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VOL. 74

"EVERY MAN IS A VALUABLE MEMBER OF SOCIETY WHO, BY HIS OBSERVATIONS, RESEARCHES, AND EXPERIMENTS, PROCURES KNOWLEDGE FOR MEN"—SMITHSON

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CHARLES D. WALCOTT,
Secretary of the Smithsonian Institution.

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SMITHSONIAN MISCELLANEOUS COLLECTIONS
VOLUME 74, NUMBER 1

SMITHSONIAN MATHEMATICAL FORMULAE AND TABLES OF ELLIPTIC FUNCTIONS

MATHEMATICAL FORMULAE PREPARED BY
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TABLES OF ELLIPTIC FUNCTIONS PREPARED UNDER THE DIRECTION OF
SIR GEORGE GREENHILL, BART.
BY
COL. R. L. HIPPISLEY, C.B.

PUBLICATION 2672

CITY OF WASHINGTON
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1922

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The Smithsonian Institution has maintained for many years a group of publications in the nature of handy books of information on geographical, meteorological, physical, and mathematical subjects. These include the Smithsonian Geographical Tables (third edition, reprint, 1918); the Smithsonian Meteorological Tables (fourth revised edition, 1918); the Smithsonian Physical Tables (seventh revised edition, 1921); and the Smithsonian Mathematical Tables: Hyperbolic Functions (second reprint, 1921).

The present volume comprises the most important formulae of many branches of applied mathematics, an illustrated discussion of the methods of mechanical integration, and tables of elliptic functions. The volume has been compiled by Dr. E. P. Adams, of Princeton University. Prof. F. R. Moulton, of the University of Chicago, contributed the section on numerical solution of differential equations. The tables of elliptic functions were prepared by Col. R. L. Hippisley, C. B., under the direction of Sir George Greenhill, Bart., who has contributed the introduction to these tables.

The compiler, Dr. Adams, and the Smithsonian Institution are indebted to many physicists and mathematicians, especially to Dr. H. L. Curtis and colleagues of the Bureau of Standards, for advice, criticism, and coöperation in the preparation of this volume.

CHARLES D. WALCOTT,
Secretary of the Smithsonian Institution.

May, 1922.

PREFACE

The original object of this collection of mathematical formulae was to bring together, compactly, some of the more useful results of mathematical analysis for the benefit of those who regard mathematics as a tool, and not as an end in itself. There are many such results that are difficult to remember, for one who is not constantly using them, and to find them one is obliged to look through a number of books which may not immediately be accessible.

A collection of formulae, to meet the object of the present one, must be largely a matter of individual selection; for this reason this volume is issued in an interleaved edition, so that additions, meeting individual needs, may be made, and be readily available for reference.

It was not originally intended to include any tables of functions in this volume, but merely to give references to such tables. An exception was made, however, in favor of the tables of elliptic functions, calculated, on Sir George Greenhill's new plan, by Colonel Hippisley, which were fortunately secured for this volume, inasmuch as these tables are not otherwise available.

In order to keep the volume within reasonable bounds, no tables of indefinite and definite integrals have been included. For a brief collection, that of the late Professor B. O. Peirce can hardly be improved upon; and the elaborate collection of definite integrals by Bierens de Haan show how inadequate any brief tables of definite integrals would be. A short list of useful tables of this kind, as well as of other volumes, having an object similar to this one, is appended.

Should the plan of this collection meet with favor, it is hoped that suggestions for improving it and making it more generally useful may be received.

To Professor Moulton, for contributing the chapter on the Numerical Integration of Differential Equations, and to Sir George Greenhill, for his Introduction to the Tables of Elliptic Functions, I wish to express my gratitude. And I wish also to record my obligations to the Secretary of the Smithsonian Institution, and to Dr. C. G. Abbot, Assistant Secretary of the Institution, for the way in which they have met all my suggestions with regard to this volume.

E. P. ADAMS

PRINCETON, NEW JERSEY

COLLECTIONS OF MATHEMATICAL FORMULAE, ETC.

B. O. PEIRCE: A Short Table of Integrals, Boston, 1899.

G. PETIT BOIS: Tables d'Integrales Indefinies, Paris, 1906.

T. J. I'A. BROMWICH: Elementary Integrals, Cambridge, 1911.

D. BIERENS DE HAAN: Nouvelles Tables d'Integrales Definies, Leiden, 1867.

E. JAHNKE and F. EMDE: Funktionentafeln mit Formeln und Kurven, Leipzig, 1909.

G. S. CARR: A Synopsis of Elementary Results in Pure and Applied Mathematics, London, 1880.

W. LASKA: Sammlung von Formeln der reinen und angewandten Mathematik, Braunschweig, 1888–1894.

W. LIGOWSKI: Taschenbuch der Mathematik, Berlin, 1893.

O. TH. BÜRKLEN: Formelsammlung und Repetitorium der Mathematik, Berlin, 1922.

F. AUERBACH: Taschenbuch fur Mathematiker und Physiker, 1. Jahrgang, 1909. Leipzig, 1909.

CONTENTS

SYMBOLS

log	logarithm. Whenever used the Naperian logarithm is understood. To find the common logarithm to base 10: $\log_{10} a = 0.43429 \ldots \log a.$ $\log a = 2.30259 \ldots \log_{10} a.$
!	Factorial. $n!$ where n is an integer denotes $1 . 2 . 3 . 4 \ldots\ldots n.$ Equivalent notation $\lfloor\underline{n}$
$\neq$	Does not equal.
$>$	Greater than.
$<$	Less than.
$\geqslant$	Greater than, or equal to.
$\leqslant$	Less than, or equal to.
$\binom{n}{k}$	Binomial coefficient. See **1.51**.
$\rightarrow$	Approaches.
$\lvert a_{ik} \rvert$	Determinant where a_{ik} is the element in the ith row and kth column,
$\dfrac{\partial(u_1, u_2, \ldots .)}{\partial(x_1, x_2 . \ldots .)}$	Functional determinant. See **1.37.**
$\lvert a \rvert$	Absolute value of a. If a is a real quantity its numerical value, without regard to sign. If a is a complex quantity, $a = \alpha + i\beta$, $\lvert a \rvert$ = modulus of $a = +\sqrt{\alpha^2 + \beta^2}$.
i	The imaginary $= +\sqrt{-1}$.
Σ	Sign of summation, i.e., $\sum_{k=1}^{k=n} a_k = a_1 + a_2 + a_3 + \ldots . + a_n.$
Π	Product, i.e., $\prod_{k=1}^{k=n}(1 + kx) = (1 + x)(1 + 2x)(1 + 3x) \ldots . (1 + nx).$

I. ALGEBRA

1.00 Algebraic Identities.

1. $a^n - b^n = (a - b)(a^{n-1} + a^{n-2}b + a^{n-3}b^2 + \ldots\ldots + ab^{n-2} + b^{n-1}).$

2. $a^n \pm b^n = (a + b)(a^{n-1} - a^{n-2}b + a^{n-3}b^2 - \ldots\ldots \mp ab^{n-2} \pm b^{n-1}).$

n odd: upper sign.
n even: lower sign.

3. $(x + a_1)(x + a_2) \ldots\ldots (x + a_n) = x^n + P_1x^{n-1} + P_2x^{n-2} + \ldots\ldots + P_{n-1}x + P_n.$

$P_1 = a_1 + a_2 + \ldots\ldots + a_n.$

$P_k =$ sum of all the products of the a's taken k at a time.

$P_n = a_1a_2a_3 \ldots\ldots a_n.$

4. $(a^2 + b^2)(\alpha^2 + \beta^2) = (a\alpha \mp b\beta)^2 + (a\beta \pm b\alpha)^2.$

5. $(a^2 - b^2)(\alpha^2 - \beta^2) = (a\alpha \pm b\beta)^2 - (a\beta \pm b\alpha)^2.$

6. $(a^2 + b^2 + c^2)(\alpha^2 + \beta^2 + \gamma^2) = (a\alpha + b\beta + c\gamma)^2 + (b\gamma - \beta c)^2 + (c\alpha - \gamma a)^2 + (a\beta - \alpha b)^2.$

7. $(a^2 + b^2 + c^2 + d^2)(\alpha^2 + \beta^2 + \gamma^2 + \delta^2) = (a\alpha + b\beta + c\gamma + d\delta)^2 + (a\beta - b\alpha + c\delta - d\gamma)^2 + (a\gamma - b\delta - c\alpha + d\beta)^2 + (a\delta + b\gamma - c\beta - d\alpha)^2.$

8. $(ac - bd)^2 + (ad + bc)^2 = (ac + bd)^2 + (ad - bc)^2.$

9. $(a + b)(b + c)(c + a) = (a + b + c)(ab + bc + ca) - abc.$

10. $(a + b)(b + c)(c + a) = a^2(b + c) + b^2(c + a) + c^2(a + b) + 2abc.$

11. $(a + b)(b + c)(c + a) = bc(b + c) + ca(c + a) + ab(a + b) + 2abc.$

12. $3(a + b)(b + c)(c + a) = (a + b + c)^3 - (a^3 + b^3 + c^3).$

13. $(b - a)(c - a)(c - b) = a^2(c - b) + b^2(a - c) + c^2(b - a).$

14. $(b - a)(c - a)(c - b) = a(b^2 - c^2) + b(c^2 - a^2) + c(a^2 - b^2).$

15. $(b - a)(c - a)(c - b) = bc(c - b) + ca(a - c) + ab(b - a).$

16. $(a - b)^2 + (b - c)^2 + (c - a)^2 = 2[(a - b)(a - c) + (b - a)(b - c) + (c - a)(c - b)].$

17. $a^3(b^2 - c^2) + b^3(c^2 - a^2) + c^3(a^2 - b^2) = (a - b)(b - c)(a - c)(ab + bc + ca).$

18. $(a + b + c)(a^2 + b^2 + c^2) = bc(b + c) + ca(c + a) + ab(a + b) + a^3 + b^3 + c^3.$

19. $(a + b + c)(bc + ca + ab) = a^2(b + c) + b^2(c + a) + c^2(a + b) + 3abc.$

20. $(b + c - a)(c + a - b)(a + b - c) = a^2(b + c) + b^2(c + a) + c^2(a + b) - (a^3 + b^3 + c^3 + 2abc).$

21. $(a+b+c)(-a+b+c)(a-b+c)(a+b-c) = 2(b^2c^2+c^2a^2+a^2b^2) - (a^4+b^4+c^4).$

22. $(a+b+c+d)^2+(a+b-c-d)^2+(a+c-b-d)^2+(a+d-b-c)^2 = 4(a^2+b^2+c^2+d^2).$

If
$$A = a\alpha + b\gamma + c\beta$$
$$B = a\beta + b\alpha + c\gamma$$
$$C = a\gamma + b\beta + c\alpha$$

23. $(a+b+c)(\alpha+\beta+\gamma) = A+B+C.$

24. $[a^2+b^2+c^2-(ab+bc+ca)][\alpha^2+\beta^2+\gamma^2-(\alpha\beta+\beta\gamma+\gamma\alpha)] = A^2+B^2+C^2-(AB+BC+CA).$

25. $(a^3+b^3+c^3-3abc)(\alpha^3+\beta^3+\gamma^3-3\alpha\beta\gamma) = A^3+B^3+C^3-3ABC.$

ALGEBRAIC EQUATIONS

1.200 The expression

$$f(x) = a_0x^n + a_1x^{n-1} + a_2x^{n-2} + \ldots\ldots + a_{n-1}x + a_n$$

is an integral rational function, or a polynomial, of the nth degree in x.

