory," a large quarto for the publication of important monographs. He was also one of the editors of the "Journal of Experimental Zoölogy."

As a scientific investigator Brooks showed sound judgment, depth of insight, and untiring industry and enthusiasm. In his research he did not attempt to cover the whole field of zoölogy, but he did attempt to do thoroughly and well all that he undertook. His work began at a time when descriptive embryology was the newest and most promising branch of zoology and much of his earlier work was devoted to this field. His first important paper was on the "Development of *Salpa*," and many of his later works, some of them monumental monographs, were devoted to the anatomy, embryology and evolution of this interesting group of ascidians. Indeed his latest work which was left in manuscript and for which he had prepared hundreds of beautiful drawings, was a continuation of his great "Monograph on the Genus *Salpa*." Among other important researches may be mentioned his studies on the "Lucayan Indians," "Development of Marine Prosobranchiate Gasteropods," "Early Stages in the Development of Fresh Water Pulminates," "The Development of Lingula and the Systematic Position of the Brachiopoda," "The Relationships of Mollusca and Molluscoidea," "The Life History of the Hydromedusæ," "The Stomatopoda of the Challenger Expedition," "Lucifer: A Study in Morphology," "The Embryology and Metamorphosis of the Macroura" (with F. H. Herrick), and a "Monograph of the Genus *Doliolum*."

His studies on the development of mollusks led him to an examination of the life history and habits of the oyster and this was followed by a consideration of the best methods of propagating and cultivating oysters. His work on this subject was embodied in a book called "The Oyster," which has recently appeared in a second edition. Because of its economic importance, Brooks has been more widely known through this work than through any other. He was made chairman of the Maryland Oyster Commission and did much to improve this industry by a scientific treatment of the subject.

He wrote but one text-book, his "Handbook of Invertebrate Zoölogy" (1882) but this was so excellent that it still remains a model, and in some respects has not been excelled, if equalled, by any later book on that subject.

His chief interest was always in the philosophical side of biology and into this he put the larger part of his life work. Even the special researches, some of which have been named above, were permeated by philosophical inquiry, and most of his books and later contributions were devoted to the deeper philosophical meanings of vital phenomena.

As a boy he had read the works of Darwin and had been immensely impressed by them and to the last he yielded to no one in his admiration and reverence for that great master. Probably no other disciple of Darwin was more thoroughly acquainted with his works, and very frequently when criticisms of Darwinism appeared he would point out the fact that the critic did not understand what Darwinism is, or that Darwin had already met and answered the objections raised.

In 1884 he published a book entitled "The Law of Heredity," which in some respects anticipated the theories of Weismann, and which won the highest commendation from Huxley and other leaders of biology. But probably the book by which he will be longest remembered is the series of lectures delivered at Columbia University and published in the Biological Series of that institution under the title "The Foundations of Zoölogy" (1899). In this book he deals with many subjects fundamental not only to zoölogy, but to science and philosophy in general. Among these may be mentioned "Nature and Nurture," "Zoölogy and the Philosophy of Evolution," "Natural Selection and the Antiquity of Life," "Natural Selection and Natural Theology," "Paley and the Argument from Contrivance," "The Mechanism of Nature," "Louis Agassiz and George Berkeley," etc. On the whole his chief points of view may be summarized in his oft-quoted remark of Aristotle that the "essence of a living thing is not what it is made of nor what it does, but why it does it," or as he expresses it elsewhere, "the essence of a living thing is not protoplasm but purpose"; and in the further statements which he draws from Berkeley, that "nature is a language," that "phenomena are appearances," and that "natural laws are not arbitrary nor necessary, but natural, *i. e.,* neither less nor more than one who has the data has every reason to expect."

On March 25, 1898, sixty of his former students united in presenting to him an oil portrait of himself together with a congratulatory address, and at the end of his book on the "Foundations of Zoölogy," he added on this date, the following note:

> "For you who have, at this time, for my encouragement, called yourselves my students, I have written this book which has been my own so long that I should part with it with regret, did I not hope that, as you study the great works to which I have directed you, you may still call me teacher. . . . If you are indeed my students, you are not afraid of hard work, so in this day of light literature, when even learning must be made easy, you must be my readers, and you must do double duty; for I take the liberty of a teacher with his pupils, and ask that, after you have read the book, you will some day read it again; since I hope that what may seem obscure, may, on review, be found consistent and intelligible."