1.201 The equation $f(x) = 0$ has n roots which may be real or complex, distinct or repeated.

1.202 If the roots of the equation $f(x) = 0$ are $c_1, c_2, \ldots, c_n$,

$$f(x) = a_0(x-c_1)(x-c_2)\ldots\ldots(x-c_n)$$

1.203 Symmetric functions of the roots are expressions giving certain combinations of the roots in terms of the coefficients. Among the more important are:

$$c_1 + c_2 + \ldots\ldots\ldots\ldots + c_n = -\frac{a_1}{a_0}$$

$$c_1c_2 + c_1c_3 + \ldots + c_2c_3 + c_2c_4 + \ldots\ldots + c_{n-1}c_n = \frac{a_2}{a_0}$$

$$c_1c_2c_3 + c_1c_2c_4 + \ldots + c_1c_3c_4 + \ldots\ldots + c_{n-2}c_{n-1}c_n = -\frac{a_3}{a_0}$$

. . . .

. . . .

$$c_1c_2c_3 \ldots\ldots c_n = (-1)^n\frac{a_n}{a_0}.$$

1.204 Newton's Theorem. If s_k denotes the sum of the kth powers of all the roots of $f(x) = 0$,

$$s_k = c_1^k + c_2^k + \ldots\ldots + c_n^k$$

$$1a_1 + s_1a_0 = 0$$

$$2a_2 + s_1a_1 + s_2a_0 = 0$$

$$3a_3 + s_1a_2 + s_2a_1 + s_3a_0 = 0$$

$$4a_4 + s_1a_3 + s_2a_2 + s_3a_1 + s_4a_0 = 0$$

. . . .

. . . .

. . . .

or:

$$s_1 = -\frac{a_1}{a_0}$$

$$s_2 = -\frac{2a_2}{a_0} + \frac{a_1^2}{a_0^2}$$

$$s_3 = -\frac{3a_3}{a_0} + \frac{3a_1a_2}{a_0^2} - \frac{a_1^3}{a_0^3}$$

$$s_4 = -\frac{4a_4}{a_0} + \frac{4a_1a_3}{a_0^2} - \frac{4a_1^2a_2}{a_0^3} + \frac{2a_2^2}{a_0^2} + \frac{a_1^4}{a_0^4}$$

. . . .

. . . .

1.205 If S_k denotes the sum of the reciprocals of the kth powers of all the roots of the equation $f(x) = 0$:

$$S_k = \frac{1}{c_1^k} + \frac{1}{c_2^k} + \ldots\ldots + \frac{1}{c_n^k}$$

$$1a_{n-1} + S_1a_n = 0$$

$$2a_{n-2} + S_1a_{n-1} + S_2a_n = 0$$

$$3a_{n-3} + S_1a_{n-2} + S_2a_{n-1} + S_3a_n = 0$$

. . . . .

. . . . .

$$S_1 = -\frac{a_{n-1}}{a_n}$$

$$S_2 = -\frac{2a_{n-2}}{a_n} + \frac{a^2_{n-1}}{a_n^2}$$

$$S_3 = -\frac{3a_{n-3}}{a_n} + \frac{3a_{n-1}a_{n-2}}{a_n^2} - \frac{a^3_{n-1}}{a^3_n}$$

. . . .

. . . .

. . . .

1.220 If $f(x)$ is divided by $x - h$ the result is

$$f(x) = (x - h)Q + R.$$

Q is the quotient and R the remainder. This operation may be readily performed as follows:

Write in line the values of $a_0, a_1, \ldots, a_n$. If any power of x is missing write 0 in the corresponding place. Multiply a_0 by h and place the product in the second line under a_1; add to a_1 and place the sum in the third line under a_1. Multiply this sum by h and place the product in the second line under a_2; add to a_2 and place the sum in the third line under a_2. Continue this series of operations until the third line is full. The last term in the third line is the remainder, R. The first term in the third line, which is a_0, is the coefficient of x^{n-1} in the quotient, Q; the second term is the coefficient of x^{n-2}, and so on.

1.221 It follows from **1.220** that $f(h) = R$. This gives a convenient way of evaluating $f(x)$ for $x = h$.

1.222 To express $f(x)$ in the form:

$$f(x) = A_0(x-h)^n + A_1(x-h)^{n-1} + \ldots + A_{n-1}(x-h) + A_n.$$

By **1.220** form $f(h) = A_n$. Repeat this process with each quotient, and the last term of each line of sums will be a succeeding value of the series of coefficients A_n, A_{n-1}, ..., A_0.

Example:

$$f(x) = 3x^5 + 2x^4 - 8x^2 + 2x - 4 \qquad h = 2$$

3	2	0	−8	2	−4
	6	16	32	48	100
3	8	16	24	50	$96 = A_5$
	6	28	88	224	
	14	44	112	$274 = A_4$	
	6	40	168		
	20	84	$280 = A_3$		
	6	52			
	26	$136 = A_2$			
	6				
	$32 = A_1$				
$3 = A_0$					

Thus:

$$Q = 3x^4 + 8x^3 + 16x^2 + 24x + 50$$

$$R = f(2) = 96$$

$$f(x) = 3(x-2)^5 + 32(x-2)^4 + 136(x-2)^3 + 280(x-2)^2 + 274(x-2) + 96$$

TRANSFORMATION OF EQUATIONS

1.230 To transform the equation $f(x) = 0$ into one whose roots all have their signs changed: Substitute $-x$ for x.

1.231 To transform the equation $f(x) = 0$ into one whose roots are all multiplied by a constant, m: Substitute x/m for x.

1.232 To transform the equation $f(x) = 0$ into one whose roots are the reciprocals of the roots of the given equation: Substitute $1/x$ for x and multiply by x^n.

1.233 To transform the equation $f(x) = 0$ into one whose roots are all increased or diminished by a constant, h: Substitute $x \pm h$ for x in the given equation, the upper sign being used if the roots are to be diminished and the lower sign if they are to be increased. The resulting equation will be:

$$f(\pm h) + xf'(\pm h) + \frac{x^2}{2!}f''(\pm h) + \frac{x^3}{3!}f'''(\pm h) + \ldots\ldots = 0$$

where $f'(x)$ is the first derivative of $f(x)$, $f''(x)$, the second derivative, etc. The resulting equation may also be written:

$$A_0x^n + A_1x^{n-1} + A_2x^{n-2} + \ldots\ldots + A_{n-1}x + A_n = 0$$

where the coefficients may be found by the method of **1.222** if the roots are to be diminished. To increase the roots by h change the sign of h.

MULTIPLE ROOTS

1.240 If c is a multiple root of $f(x) = 0$, of order m, i.e.. repeated m times, then

$$f(x) = (x - c)^m Q; \qquad R = 0$$

c is also a multiple root of order $m - 1$ of the first derived equation, $f'(x) = 0$; of order $m - 2$ of the second derived equation, $f''(x) = 0$, and so on.

1.241 The equation $f(x) = 0$ will have no multiple roots if $f(x)$ and $f'(x)$ have no common divisor. If $F(x)$ is the greatest common divisor of $f(x)$ and $f'(x)$, $f(x)/F(x) = f_1(x)$, and $f_1(x)$ will have no multiple roots.

1.250 An equation of odd degree, n, has at least one real root whose sign is opposite to that of a_n.

1.251 An equation of even degree, n, has one positive and one negative real root if a_n is negative.

1.252 The equation $f(x) = 0$ has as many real roots between $x = x_1$ and $x = x_2$ as there are changes of sign in $f(x)$ between x_1 and x_2.

1.253 Descartes' Rule of Signs: No equation can have more positive roots than it has changes of sign from + to − and from − to +, in the terms of $f(x)$. No equation can have more negative roots than there are changes of sign in $f(-x)$.

1.254 If $f(x) = 0$ is put in the form

$$A_0(x - h)^n + A_1(x - h)^{n-1} + \ldots\ldots + A_n = 0$$

by **1.222**, and $A_0, A_1, \ldots\ldots, A_n$ are all positive, h is an upper limit of the positive roots.

If $f(-x) = 0$ is put in a similar form, and the coefficients are all positive, h is a lower limit of the negative roots.

If $f(1/x) = 0$ is put in a similar form, and the coefficients are all positive, h is a lower limit of the positive roots. And with $f(-1/x) = 0$, h is an upper limit of the negative roots.

1.255 Sturm's Theorem. Form the functions:

$$f(x) = a_0x^n + a_1x^{n-1} + a_2x^{n-2} + \dots + a_n$$
$$f_1(x) = f'(x) = na_0x^{n-1} + (n-1)a_1x^{n-2} + \dots + a_{n-1}$$
$$f_2(x) = -R_1 \text{ in } f(x) = Q_1f_1(x) + R_1$$
$$f_3(x) = -R_2 \text{ in } f_1(x) = Q_2f_2(x) + R_2$$
$$\dots\dots\dots$$
$$\dots\dots\dots$$

The number of real roots of $f(x) = 0$ between $x = x_1$ and $x = x_2$ is equal to the number of changes of sign in the series $f(x)$, $f_1(x)$, $f_2(x)$, ... when x_1 is substituted for x minus the number of changes of sign in the same series when x_2 is substituted for x. In forming the functions f_1, f_2, ... numerical factors may be introduced or suppressed in order to remove fractional coefficients.

Example:

$$f(x) = x^4 - 2x^3 - 3x^2 + 10x - 4$$
$$f_1(x) = 2x^3 - 3x^2 - 3x + 5$$
$$f_2(x) = 9x^2 - 27x + 11$$
$$f_3(x) = -8x - 3$$
$$f_4(x) = -1433$$

	f	f_1	f_2	f_3	f_4	
$x = -\infty$	+	−	+	+	−	3 changes
$x = 0$	−	+	+	−	−	2 changes
$x = +\infty$	+	+	+	−	−	1 change

Therefore there is one positive and one negative real root.

If it can be seen that all the roots of any one of Sturm's functions are imaginary it is unnecessary to calculate any more of them after that one.

If there are any multiple roots of the equation $f(x) = 0$ the series of Sturm's functions will terminate with f_r, $r < n$. $f_r(x)$ is the highest common factor of f and f_1. In this case the number of real roots of $f(x) = 0$ lying between $x = x_1$ and $x = x_2$, each multiple root counting only once, will be the difference between the number of changes of sign in the series $f, f_1, f_2, \dots, f_r$ when x_1 and x_2 are successively substituted in them.

1.256 Routh's rule for finding the number of roots whose real parts are positive. (Rigid Dynamics, Part II, Art. 297.)

Arrange the coefficients in two rows:

x^n	a_0	a_2	a_4	....
x^{n-1}	a_1	a_3	a_5	....

Form a third row by cross-multiplication:

$$x^{n-2} \qquad \frac{a_1a_2 - a_0a_3}{a_1} \qquad \frac{a_1a_4 - a_0a_5}{a_1} \qquad \frac{a_1a_6 - a_0a_7}{a_1} \qquad \cdots\cdot$$

Form a fourth row by operating on these last two rows by a similar cross-multiplication. Continue this operation until there are no terms left. The number of variations of sign in the first column gives the number of roots whose real parts are positive.

If there are any equal roots some of the subsidiary functions will vanish. In place of one which vanishes write the differential coefficient of the last one which does not vanish and proceed in the same way. At the left of each row is written the power of x corresponding to the first subsidiary function in that row. This power diminishes by 2 for each succeeding coefficient in the row.

Any row may be multiplied or divided by any positive quantity in order to remove fractions.

DETERMINATION OF THE ROOTS OF AN EQUATION

1.260 Newton's Method. If a root of the equation $f(x) = 0$ is known to lie between x_1 and x_2 its value can be found to any desired degree of approximation by Newton's method. This method can be applied to transcendental equations as well as to algebraic equations.

If b is an approximate value of a root,

$$b - \frac{f(b)}{f'(b)} = c \text{ is a second approximation,}$$

$$c - \frac{f(c)}{f'(c)} = d \text{ is a third approximation.}$$

This process may be repeated indefinitely.

1.261 Horner's Method for approximating to the real roots of $f(x) = 0$.

Let p_1 be the first approximation, such that $p_1 + 1 > c > p_1$, where c is the root sought. The equation can always be transformed into one in which this condition holds by multiplying or dividing the roots by some power of 10 by **1.231**. Diminish the roots by p_1 by **1.233**. In the transformed equation

$$A_0(x - p_1)^n + A_1(x - p_1)^{n-1} + \cdots\cdot + A_{n-1}(x - p_1) + A_n = 0$$

put

$$\frac{p_2}{10} = \frac{A_n}{A_{n-1}}$$

and diminish the roots by $p_2/10$, yielding a second transformed equation

$$B_0\left(x - p_1 - \frac{p_2}{10}\right)^n + B_1\left(x - p_1 - \frac{p_2}{10}\right)^{n-1} + \cdots\cdot + B_n = 0.$$

If B_n and B_{n-1} are of the same sign p_2 was taken too large and must be diminished. Then take

$$\frac{p_3}{100} = \frac{B_n}{B_{n-1}}$$

and continue the operation. The required root will be:

$$c = p_1 + \frac{p_2}{10} + \frac{p_3}{100} + \dots\dots$$

1.262 Graeffe's Method. This method determines approximate values of all the roots of a numerical equation, complex as well as real. Write the equation of the nth degree

$$f(x) = a_0x^n - a_1x^{n-1} + a_2x^{n-2} - \dots \pm a_n = 0.$$

The product

$$f(x) \cdot f(-x) = A_0x^{2n} - A_1x^{2n-2} + A_2x^{2n-4} - \dots \pm A_n = 0$$

contains only even powers of x. It is an equation of the nth degree in x^2. The coefficients are determined by

$$\begin{aligned}
A_0 &= a_0^2 \\
A_1 &= a_1^2 - 2a_0a_2 \\
A_2 &= a_2^2 - 2a_1a_3 + 2a_0a_4 \\
A_3 &= a_3^2 - 2a_2a_4 + 2a_1a_5 - 2a_0a_6 \\
A_4 &= a_4^2 - 2a_3a_5 + 2a_2a_6 - 2a_1a_7 + 2a_0a_8 \\
&\dots\dots \\
&\dots\dots
\end{aligned}$$

The roots of the equation

$$A_0y^n - A_1y^{n-1} + A_2y^{n-2} - \dots \pm A_n = 0$$

are the squares of the roots of the given equation. Continuing this process we get an equation

$$R_0u^n - R_1u^{n-1} + R_2u^{n-2} - \dots \pm R_n = 0$$

whose roots are the 2^rth powers of the roots of the given equation. Put $\lambda = 2^r$. Let the roots of the given equation be $c_1, c_2, \dots, c_n$. Suppose first that

$$c_1 > c_2 > c_3 > \dots\dots > c_n$$

Then for large values of λ,

$$c_1^\lambda = \frac{R_1}{R_0}, \qquad c_2^\lambda = \frac{R_2}{R_1}, \qquad \dots, \qquad c_n^\lambda = \frac{R_n}{R_{n-1}}.$$

If the roots are real they may be determined by extracting the λth roots of these quantities. Whether they are $\pm$ is determined by taking the sign which approximately satisfies the equation $f(x) \doteq 0$.

Suppose next that complex roots enter so that there are equalities among the absolute values of the roots. Suppose that

$$|c_1| \geqq |c_2| \geqq |c_3| \geqq \dots \geqq |c_p|; \qquad |c_p| > |c_{p+1}|;$$
$$|c_{p+1}| \geqq |c_{p+2}| \geqq \dots \geqq |c_n|$$

Then if λ is large enough so that c_p^λ is large compared to c_{p+1}^λ, c_1^λ, c_2^λ, ... c_p^λ approximately satisfy the equation:

$$R_0u^p - R_1u^{p-1} + R_2u^{p-2} - \dots \pm R_p = 0$$

and c_{p+1}^λ, c_{p+2}^λ, . . . , c_n^λ approximately satisfy the equation:

$$R_pu^{n-p} - R_{p+1}u^{n-p-1} + R_{p+2}u^{n-p-2} - \dots \pm R_n = 0.$$

Therefore when λ is large enough the given equation breaks down into a number of simpler equations. This stage is shown in the process of deriving the successive equations when certain of the coefficients are obtained from those of the preceding equation simply by squaring.

REFERENCES: Encyklopadie der Math. Wiss. I, 1, 3a (Runge). BAIRSTOW: Applied Aerodynamics, pp. 553–560; the solution of a numerical equation of the 8th degree is given by Graeffe's Method.

1.270 Quadratic Equations.

$$x^2 + 2ax + b = 0.$$

The roots are:

$$x_1 = -a + \sqrt{a^2 - b}$$
$$x_2 = -a - \sqrt{a^2 - b}$$
$$x_1 + x_2 = -2a$$
$$x_1x_2 = b.$$

If

$a^2 > b$ roots are real,
$a^2 < b$ roots are complex,
$a^2 = b$ roots are equal.

1.271 Cubic equations.

$$(1)\quad x^3 + ax^2 + bx + c = 0.$$

Substitute

$$(2)\quad x = y - \frac{a}{3}$$

$$(3)\quad y^3 - 3py - 2q = 0$$

where

$$3p = \frac{a^2}{3} - b$$

$$2q = \frac{ab}{3} - \frac{2}{27}a^3 - c.$$

Roots of (3):

If $p > 0$, $q > 0$, $q^2 > p^3$

$$\cosh\phi = \frac{q}{\sqrt{p^3}}$$

$$y_1 = 2\sqrt{p}\,\cosh\frac{\phi}{3}$$

$$y_2 = -\frac{y_1}{2} + i\sqrt{3p}\,\sinh\frac{\phi}{3}$$

$$y_3 = -\frac{y_1}{2} - i\sqrt{3p}\,\sinh\frac{\phi}{3}.$$

If $p > 0$, $q < 0$, $q^2 > p^3$,

$$\cosh\phi = \frac{-q}{\sqrt{p^3}}$$

$$y_1 = -2\sqrt{p}\,\cosh\frac{\phi}{3}$$

$$y_2 = -\frac{y_1}{2} + i\sqrt{3p}\,\sinh\frac{\phi}{3}$$

$$y_3 = -\frac{y_1}{2} - i\sqrt{3p}\,\sinh\frac{\phi}{3}.$$

If $p < 0$

$$\sinh\phi = \frac{q}{\sqrt{-p^3}}$$

$$y_1 = 2\sqrt{-p}\,\sinh\frac{\phi}{3}$$

$$y_2 = -\frac{y_1}{2} + i\sqrt{-3p}\,\cosh\frac{\phi}{3}$$

$$y_3 = -\frac{y_1}{2} - i\sqrt{-3p}\,\cosh\frac{\phi}{3}.$$

If $p > 0$, $q^2 < p^3$,

$$\cos\phi = \frac{q}{\sqrt{p^3}}$$

$$y_1 = 2\sqrt{p}\,\cos\frac{\phi}{3}$$

$$y_2 = -\frac{y_1}{2} + \sqrt{3p}\,\sin\frac{\phi}{3}$$

$$y_3 = -\frac{y_1}{2} - \sqrt{3p}\,\sin\frac{\phi}{3}.$$

1.272 Biquadratic equations.

$$a_0x^4 + a_1x^3 + a_2x^2 + a_3x + a_4 = 0.$$

Substitute

$$x = y - \frac{a_1}{a_0}$$

$$y^4 + \frac{6}{a_0^2}Hy^2 + \frac{4}{a_0^3}Gy + \frac{1}{a_0^4}F = 0$$

$$H = a_0a_2 - a_1^2$$
$$G = a_0^2a_3 - 3a_0a_1a_2 + 2a_1^3$$
$$F = a_0^3a_4 - 4a_0^2a_1a_3 + 6a_0a_1^2a_2 - 3a_1^4$$
$$I = a_0a_4 - 4a_1a_3 + 3a_2^2$$
$$F = a_0^2I - 3H^2$$
$$J = a_0a_2a_4 + 2a_1a_2a_3 - a_0a_3^2 - a_1^2a_4 - a_2^3$$
$$\triangle = I^3 - 27J^2 = \text{the discriminant}$$
$$G^2 + 4H^3 = a_0^2(HI - a_0J).$$

Nature of the roots of the biquadratic:

$\triangle = 0$ Equal roots are present

Two roots only equal: I and J are not both zero

Three roots are equal: $I = J = 0$

Two distinct pairs of equal roots: $G = 0$; $a_0^2I - 12H^2 = 0$

Four roots equal: $H = I = J = 0$.

$\triangle < 0$ Two real and two complex roots

$\triangle > 0$ Roots are either all real or all complex:

$H < 0$ and $a_0^2I - 12H^2 < 0$ Roots all real

$H > 0$ and $a_0^2I - 12H^2 > 0$ Roots all complex.

DETERMINANTS

1.300 A determinant of the nth order, with n^2 elements, is written:

$$\triangle = \begin{vmatrix} a_{11} & a_{12} & a_{13} & \cdots & a_{1n} \\ a_{21} & a_{22} & a_{23} & \cdots & a_{2n} \\ a_{31} & a_{32} & a_{33} & \cdots & a_{3n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & a_{n3} & \cdots & a_{nn} \end{vmatrix} = |\, a_{ij} \,|, \quad (i, j, = 1, 2, \ldots, n)$$

1.301 A determinant is not changed in value by writing rows for columns and columns for rows.

1.302 If two columns or two rows of a determinant are interchanged the resulting determinant is unchanged in value but is of the opposite sign.

1.303 A determinant vanishes if it has two equal columns or two equal rows.

1.304 If each element of a row or a column is multiplied by the same factor the determinant itself is multiplied by that factor.

1.305 A determinant is not changed in value if to each element of a row or column is added the corresponding element of another row or column multiplied by a common factor.

1.306 If each element of the lth row or column consists of the sum of two or more terms the determinant splits up into the sum of two or more determinants having for elements of the lth row or column the separate terms of the lth row or column of the given determinant.

1.307 If corresponding elements of two rows or columns of a determinant have a constant ratio the determinant vanishes.

1.308 If the ratio of the differences of corresponding elements in the pth and qth rows or columns to the differences of corresponding elements in the rth and sth rows or columns be constant the determinant vanishes.

1.309 If p rows or columns of a determinant whose elements are rational integral functions of x become equal or proportional when $x = h$, the determinant is divisible by $(x - h)^{p-1}$.