David Starr Jordan review this book in *Science* under the caption "A sage in biology." Whatever one may be inclined to say of his conclusions and theories, it cannot be denied that in an age when biological investigators have been content with discovering phenomena, he has attempted to go back of phenomena to their real meaning and significance and to point out the relationship of these newly discovered phenomena to the great current of philosophy which has flowed down to us from the remote past.

In his philosophical writing he was most deeply influenced by Aristotle, Berkeley and Huxley. Much that he has written still seems to me obscure, although I have read it more than once, but I bear in mind his parting request, and in the meantime profit by that which I do understand and am charmed by the classical and almost poetical diction in which it is written.

His abilities received early and generous recognition. Apart from his university advancement he received many honors. He received the honorary degree of LL.D. from Williams College in 1893, from Hobart College in 1899, and from the University of Pennsylvania at the Franklin Bicentennary in 1906. In 1884, at the age of thirty-six, he was elected a member of the National Academy of Sciences; he was chosen a member of the American Philosophical Society in 1886; of the Academy of Natural Sciences of Philadelphia in 1887; he was also a member of the Boston Society of Natural History, the American Academy of Arts and Sciences, of the Maryland Academy of Arts and Sciences, and of the American Society of Zoölogists; he was a fellow of the American Association for the Advancement of Science, and also a fellow of the Royal Microscopical Society. For his work on the oyster he received the medal of the Société d'Acclimatation of Paris; for his work on the scientific results of the Challenger Expedition he was given a Challenger Medal; and he received a medal at the St. Louis Exposition of 1904, where he gave an address. He was Lowell Lecturer in Boston in 1901, and he gave one of the principal addresses before the International Zoölogical Congress in 1907.

These honors he highly prized, and perhaps none of them more than his membership in this society. Whenever he was able, he attended the general meetings of the society, and usually presented a paper on some philosophical subject. He served as a counsellor of the society and frequently spoke to me of its purposes and policies. He greatly enjoyed coming into this historic hall, rich in its associations with great men of the past, and on one occasion when I spoke to him of the plan to provide a larger home for the society in a more central part of the city, he said to me, "Do you think you have any right to move the home of the society? It seems to me that you are only trustees of a historic institution, executors of an ancient trust, and that you have no right to remove this monument from its historic site."

In personal character Professor Brooks was simple and childlike, unconventional in manners, dress and speech. With him talking meant expressing ideas, not merely passing the time, and if he had no answer ready when a question was asked him, he usually gave no answer until he was ready. These characteristics made him appear somewhat unique and picturesque, and gave rise to many charming anecdotes about him which his students and friends relate with merriment, but real affection. He was kind and gentle; and neither in his publications nor in his relations with his students did he ever deal in scorn, irony, nor invective. President Remsen said of him that he had been called the most lovable man in the faculty. His interest in his former students was genuine and hearty though he rarely expressed it directly to the person concerned. He was modest and dignified; sincerity itself; loyal to his friends, his university, and his ideals; independent in thought and action, and not easily moved from a position he had once taken. He was a man of wide culture; he loved the best literature, music and art. When I last saw him at his home we spent the entire evening until after midnight playing, on his automatic piano, great compositions of Beethoven, Mozart, Wagner and other masters of harmony.

In his home life he was most happy and devoted. He married in June, 1878, Amelia Schultz, of Baltimore, by whom he had two children, Chas. E. Brooks, Ph.D., of Elizabeth, N. J., and Menetta W. Brooks, A.B., who, after the death of Mrs. Brooks in 1901, took charge of his home.

Professor Brooks once told me that he proposed to retire from his professorship when he had reached the age of sixty and thereafter devote himself entirely to philosophical and scientific work. He reached the age of sixty last March, but how different was his realization from his plan. His retirement was not to the scholarly leisure for which he longed, but to pain, weakness and mortal sickness. For nine months he struggled against a complication of organic heart trouble and kidney disease and at sunrise on Thursday, November twelfth, he breathed his last.

In his death this society has lost a worthy and devoted member, the world of scholars a man of rare ability and accomplishments, and his friends and associates a noble and lovable companion. Peace to his ashes, honor and reverence to his memory!

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