MULTIPLICATION OF DETERMINANTS

1.320 Two determinants of equal order may be multiplied together by the scheme:

$$| a_{ij} | \times | b_{ij} | = | c_{ij} |$$

where

$$c_{ij} = a_{i1}b_{j1} + a_{i2}b_{j2} + \dots\dots + a_{in}b_{jn}.$$

1.321 If the two determinants to be multiplied are of unequal order the one of lower order can be raised to one of equal order by bordering it; i.e.:

$$\begin{vmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{vmatrix} = \begin{vmatrix} 1 & 0 & 0 & \dots & \dots & \dots & \dots & 0 \\ 0 & 1 & 0 & \dots & \dots & \dots & \dots & 0 \\ 0 & 0 & 1 & \dots & \dots & \dots & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & \dots & a_{11} & a_{12} & \dots & a_{1n} \\ 0 & 0 & 0 & \dots & a_{21} & a_{22} & \dots & a_{2n} \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & \dots & a_{n1} & a_{n2} & \dots & a_{nn} \end{vmatrix}$$

1.322 The product of two determinants may be written:

$$\begin{vmatrix} a_{11} & \dots & a_{1n} \\ \dots & \dots & \dots \\ \dots & \dots & \dots \\ a_{n1} & \dots & a_{nn} \end{vmatrix} \times \begin{vmatrix} b_{11} & \dots & b_{1n} \\ \dots & \dots & \dots \\ \dots & \dots & \dots \\ b_{n1} & \dots & b_{nn} \end{vmatrix}$$

$$= \begin{vmatrix} a_{11} & \cdots & a_{1n} & 0 & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ a_{n1} & \cdots & a_{nn} & 0 & \cdots & 0 \\ 0 & \cdots & 0 & b_{11} & \cdots & b_{1n} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & \cdots & 0 & b_{n1} & \cdots & b_{nn} \end{vmatrix}$$

DIFFERENTIATION OF DETERMINANTS

1.330 If the elements of a determinant, Δ, are functions of a variable, t:

$$\frac{d\Delta}{dt} = \begin{vmatrix} a'_{11} & a_{12} & \cdots & a_{1n} \\ a'_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ a'_{n1} & a_{n2} & \cdots & a_{nn} \end{vmatrix} + \begin{vmatrix} a_{11} & a'_{12} & \cdots & a_{1n} \\ a_{21} & a'_{22} & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a'_{n2} & \cdots & a_{nn} \end{vmatrix}$$

$$+ \cdots\cdots\cdots + \begin{vmatrix} a_{11} & a_{12} & \cdots & a'_{1n} \\ a_{21} & a_{22} & \cdots & a'_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & a'_{nn} \end{vmatrix}$$

where the accents denote differentiation by t.

EXPANSION OF DETERMINANTS

1.340 The complete expansion of a determinant of the nth order contains $n!$ terms. Each of these terms contains one element from each row and one element from each column. Any term may be obtained from the leading term:

$$a_{11}a_{22}a_{33} \cdots\cdots a_{nn}$$

by keeping the first suffixes unchanged and permuting the second suffixes among $1, 2, 3, \ldots, n$. The sign of any term is determined by the number of inversions from the second suffixes of the leading term, being positive if there is an even number of inversions and negative if there is an odd number of inversions.

1.341 The coefficient of a_{ij} when the determinant Δ is fully expanded is:

$$\frac{\partial \Delta}{\partial a_{ij}} = \Delta_{ij}.$$

Δ_{ij} is the first minor of the determinant Δ corresponding to a_{ij} and is a determinant of order $n-1$. It may be obtained from Δ by crossing out the row and column which intersect in a_{ij}, and multiplying by $(-1)^{i+j}$.

1.342

$$a_{i1}\Delta_{j1} + a_{i2}\Delta_{j2} + \ldots + a_{in}\Delta_{jn} = \frac{0 \text{ if } i \neq j}{\Delta \text{ if } i = j}$$

$$a_{1i}\Delta_{1j} + a_{2i}\Delta_{2j} + \ldots + a_{ni}\Delta_{nj} = \frac{0 \text{ if } i \neq j}{\Delta \text{ if } i = j}.$$

1.343

$$\frac{\partial^2\Delta}{\partial a_{ij}\partial a_{kl}} = \frac{\partial\Delta_{kl}}{\partial a_{ij}} = \frac{\partial\Delta_{ij}}{\partial a_{kl}}$$

is the coefficient of $a_{ij}a_{kl}$ in the complete expansion of the determinant Δ. It may be obtained from Δ, except for sign, by crossing out the rows and columns which intersect in a_{ij} and a_{kl}.

1.344

$$|\Delta_{ij}| \times |a_{ij}| = \Delta^n$$
$$|\Delta_{ij}| = \Delta^{n-1}.$$

The determinant $|\Delta_{ij}|$ is the reciprocal determinant to Δ.

1.345

$$\Delta \cdot \frac{\partial^2\Delta}{\partial a_{ij}\partial a_{kl}} = \begin{vmatrix} \Delta_{ij} & \Delta_{il} \\ \Delta_{kj} & \Delta_{kl} \end{vmatrix} = \frac{\partial\Delta}{\partial a_{ij}}\frac{\partial\Delta}{\partial a_{kl}} - \frac{\partial\Delta}{\partial a_{il}}\frac{\partial\Delta}{\partial a_{kj}}.$$

1.346

$$\Delta^2 \frac{\partial^3\Delta}{\partial a_{ij}\partial a_{kl}\partial a_{pq}} = \begin{vmatrix} \Delta_{ij} & \Delta_{il} & \Delta_{iq} \\ \Delta_{kj} & \Delta_{kl} & \Delta_{kq} \\ \Delta_{pj} & \Delta_{pl} & \Delta_{pq} \end{vmatrix}$$

1.347

$$\frac{\partial^2\Delta}{\partial a_{ij}\partial a_{kl}} = -\frac{\partial^2\Delta}{\partial a_{il}\partial a_{kj}}.$$

1.348 If $\Delta = 0$,

$$\frac{\partial\Delta}{\partial a_{ij}}\frac{\partial\Delta}{\partial a_{kl}} = \frac{\partial\Delta}{\partial a_{il}}\frac{\partial\Delta}{\partial a_{kj}}.$$

1.350 If $a_{ij} = a_{ji}$ the determinant is symmetrical. In a symmetrical determinant

$$\Delta_{ij} = \Delta_{ji}.$$

1.351 If $a_{ij} = -a_{ji}$ the determinant is a skew determinant. In a skew determinant

$$\Delta_{ij} = (-1)^{n-1}\Delta_{ji}.$$

1.352 If $a_{ij} = -a_{ji}$, and $a_{ii} = 0$, the determinant is a skew symmetrical determinant.

A skew symmetrical determinant of even order is a perfect square.

A skew symmetrical determinant of odd order vanishes.

1.360 A system of linear equations:

$$\begin{array}{l} a_{11}x_1 + a_{12}x_2 + \ldots\ldots + a_{1n}x_n = k_1 \\ a_{21}x_1 + a_{22}x_2 + \ldots\ldots + a_{2n}x_n = k_2 \\ \ldots\ldots\ldots\ldots \\ \ldots\ldots\ldots\ldots \\ a_{n1}x_1 + a_{n2}x_2 + \ldots\ldots + a_{nn}x_n = k_n \end{array}$$

has a solution:

$$\Delta\cdot x_i = k_1\Delta_{1i} + k_2\Delta_{2i} + \ldots\ldots + k_n\Delta_{ni}$$

provided that

$$\Delta = |a_{ij}| \neq 0.$$

1.361 If $\Delta = 0$, but all the first minors are not 0,

$$\Delta_{ss}\cdot x_j = x_s\Delta_{sj} + \sum_{r=1}^{n} k_r \frac{\partial^2\Delta}{\partial a_{ss}\partial a_{rj}} \qquad (j = 1, 2, \ldots\ldots n)$$

where s may be any one of the integers $1, 2, \ldots\ldots, n$.

1.362 If $k_1 = k_2 = \ldots\ldots = k_n = 0$, the linear equations are homogeneous, and if $\Delta = 0$,

$$\frac{x_j}{\Delta_{sj}} = \frac{x_s}{\Delta_{ss}} \qquad (j = 1, 2, \ldots n).$$

1.363 The condition that n linear homogeneous equations in n variables shall be consistent is that the determinant, Δ, shall vanish.

1.364 If there are $n + 1$ linear equations in n variables:

$$\begin{array}{l} a_{11}x_1 + a_{12}x_2 + \ldots\ldots + a_{1n}x_n = k_1 \\ a_{21}x_1 + a_{22}x_2 + \ldots\ldots + a_{2n}x_n = k_2 \\ \ldots\ldots\ldots\ldots\ldots \\ \ldots\ldots\ldots\ldots\ldots \\ a_{n1}x_1 + a_{n2}x_2 + \ldots\ldots + a_{nn}x_n = k_n \\ c_1x_1 + c_2x_2 + \ldots\ldots + c_nx_n = k_{n+1} \end{array}$$

the condition that this system shall be consistent is that the determinant:

$$\begin{vmatrix} a_{11} & a_{12} & \ldots\ldots & a_{1n} & k_1 \\ a_{21} & a_{22} & \ldots\ldots & a_{2n} & k_2 \\ \ldots & \ldots & \ldots\ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots\ldots & \ldots & \ldots \\ a_{n1} & a_{n2} & \ldots\ldots & a_{nn} & k_n \\ c_1 & c_2 & \ldots\ldots & c_n & k_{n+1} \end{vmatrix} = 0$$

1.370 Functional Determinants.

If $y_1, y_2, \ldots, y_n$ are n functions of $x_1, x_2, \ldots, x_n$:

$$y_k = f_k(x_1, x_2, \ldots, x_n)$$

the determinant:

$$J = \begin{vmatrix} \frac{\partial y_1}{\partial x_1} & \frac{\partial y_1}{\partial x_2} & \cdots\cdots & \frac{\partial y_1}{\partial x_n} \\ \frac{\partial y_2}{\partial x_1} & \frac{\partial y_2}{\partial x_2} & \cdots\cdots & \frac{\partial y_2}{\partial x_n} \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ \frac{\partial y_n}{\partial x_1} & \frac{\partial y_n}{\partial x_2} & \cdots\cdots & \frac{\partial y_n}{\partial x_n} \end{vmatrix} = \left|\frac{\partial y_i}{\partial x_j}\right| = \frac{\partial(y_1, y_2, \ldots, y_n)}{\partial(x_1, x_2, \ldots, x_n)}$$

is the Jacobian.

1.371 If $y_1, y_2, \ldots, y_n$ are the partial derivatives of a function $F(x_1, x_2, \ldots, x_n)$:

$$y_i = \frac{\partial F}{\partial x_i} \quad (i = 1, 2, \ldots, n)$$

the symmetrical determinant:

$$H = \left|\frac{\partial^2 F}{\partial x_i \, \partial x_j}\right| = \frac{\partial\left(\frac{\partial F}{\partial x_1}, \frac{\partial F}{\partial x_2} \cdots \frac{\partial F}{\partial x_n}\right)}{\partial(x_1, x_2, \ldots, x_n)}$$

is the Hessian.

1.372 If $y_1, y_2, \ldots, y_n$ are given as implicit functions of $x_1, x_2, \ldots, x_n$ by the n equations:

$$\begin{aligned} &F_1(y_1, y_2, \ldots, y_n, x_1, x_2, \ldots, x_n) = 0 \\ &\cdots\cdots \\ &\cdots\cdots \\ &F_n(y_1, y_2, \ldots, y_n, x_1, x_2, \ldots, x_n) = 0 \end{aligned}$$

then

$$\frac{\partial(y_1, y_2, \ldots, y_n)}{\partial(x_1, x_2, \ldots, x_n)} = (-1)^n \frac{\partial(F_1, F_2, \ldots, F_n)}{\partial(x_1, x_2, \ldots, x_n)} \div \frac{\partial(F_1, F_2, \ldots, F_n)}{\partial(y_1, y_2, \ldots, y_n)}$$

1.373 If the n functions $y_1, y_2, \ldots, y_n$ are not independent of each other the Jacobian, J, vanishes; and if $J = 0$ the n functions $y_1, y_2, \ldots, y_n$ are not independent of each other but are connected by a relation

$$F(y_1, y_2, \ldots, y_n) = 0$$

1.374 Covariant property. If the variables $x_1, x_2, \ldots, x_n$ are transformed by a linear substitution:

$$x_i = a_{i1}\xi_1 + a_{i2}\xi_2 + \ldots\ldots + a_{in}\xi_n \qquad (i = 1, 2, \ldots, n)$$

and the functions $y_1, y_2, \ldots, y_n$ of $x_1, x_2, \ldots, x_n$ become the functions $\eta_1, \eta_2, \ldots, \eta_n$ of $\xi_1, \xi_2, \ldots, \xi_n$:

$$J' = \frac{\partial(\eta_1, \eta_2, \ldots, \eta_n)}{\partial(\xi_1, \xi_2, \ldots, \xi_n)} = \frac{\partial(y_1, y_2, \ldots, y_n)}{\partial(x_1, x_2, \ldots, x_n)} \cdot |a_{ij}|$$

or

$$J' = J \cdot |a_{ij}|$$

where $|a_{ij}|$ is the determinant or modulus of the transformation.

For the Hessian,

$$H' = H \cdot |a_{ij}|^2.$$

1.380 To change the variables in a multiple integral:

$$I = \int \ldots\ldots \int F(y_1, y_2, \ldots, y_n)dy_1dy_2 \ldots\ldots dy_n$$

to new variables, $x_1, x_2, \ldots, x_n$ when $y_1, y_2, \ldots, y_n$ are given functions of $x_1, x_2, \ldots, x_n$:

$$I = \int \ldots\ldots \int \frac{\partial(y_1, y_2, \ldots, y_n)}{\partial(x_1, x_2, \ldots, x_n)} F(x)dx_1dx_2 \ldots\ldots dx_n$$

where $F(x)$ is the result of substituting $x_1, x_2, \ldots, x_n$ for $y_1, y_2, \ldots, y_n$ in $F(y_1, y_2, \ldots, y_n)$.

PERMUTATIONS AND COMBINATIONS

1.400 Given n different elements. Represent each by a number, 1, 2, 3, ..., n. The number of permutations of the n different elements is,

$$_nP_n = n!$$

e.g., $n = 3$:

$$(123), (132), (213), (231), (312), (321) = 6 = 3!$$

1.401 Given n different elements. The number of permutations in groups of r $(r<n)$, or the number of r-permutations, is,

$$_nP_r = \frac{n!}{(n-r)!}$$

e.g., $n = 4$, $r = 3$:

(123)(132)(124)(142)(134)(143)(234)(243)(231)(213)(214)(241)(341)(314)
(312)(321)(324)(342)(412)(421)(431)(413)(423)(432) = 24

1.402 Given n different elements. The number of ways they can be divided into m specified groups, with $x_1, x_2, \ldots, x_m$ in each group respectively, $(x_1 + x_2 + \ldots + x_m) = n$ is

$$\frac{n!}{x_1!x_2!\ldots x_m!}$$

e.g., $n = 6$, $m = 3$, $x_1 = 2$, $x_2 = 3$, $x_3 = 1$:

(12) (345) (6)	(13) (245) (6)	$\times 6 = 60$
(23) (145) (6)	(24) (135) (6)	
(34) (125) (6)	(35) (124) (6)	
(45) (123) (6)	(25) (234) (6)	
(14) (235) (6)	(15) (234) (6)	

1.403 Given n elements of which x_1 are of one kind, x_2 of a second kind, $\ldots\ldots$, x_m of an mth kind. The number of permutations is

$$\frac{n!}{x_1!x_2!\ldots\ldots x_m!}$$

$$x_1 + x_2 + \ldots\ldots + x_m = n.$$

1.404 Given n different elements. The number of ways they can be permuted among m specified groups, when blank groups are allowed, is

$$\frac{(m + n - 1)!}{(m - 1)!}$$

e.g., $n = 3$, $m = 2$:

(123,0)(132,0)(213,0)(231,0)(312,0)(321,0)(12,3)(21,3)(13,2)(31,2)(23,1)
(32,1)(1,23)(1,32)(2,31)(2,13)(3,12)(3,21)(0,123)(0,213)(0,132)(0,231)
(0,312)(0,321) = 24

1.405 Given n different elements. The number of ways they can be permuted among m specified groups, when blank groups are not allowed, so that each group contains at least one element, is

$$\frac{n!(n - 1)!}{(n - m)!(m - 1)!}$$

e.g., $n = 3$, $m = 2$:

(12,3)(21,3)(13,2)(31,2)(23,1)(32,1)(1,23)(1,32)(2,31)(2,13)(3,12)(3,21) = 12

1.406 Given n different elements. The number of ways they can be combined into m specified groups when blank groups are allowed is

$$m^n$$

e.g., $n = 3$, $m = 2$:

(123,0)(12,3)(13,2)(23,1)(1,23)(2,31)(3,12)(0,123) = 8

1.407 Given n similar elements. The number of ways they can be combined into m different groups when blank groups are allowed is

$$\frac{(n+m-1)!}{(m-1)!n!}$$

e.g., $n = 6$, $m = 3$:

Group 1	6	5	5	4	4	4	3	3	3	3	2	2	2	2	2	1	1	1	1	1	1	0	0	0	0	0	0	0	
Group 2	0	1	0	2	0	1	3	0	2	1	4	0	3	1	2	5	0	4	1	3	2	6	0	5	1	4	2	3	= 28
Group 3	0	0	1	0	2	1	0	3	1	2	0	4	1	3	2	0	5	1	4	2	3	0	6	1	5	2	4	3	

1.408 Given n similar elements. The number of ways they can be combined into m different groups when blank groups are not allowed, so that each group shall contain at least one element, is

$$\frac{(n-1)!}{(m-1)!(n-m)!}.$$

BINOMIAL COEFFICIENTS

1.51

1. $\binom{n}{k} = \dfrac{n!}{k!(n-k)!} = \binom{n}{n-k} = {}_nC_k = \dfrac{n(n-1)(n-2)\ .\ .\ .\ (n-k+1)}{k!}.$

2. $\binom{n}{k} + \binom{n}{k+1} = \binom{n+1}{k+1}.$

3. $\binom{n}{0} = 1,\ \binom{n}{1} = n,\ \binom{n}{n} = 1.$

4. $\binom{-n}{k} = (-1)^k\binom{n+k-1}{k}.$

5. $\binom{n}{k} = 0$ if $n < k$.

6. $\binom{k}{k} + \binom{k+1}{k} + \binom{k+2}{k} + \ .\ .\ .\ . + \binom{n}{k} = \binom{n+1}{k+1}.$

7. $1 - \binom{n}{1} + \binom{n}{2} - \ .\ .\ .\ . + (-1)^k\binom{n}{k} = (-1)^k\binom{n-1}{k}.$

8. $\binom{n}{k} + \binom{n}{k-1}\binom{r}{1} + \binom{n}{k-2}\binom{r}{2} + \ .\ .\ .\ . + \binom{r}{k} = \binom{n+r}{k}.$

9. $1 + \binom{n}{1} + \binom{n}{2} + \ .\ .\ .\ . + \binom{n}{n} = 2^n.$

10. $1 - \binom{n}{1} + \binom{n}{2} - \ .\ .\ .\ . + (-1)^n\binom{n}{n} = 0.$

11. $1 + \binom{n}{1}^2 + \binom{n}{2}^2 + \ .\ .\ .\ . + \binom{n}{n}^2 = \binom{2n}{n}.$

1.52 Table of Binomial Coefficients.

$$\binom{n}{1} = n.$$

$\binom{n}{1}$	$\binom{n}{2}$	$\binom{n}{3}$	$\binom{n}{4}$	$\binom{n}{5}$	$\binom{n}{6}$	$\binom{n}{7}$	$\binom{n}{8}$	$\binom{n}{9}$	$\binom{n}{10}$	$\binom{n}{11}$	$\binom{n}{12}$
1											
2	1										
3	3	1									
4	6	4	1								
5	10	10	5	1							
6	15	20	15	6	1						
7	21	35	35	21	7	1					
8	28	56	70	56	28	8	1				
9	36	84	126	126	84	36	9	1			
10	45	120	210	252	210	120	45	10	1		
11	55	165	330	462	462	330	165	55	11	1	
12	66	220	495	792	924	792	495	220	66	12	1

1.521 Glaisher, Mess. of Math. 47, p. 97, 1918, has given a complete table of binomial coefficients, from $n = 2$ to $n = 50$, and $k = 0$ to $k = n$.

1.61 Resolution into Partial Fractions.

If $F(x)$ and $f(x)$ are two polynomials in x and $f(x)$ is of higher degree than $F(x)$,

$$\frac{F(x)}{f(x)} = \sum \frac{F(a)}{\phi(a)} \frac{1}{x-a} + \sum \frac{1}{(p-1)!} \frac{d^{p-1}}{dc^{p-1}}\left[\frac{F(c)}{\phi(c)} \frac{1}{x-c}\right]$$

where

$$\phi(a) = \left[\frac{f(x)}{x-a}\right]_{x=a},$$

$$\phi(c) = \left[\frac{f(x)}{(x-c)^p}\right]_{x=c}.$$

The first summation is to be extended for all the simple roots, a, of $f(x)$ and the second summation for all the multiple roots, c, of order p, of $f(x)$.

FINITE DIFFERENCES AND SUMS.

1.811 Definitions.

1. $\Delta f(x) = f(x+h) - f(x).$
2. $\Delta^2 f(x) = \Delta f(x+h) - \Delta f(x).$
$\qquad = f(x+2h) - 2f(x+h) + f(x).$

3. $\Delta^3 f(x) = \Delta^2 f(x+h) - \Delta^2 f(x).$

$$= f(x+3h) - 3f(x+2h) + 3f(x+h) - f(x).$$

. . . .

. . . .

4. $\Delta^n f(x) = f(x+nh) - \frac{n}{1} f(x+\overline{n-1}h) + \frac{n(n-1)}{2!} f(x+\overline{n-2}h) - \ldots.$

$$+ (-1)^n f(x).$$

1.812

1. $\Delta[cf(x)] = c\Delta f(x)$ (c a constant).

2. $\Delta[f_1(x) + f_2(x) + \ldots] = \Delta f_1(x) + \Delta f_2(x) + \ldots.$

3. $\Delta[f_1(x) \cdot f_2(x)] = f_1(x) \cdot \Delta f_2(x) + f_2(x+h) \cdot \Delta f_1(x)$

$$= f_1(x) \cdot \Delta f_2(x) + f_2(x) \cdot \Delta f_1(x) + \Delta f_1(x) \cdot \Delta f_2(x).$$

4. $\Delta \frac{f_1(x)}{f_2(x)} = \frac{f_2(x) \cdot \Delta f_1(x) - f_1(x) \cdot \Delta f_2(x)}{f_2(x) \cdot f_2(x+h)}.$

1.813 The nth difference of a polynomial of the nth degree is constant. If

$$f(x) = a_0 x_n + a_1 x^{n-1} + \ldots + a_{n-1} x + a_n$$

$$\Delta^n f(x) = n! a_0 h^n.$$

1.82

1. $\frac{\Delta^m \{(x-b)(x-b-h)(x-b-2h) \ldots (x-b-\overline{n-1}h)\}}{n(n-1)(n-2) \ldots (n-m+1)h^m}$

$$= (x-b)(x-b-h)(x-b-2h) \ldots (x-b-\overline{n-m-1}h).$$

2. $\Delta^m \frac{1}{(x+b)(x+b+h)(x+b+2h) \ldots (x+b+\overline{n-1}h)}$

$$= (-1)^m \frac{n(n+1)(n+2) \ldots (n+m-1)h^m}{(x+b)(x+b+h)(x+b+2h) \ldots (x+b+\overline{n+m-1}h)}.$$

3. $\Delta^m a^x = (a^h - 1)^m a^x$

4. $\Delta \log f(x) = \log\left(1 + \frac{\Delta f(x)}{f(x)}\right).$

5. $\Delta^m \sin(cx+d) = \left(2 \sin \frac{ch}{2}\right)^m \sin\left(cx + d + m\frac{ch+\pi}{2}\right).$

6. $\Delta^m \cos(cx+d) = \left(2 \sin \frac{ch}{2}\right)^m \cos\left(cx + d + m\frac{ch+\pi}{2}\right).$

1.83 Newton's Interpolation Formula.

$$f(x) = f(a) + \frac{x-a}{h}\Delta f(a) + \frac{(x-a)(x-a-h)}{2!\,h^2}\Delta^2 f(a) +$$

$$+ \frac{(x-a)(x-a-h)(x-a-2h)}{3!\,h^3}\Delta^3 f(a) + \ldots\ldots$$

$$+ \frac{(x-a)(x-a-h)\ldots\ldots(x-a-\overline{n-1}h)}{n!\,h^n}\Delta^n f(a)$$

$$+ \frac{(x-a)(x-a-h)\ldots\ldots(x-a-nh)}{\overline{n+1}!} f^{(n+1)}(\xi)$$

where ξ has a value intermediate between the greatest and least of a, $(a+nh)$, and x.

1.831

$$f(a+nh) = f(a) + \frac{n}{1!}\Delta f(a) + \frac{n(n-1)}{2!}\Delta^2 f(a) + \frac{n(n-1)(n-2)}{3!}\Delta^3 f(a)$$

$$+ \ldots\ldots + n\Delta^{n-1} f(a) + \Delta^n f(a).$$

1.832 Symbolically

1. $\Delta = e^{h\frac{\partial}{\partial x}} - 1$

2. $f(a+nh) = (1+\Delta)^n f(a)$

1.833 If $u_0 = f(a)$, $u_1 = f(a+h)$, $u_2 = f(a+2h)$, ..., $u_x = f(a+xh)$,

$$u_x = (1+\Delta)^x u_0 = e^{hx\frac{\partial}{\partial x}} u_0.$$

1.840 The operator inverse to the difference, Δ, is the sum, Σ.

$$\Sigma = \Delta^{-1} = \frac{1}{e^{\lambda\frac{\partial}{\partial x}} - 1}.$$

1.841 If $\Delta F(x) = f(x)$,

$$\Sigma f(x) = F(x) + C,$$

where C is an arbitrary constant.

1.842

1. $\Sigma c f(x) = c\Sigma f(x).$
2. $\Sigma[f_1(x) + f_2(x) + \ldots] = \Sigma f_1(x) + \Sigma f_2(x) + \ldots$
3. $\Sigma[f_1(x)\cdot\Delta f_2(x)] = f_1(x)\cdot f_2(x) - \Sigma[f_2(x+h)\cdot\Delta f_1(x)].$

1.843 Indefinite Sums.

1. $\Sigma[(x-b)(x-b-h)(x-b-2h)\ \ldots\ (x-b-\overline{n-1}h)]$

$$= \frac{1}{(n+1)h}(x-b)(x-b-h)\ \ldots\ldots\ (x-b-nh)+C.$$

2. $$\sum \frac{1}{(x+b)(x+b+h)\ \ldots\ (x+b+\overline{n-1}h)}$$

$$= -\frac{1}{(n-1)h}\,\frac{1}{(x+b)(x+b+h)\ \ldots\ (x+b+\overline{n-2}h)}+C.$$

3. $$\sum a^x = \frac{a^x}{a^h-1}+C.$$

4. $$\sum \cos(cx+d) = \frac{\sin\left(cx-\frac{ch}{2}+d\right)}{2\sin\frac{ch}{2}}+C.$$

5. $$\sum \sin(cx+d) = -\frac{\cos\left(cx-\frac{ch}{2}+d\right)}{2\sin\frac{ch}{2}}+C.$$

1.844 If $f(x)$ is a polynomial of degree n,

$$\sum a^x f(x) = \frac{a^x}{a^h-1}\left\{f(x) - \frac{a^h}{a^h-1}\Delta f(x) + \left(\frac{a^h}{a^h-1}\right)^2 \Delta^2 f(x) - \ldots\right.$$
$$\left. + \left(\frac{-a^h}{a^h-1}\right)^n \Delta^n f(x)\right\} + C.$$

1.845 If $f(x)$ is a polynomial of degree n,

$$f(x) = a_0x^n + a_1x^{n-1} + \ldots + a_{n-1}x + a_n,$$

and

$$\Sigma f(x) = F(x) + C,$$
$$F(x) = c_0x^{n+1} + c_1x^n + c_2x^{n-1} + \ldots + c_nx + c_{n+1},$$

where

$$(n+1)hc_0 = a_0$$
$$\frac{(n+1)n}{2!}h^2c_0 + nhc_1 = a_1$$
$$\frac{(n+1)n(n-1)}{3!}h^3c_0 + \frac{n(n-1)}{2!}h^2c_1 + (n-1)hc_2 = a_2$$
$$\ldots\ldots\ldots\ldots$$
$$\ldots\ldots\ldots\ldots$$

The coefficient c_{n+1} may be taken arbitrarily.

1.850 Definite Sums. From the indefinite sum,

$$\Sigma f(x) = F(x) + C,$$

a definite sum is obtained by subtraction,

$$\sum_{a+mh}^{a+nh} f(x) = F(a + nh) - F(a + mh).$$

1.851

$$\sum_{a}^{a+nh} f(x) = f(a) + f(a + h) + f(a + 2h) + \dots + f(a + \overline{n - 1}h)$$
$$= F(a + nh) - F(a).$$

By means of this formula many finite sums may be evaluated.

1.852

$$\sum_{a}^{a+nh} (x - b)(x - b - h)(x - b - 2h) \dots (x - b - \overline{k - 1}h)$$
$$= \frac{(a - b + nh)(a - b + \overline{n - 1}h) \dots (a - b + \overline{n - k}h)}{(k + 1)h}$$
$$- \frac{(a - b)(a - b - h) \dots (a - b - kh)}{(k + 1)h}.$$

1.853

$$\sum_{a}^{a+nh} (x - a)(x - a - h) \dots (x - a - \overline{k - 1}h)$$
$$= \frac{n(n - 1)(n - 2) \dots (n - k)}{(k + 1)} h^k.$$

1.854 If $f(x)$ is a polynomial of degree m it can be expressed:

$$f(x) = A_0 + A_1(x - a) + A_2(x - a)(x - a - h) + \dots$$
$$+ A_m(x - a)(x - a - h) \dots (x - a - \overline{m - 1}h),$$

$$\sum_{a}^{a+nh} f(x) = A_0 n + A_1 \frac{n(n - 1)}{2} h + A_2 \frac{n(n - 1)(n - 2)}{3} h^2$$
$$+ A_m \frac{n(n - 1) \dots (n - m)}{(m + 1)} h^m.$$

1.855 If $f(x)$ is a polynomial of degree $(m - 1)$ or lower, it can be expressed:

$$f(x) = A_0 + A_1(x + mh) + A_2(x + mh)(x + \overline{m - 1}h)$$
$$+ \dots + A_{m-1}(x + mh) \dots (x + 2h)$$

and,

$$\sum_{a}^{a+nh} \frac{f(x)}{x(x + h)(x + 2h) \dots (x + mh)} = \frac{A_0}{mh} \left\{ \frac{1}{a(a + h) \dots (a + \overline{m - 1}h)} \right.$$

$$- \frac{1}{(a+nh)\ .\ .\ .\ .\ .\ (a+\overline{n+m-1}h)} \Bigg\}$$

$$+ \frac{A_1}{(m-1)h} \left\{ \frac{1}{a(a+h)\ldots(a+\overline{m-2}h)} - \frac{1}{(a+nh)\ldots(a+\overline{n+m-2}h)} \right\}$$

$$+\ .\ .\ .\ .\ . + \frac{A_{m-1}}{h} \left\{ \frac{1}{a} - \frac{1}{a+nh} \right\}.$$

1.856 If $f(x)$ is a polynomial of degree m it can be expressed:

$$f(x) = A_0 + A_1(x+mh) + A_2(x+mh)(x+\overline{m-1}h) + \ .\ .\ .\ .$$
$$+ A_m(x+mh)\ .\ .\ .\ (x+h)$$

and,

$$\sum_a^{a+nh} \frac{f(x)}{x(x+h)\ .\ .\ .\ (x+mh)} = \frac{A_0}{mh} \Bigg\{ \frac{1}{a(a+h)\ .\ .\ .\ .\ (a+\overline{m-1}h)}$$
$$- \frac{1}{(a+nh)\ .\ .\ .\ .\ .\ (a+\overline{m+n-1}h)} \Bigg\}$$
$$+\ .\ .\ .\ .\ . + \frac{A_{m-1}}{h} \left\{ \frac{1}{a} - \frac{1}{a+nh} \right\} + A_m \sum_a^{a+nh} \frac{1}{x}$$

where,

$$\sum_a^{a+nh} \frac{1}{x} = \frac{1}{a} + \frac{1}{a+h} + \frac{1}{a+2h} + \ .\ .\ .\ . + \frac{1}{a+\overline{n-1}h}.$$

1.86 Euler's Summation Formula.

$$\sum_a^b f(x) = \frac{1}{h}\int_a^b f(z)dz + A_1 \Big\{ f(b) - f(a) \Big\} + A_2 h \Big\{ f'(b) - f'(a) \Big\},$$
$$+\ .\ .\ .\ . + A_{m-1}h^{m-2} \{ f^{(m-2)}(b) - f^{(m-2)}(a) \},$$
$$- \int_0^h \phi_m(z) \sum_{x=a}^{x=b} \frac{d^m f(x+h-z)}{h dx^m} \cdot dz$$

$$\phi_m(z) = \frac{z^m}{m!} + A_1 \frac{hz^{m-1}}{(m-1)!} + A_2 \frac{h^2 z^{m-2}}{(m-2)!} + \ .\ .\ .\ . + A_{m-1}h^{m-1}z.$$

$m!\phi_m(z)$, with $h = 1$, is the Bernoullian polynomial.

$A_1 = -\frac{1}{2}$, $A_{2k+1} = 0$; the coefficients A_{2k} are connected with Bernoulli's numbers (**6.902**), B_k, by the relation,

$$A_{2k} = (-1)^{k+1} \frac{B_k}{(2k)!}$$

$$A_1 = -\frac{1}{2}, \qquad A_2 = \frac{1}{12}, \qquad A_4 = -\frac{1}{720}, \qquad A_6 = \frac{1}{30240}\ .\ .\ .\ .$$

1.861

$$\sum_a^b f(x) = \frac{1}{h}\int_a^b f(z)dz - \frac{1}{2}\Big\{f(b) - f(a)\Big\} + \frac{h}{12}\Big\{f'(b) - f'(a)\Big\}$$

$$- \frac{h^3}{720}\Big\{f'''(b) - f'''(a)\Big\} + \frac{h^5}{30240}\Big\{f^{\text{v}}(b) - f^{\text{v}}(a)\Big\} - \ldots\ldots$$

1.862

$$\sum u_x = C + \int u_x dx - \frac{1}{2}u_x + \frac{1}{12}\frac{du_x}{dx} - \frac{1}{720}\frac{d^3u_x}{dx^3} + \frac{1}{30240}\frac{d^5u_x}{dx^5} - \ldots\ldots$$

SPECIAL FINITE SERIES

1.871 Arithmetical progressions. If s is the sum, a the first term, δ the common difference, l the last term, and n the number of terms,

$$s = a + (a + \delta) + (a + 2\delta) + \ldots . [a + (n - 1)\delta]$$

$$l = a + (n - 1)\,\delta$$

$$s = \frac{n}{2}[2a + (n - 1)\delta]$$

$$= \frac{n}{2}(a + l).$$

1.872 Geometrical progressions.

$$s = a + ap + ap^2 + \ldots\ldots + ap^{n-1}$$

$$s = a\frac{p^n - 1}{p - 1}$$

If $p < 1$, $n = \infty$, $s = \dfrac{a}{1 - p}$.

1.873 Harmonical progressions. $a, b, c, d, \ldots .$ form an harmonical progression if the reciprocals, $1/a$, $1/b$, $1/c$, $1/d$, $\ldots .$ form an arithmetical progression.

1.874.

1. $$\sum_{x=1}^{x=n} x = \frac{n(n+1)}{2}$$

2. $$\sum_{x=1}^{x=n} x^2 = \frac{n(n+1)(2n+1)}{6}$$

3. $$\sum_{x=1}^{x=n} x^3 = \left[\frac{n(n+1)}{2}\right]^2$$

4. $$\sum_{x=1}^{x=n} x^4 = \frac{n^5}{5} + \frac{n^4}{2} + \frac{n^3}{3} - \frac{n}{30}.$$

1.875 In general,

$$\sum_{x=1}^{x=n} x^k = \frac{n^{k+1}}{k+1} + \frac{n^k}{2} + \frac{1}{2}\binom{k}{1} B_1 n^{k-1} - \frac{1}{4}\binom{k}{3} B_2 n^{k-3} + \frac{1}{6}\binom{k}{5} B_3 n^{k-5} - \ldots$$

B_1, B_2, B_3, . . . are Bernoulli's numbers (**6.902**), $\binom{k}{h}$ are the binomial coefficients (**1.51**); the series ends with the term in n if k is even, and with the term in n^2 if k is odd.

1.876

$$\frac{1}{1} + \frac{1}{2} + \frac{1}{3} + \frac{1}{4} + \ldots\ldots + \frac{1}{n} = \gamma + \log n + \frac{1}{2n} - \frac{a_2}{n(n+1)} - \frac{a_3}{n(n+1)(n+2)} - \ldots .$$

γ = Euler's constant = 0.5772156649 . . .

$$a_2 = \frac{1}{12}$$

$$a_3 = \frac{1}{12}$$

$$a_4 = \frac{19}{80} \qquad a_k = \frac{1}{k}\int_0^1 x(1-x)(2-x)\ldots\ldots(k-1-x)dx$$

$$a_5 = \frac{9}{20}$$

1.877

$$\frac{1}{1^2} + \frac{1}{2^2} + \frac{1}{3^2} + \ldots\ldots + \frac{1}{n^2} = \frac{\pi^2}{6} - \frac{b_1}{n+1} - \frac{b_2}{(n+1)(n+2)} - \frac{b_3}{(n+1)(n+2)(n+3)} - \ldots\ldots$$

$$b_k = \frac{(k-1)!}{k}$$

1.878

$$\frac{1}{1^3} + \frac{1}{2^3} + \frac{1}{3^3} + \ldots\ldots + \frac{1}{n^3} = C - \frac{c_2}{(n+1)(n+2)} - \frac{c_3}{(n+1)(n+2)(n+3)} - \ldots .$$

$$C = \sum_{k=1}^{\infty} \frac{1}{k^3} = 1.2020569032$$

$$c_k = \frac{(k-1)!}{k}\left(\frac{1}{1} + \frac{1}{2} + \frac{1}{3} + \ldots\ldots + \frac{1}{k-1}\right).$$

1.879 Stirling's Formula.

$$\log(n!) = \log\sqrt{2\pi} + \left(n + \frac{1}{2}\right)\log n - n$$
$$+ \frac{A_2}{n} + \ldots\ldots + A_{2k-2}\frac{(2k-4)!}{n^{2k-3}}$$
$$+ \theta\, A_{2k}\frac{(2k-2)!}{n^{2k-1}}$$

$0<\theta<1$. The coefficients A_k are given in **1.86.**

1.88

1. $1 + 1! + 2\cdot 2! + 3\cdot 3! + \ldots\ldots + n\cdot n! = (n+1)!$

2. $1\cdot 2\cdot 3 + 2\cdot 3\cdot 4 + 3\cdot 4\cdot 5 + \ldots\ldots + n(n+1)(n+2) = \frac{1}{4}n(n+1)(n+2)(n+3).$

3. $1\cdot 2\cdot 3\ldots\ldots r + 2\cdot 3\cdot 4\ldots(r+1) + \ldots\ldots\ldots + n(n+1)(n+2)$
$\ldots\ldots(n+r-1)$
$$= \frac{n(n+1)(n+2)\ldots\ldots(n+r)}{r+1}.$$

4. $1\cdot p + 2(p+1) + 3(p+2) + \ldots\ldots\ldots + n(p+n-1)$
$$= \frac{1}{6}n(n+1)(3p+2n-2).$$

5. $p\cdot q + (p-1)(q-1) + (p-2)(q-2) + \ldots\ldots\ldots(p-n)(q-n)$
$$= \frac{1}{6}n[6pq - (n-1)(3p+3q-2n+1)].$$

6. $$1 + \frac{b}{a} + \frac{b(b+1)}{a(a+1)} + \ldots\ldots + \frac{b(b+1)\ldots\ldots(b+n-1)}{a(a+1)\ldots\ldots(a+n-1)}.$$
$$= \frac{b(b+1)\ldots\ldots(b+n)}{(b+1-a)a(a+1)\ldots\ldots(a+n-1)} - \frac{a-1}{b+1-a}.$$

II. GEOMETRY

2.00 Transformation of coördinates in a plane.

2.001 Change of origin. Let x, y be a system of *rectangular* or *oblique* coördinates with origin at O. Referred to x, y the coördinates of the new origin O' are a, b. Then referred to a parallel system of coördinates with origin at O' the coördinates are x', y'.

$$\begin{aligned} x &= x' + a \\ y &= y' + b. \end{aligned}$$

2.002 Origin unchanged. Directions of axes changed. Oblique coördinates. Let ω be the angle between the $x - y$ axes measured counter-clockwise from the x- to the y-axis. Let the x'-axis make an angle α with the x-axis and the y'-axis an angle β with the x-axis. All angles are measured counter-clockwise from the x-axis. Then

$$\begin{aligned} x \sin \omega &= x' \sin (\omega - \alpha) + y' \sin (\omega - \beta) \\ y \sin \omega &= x' \sin \alpha + y' \sin \beta \\ \omega' &= \beta - \alpha. \end{aligned}$$

2.003 Rectangular axes. Let both new and old axes be rectangular, the new axes being turned through an angle θ with respect to the old axes. Then $\omega = \frac{\pi}{2}, \alpha = \theta, \beta = \frac{\pi}{2} + \theta.$

$$\begin{aligned} x &= x' \cos \theta - y' \sin \theta \\ y &= x' \sin \theta + y' \cos \theta. \end{aligned}$$

2.010 Polar coördinates. Let the y-axis make an angle ω with the x-axis and let the x-axis be the initial line for a system of polar coördinates r, θ. All angles are measured in a counter-clockwise direction from the x-axis.

$$x = \frac{r \sin (\omega - \theta)}{\sin \omega}$$

$$y = r \frac{\sin \theta}{\sin \omega}.$$

2.011 If the x, y axes are rectangular, $\omega = \frac{\pi}{2}$,

$$\begin{aligned} x &= r \cos \theta \\ y &= r \sin \theta. \end{aligned}$$

2.020 Transformation of coördinates in three dimensions.

2.021 Change of origin. Let x, y, z be a system of *rectangular* or *oblique* coördinates with origin at O. Referred to x, y, z the coördinates of the new origin O' are a, b, c. Then referred to a parallel system of coördinates with origin at O' the coördinates are x', y', z'.

$$x = x' + a$$
$$y = y' + b$$
$$z = z' + c$$

2.022 Transformation from one to another rectangular system. Origin unchanged. The two systems are x, y, z and x' y' z'.

Referred to x, y, z the direction cosines of x' are l_1, m_1, n_1
Referred to x, y, z the direction cosines of y' are l_2, m_2, n_2
Referred to x, y, z the direction cosines of z' are l_3, m_3, n_3

The two systems are connected by the scheme:

	x'	y'	z'
x	l_1	l_2	l_3
y	m_1	m_2	m_3
z	n_1	n_2	n_3

$$x = l_1x' + l_2y' + l_3z' \qquad x' = l_1x + m_1y + n_1z$$
$$y = m_1x' + m_2y' + m_3z' \qquad y' = l_2x + m_2y + n_2z$$
$$z = n_1x' + n_2y' + n_3z' \qquad z' = l_3x + m_3y + n_3z$$

$$l_1^2 + m_1^2 + n_1^2 = 1 \qquad l_1^2 + l_2^2 + l_3^2 = 1$$
$$l_2^2 + m_2^2 + n_2^2 = 1 \qquad m_1^2 + m_2^2 + m_3^2 = 1$$
$$l_3^2 + m_3^2 + n_3^2 = 1 \qquad n_1^2 + n_2^2 + n_3^2 = 1$$

$$l_1m_1 + l_2m_2 + l_3m_3 = 0 \qquad l_1l_2 + m_1m_2 + n_1n_2 = 0$$
$$m_1n_1 + m_2n_2 + m_3n_3 = 0 \qquad l_2l_3 + m_2m_3 + n_2n_3 = 0$$
$$n_1l_1 + n_2l_2 + n_3l_3 = 0 \qquad l_3l_1 + m_3m_1 + n_3n_1 = 0$$

2.023 If the transformation from one to another rectangular system is a rotation through an angle θ about an axis which makes angles α, β, γ with x, y, z respectively,

$$2 \cos \theta = l_1 + m_2 + n_3 - 1$$

$$\frac{\cos^2 \alpha}{m_2 + n_3 - l_1 - 1} = \frac{\cos^2 \beta}{n_3 + l_1 - m_2 - 1} = \frac{\cos^2 \gamma}{l_1 + m_2 - n_3 - 1}$$

2.024 Transformation from a rectangular to an oblique system. x, y, z rectangular system: x', y', z' oblique system.

$$\begin{array}{lll} \cos \widehat{xx'} = l_1 & \cos \widehat{xy'} = l_2 & \cos \widehat{xz'} = l_3 \\ \cos \widehat{yx'} = m_1 & \cos \widehat{yy'} = m_2 & \cos \widehat{yz'} = m_3 \\ \cos \widehat{zx'} = n_1 & \cos \widehat{zy'} = n_2 & \cos \widehat{zz'} = n_3 \end{array}$$

$$\begin{aligned} x &= l_1x' + l_2y' + l_3z' \\ y &= m_1x' + m_2y' + m_3z' \\ z &= n_1x' + n_2y' + n_3z' \end{aligned}$$

$$\begin{aligned} \cos \widehat{y'z'} &= l_2l_3 + m_2m_3 + n_2n_3 \\ \cos \widehat{z'x'} &= l_3l_1 + m_3m_1 + n_3n_1 \\ \cos \widehat{x'y'} &= l_1l_2 + m_1m_2 + n_1n_2 \end{aligned}$$

$$\begin{aligned} l_1^2 + m_1^2 + n_1^2 &= 1 \\ l_2^2 + m_2^2 + n_2^2 &= 1 \\ l_3^2 + m_3^2 + n_3^2 &= 1 \end{aligned}$$

2.025 Transformation from one to another oblique system.

$$\begin{array}{lll} \cos \widehat{xx'} = l_1 & \cos \widehat{xy'} = l_2 & \cos \widehat{xz'} = l_3 \\ \cos \widehat{yx'} = m_1 & \cos \widehat{yy'} = m_2 & \cos \widehat{yz'} = m_3 \\ \cos \widehat{zx'} = n_1 & \cos \widehat{zy'} = n_2 & \cos \widehat{zz'} = n_3 \end{array}$$

$$\Delta = \begin{vmatrix} l_1 & l_2 & l_3 \\ m_1 & m_2 & m_3 \\ n_1 & n_2 & n_3 \end{vmatrix}$$

$$\begin{aligned} x &= l_1x' + l_2y' + l_3z' \\ y &= m_1x' + m_2y' + m_3z' \\ z &= n_1x' + n_2y' + n_3z' \end{aligned}$$

$$\begin{aligned} \Delta \cdot x' &= (m_2n_3 - m_3n_2)x + (n_2l_3 - n_3l_2)y + (l_2m_3 - l_3m_2)z, \\ \Delta \cdot y' &= (m_3n_1 - m_1n_3)x + (n_3l_1 - n_1l_3)y + (l_3m_1 - l_1m_3)z, \\ \Delta \cdot z' &= (m_1n_2 - m_2n_1)x + (n_1l_2 - n_2l_1)y + (l_1m_2 - l_2m_1)z. \end{aligned}$$

$$\begin{aligned} l_1^2 + m_1^2 + n_1^2 + 2m_1n_1 \cos \widehat{yz} + 2n_1l_1 \cos \widehat{zx} + 2l_1m_1 \cos \widehat{xy} &= 1, \\ l_2^2 + m_2^2 + n_2^2 + 2m_2n_2 \cos \widehat{yz} + 2n_2l_2 \cos \widehat{zx} + 2l_2m_2 \cos \widehat{xy} &= 1, \\ l_3^2 + m_3^2 + n_3^2 + 2m_3n_3 \cos \widehat{yz} + 2n_3l_3 \cos \widehat{zx} + 2l_3m_3 \cos \widehat{xy} &= 1. \end{aligned}$$

$$\begin{aligned} x + y \cos \widehat{xy} + z \cos \widehat{xz} &= l_1x' + l_2y' + l_3z', \\ y + x \cos \widehat{xy} + z \cos \widehat{zy} &= m_1x' + m_2y' + m_3z', \\ z + x \cos \widehat{xz} + y \cos \widehat{zy} &= n_1x' + n_2y' + n_3z'. \end{aligned}$$

2.026 Transformation from one to another oblique system.

If n_x, n_y, n_z are the normals to the planes yz, zx, xy and n_x', n_y', n_z' the normals to the planes $y'z'$, $z'x'$, $x'y'$,

$$\begin{aligned}
x \cos \widehat{xn_x} &= x' \cos \widehat{x'n_x} + y' \cos \widehat{y'n_x} + z' \cos \widehat{z'n_x}.\\
y \cos \widehat{yn_y} &= x' \cos \widehat{x'n_y} + y' \cos \widehat{y'n_y} + z' \cos \widehat{z'n_y}.\\
z \cos \widehat{zn_z} &= x' \cos \widehat{x'n_z} + y' \cos \widehat{y'n_z} + z' \cos \widehat{z'n_z}.
\end{aligned}$$

$$\begin{aligned}
x' \cos \widehat{x'n_x'} &= x \cos \widehat{xn_x'} + y \cos \widehat{yn_x'} + z \cos \widehat{zn_x'}.\\
y' \cos \widehat{y'n_y'} &= x \cos \widehat{xn_y'} + y \cos \widehat{yn_y'} + z \cos \widehat{zn_y'}.\\
z' \cos \widehat{z'n_z'} &= x \cos \widehat{xn_z'} + y \cos \widehat{yn_z'} + z \cos \widehat{zn_z'}.
\end{aligned}$$

2.030 Transformation from rectangular to spherical polar coördinates.

r, the radius vector to a point makes an angle θ with the z-axis, the projection of r on the x-y plane makes an angle ϕ with the x-axis.

$$x = r \sin \theta \cos \phi \qquad r^2 = x^2 + y^2 + z^2$$

$$y = r \sin \theta \sin \phi \qquad \theta = \cos^{-1} \frac{z}{\sqrt{x^2 + y^2 + z^2}}$$

$$z = r \cos \theta \qquad \phi = \tan^{-1} \frac{y}{x}$$

2.031 Transformation from rectangular to cylindrical coördinates.

ρ, the perpendicular from the z-axis to a point makes an angle θ with the x-z plane.

$$x = \rho \cos \theta \qquad \rho = \sqrt{x^2 + y^2}$$

$$y = \rho \sin \theta \qquad \theta = \tan^{-1} \frac{y}{x}$$

$$z = z$$

2.032 Curvilinear coördinates in general.

See **4.0**

2.040 Eulerian Angles.

$Oxyz$ and $Ox'y'z'$ are two systems of rectangular axes with the same origin O. OK is perpendicular to the plane zOz' drawn so that if Oz is vertical, and the projection of Oz' perpendicular to Oz is directed to the south, then OK is directed to the east.

$$\text{Angles} \quad \widehat{z'Oz} = \theta, \quad \widehat{yOK} = \phi, \quad \widehat{y'OK} = \psi.$$

The direction cosines of the two systems of axes are given by the following scheme:

	x	y	z
x'	$\cos\phi\cos\theta\cos\psi - \sin\phi\sin\psi$	$\sin\phi\cos\theta\cos\psi + \cos\phi\sin\psi$	$-\sin\theta\cos\psi$
y'	$-\cos\phi\cos\theta\sin\psi - \sin\phi\cos\psi$	$-\sin\phi\cos\theta\sin\psi + \cos\phi\cos\psi$	$\sin\theta\sin\psi$
z'	$\cos\phi\sin\theta$	$\sin\phi\sin\theta$	$\cos\theta$

2.050 Trilinear Coördinates.

A point in a plane is defined if its distances from two intersecting lines are given. Let CA, CB (Fig. 1) be these lines:

$$PR = p, \quad PS = q, \quad PT = r.$$

Taking CA and CB as the x-, y-axes, including an angle C,

$$x = \frac{p}{\sin C},$$

$$y = \frac{q}{\sin C}.$$

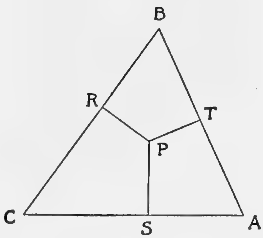

FIG. 1

Any curve $f(x,y) = 0$ becomes:

$$f\left(\frac{p}{\sin C}, \frac{q}{\sin C}\right) = 0.$$

If s is the area of the triangle CAB (triangle of reference),

$$2s = ap + bq + cr,$$
$$a = BC,$$
$$b = CA,$$
$$c = AB,$$

and the equation of a curve may be written in the homogeneous form:

$$f\left(\frac{2sp}{(ap + bq + cr)\sin C}, \frac{2sq}{(ap + bq + cr)\sin C}\right) = 0.$$

2.060 Quadriplanar Coördinates.

These are the analogue in 3 dimensions of trilinear coördinates in a plane (**2.050**).

x_1, x_2, x_3, x_4 denote the distances of a point P from the four sides of a tetrahedron (the tetrahedron of reference); l_1, m_1, n_1; l_2, m_2, n_2; l_3, m_3, n_3; and l_4, m_4, n_4 the direction cosines of the normals to the planes $x_1 = 0$, $x_2 = 0$, $x_3 = 0$, $x_4 = 0$ with respect to a rectangular system of coördinates x, y, z; and d_1, d_2, d_3, d_4 the distances of these 4 planes from the origin of coördinates:

$$(1) \quad \begin{cases} x_1 = l_1 x + m_1 y + n_1 z - d_1 \\ x_2 = l_2 x + m_2 y + n_2 z - d_2 \\ x_3 = l_3 x + m_3 y + n_3 z - d_3 \\ x_4 = l_4 x + m_4 y + n_4 z - d_4. \end{cases}$$

s_1, s_2, s_3, and s_4 are the areas of the 4 faces of the tetrahedron of reference and V its volume:

$$3V = x_1 s_1 + x_2 s_2 + x_3 s_3 + x_4 s_4.$$

By means of the first 3 equations of (1) x, y, z are determined:

$$\begin{aligned} x &= A_1 x_1 + B_1 x_2 + C_1 x_3 + D_1, \\ y &= A_2 x_1 + B_2 x_2 + C_2 x_3 + D_2, \\ z &= A_3 x_1 + B_3 x_2 + C_3 x_3 + D_3. \end{aligned}$$

The equation of any surface,

$$F(x,y,z) = 0,$$

may be written in the homogeneous form:

$$\begin{aligned} F\Bigg\{ &\left[A_1 x_1 + B_1 x_2 + C_1 x_3 + \frac{D_1}{3V}(s_1 x_1 + s_2 x_2 + s_3 x_3 + s_4 x_4)\right], \\ &\left[A_2 x_1 + B_2 x_2 + C_2 x_3 + \frac{D_2}{3V}(s_1 x_1 + s_2 x_2 + s_3 x_3 + s_4 x_4)\right], \\ &\left[A_3 x_1 + B_3 x_2 + C_3 x_3 + \frac{D_3}{3V}(s_1 x_1 + s_2 x_2 + s_3 x_3 + s_4 x_4)\right]\Bigg\} = 0. \end{aligned}$$

PLANE GEOMETRY

2.100 The equation of a line:

$$Ax + By + C = 0.$$

2.101 If p is the perpendicular from the origin upon the line, and α and β the angles p makes with the x- and y-axes:

$$p = x \cos \alpha + y \cos \beta.$$

2.102 If α' and β' are the angles the line makes with the x- and y-axes:

$$p = y \cos \alpha' - x \cos \beta'.$$

2.103 The equation of a line may be written

$$y = ax + b.$$

a = tangent of angle the line makes with the x-axis,
b = intercept of the y-axis by the line.

2.104 The two lines:

$$y = a_1x + b_1,$$
$$y = a_2x + b_2,$$

intersect at the point:

$$x = \frac{b_2 - b_1}{a_1 - a_2}, \qquad y = \frac{a_1b_2 - a_2b_1}{a_1 - a_2}.$$

2.105 If ϕ is the angle between the two lines **2.104**:

$$\tan \phi = \pm \frac{a_1 - a_2}{1 + a_1a_2}.$$

2.106 Equations of two parallel lines:

$$\begin{cases} Ax + By + C_1 = 0 \\ Ax + By + C_2 = 0 \end{cases} \quad \text{or} \quad \begin{cases} y = ax + b_1, \\ y = ax + b_2. \end{cases}$$

2.107 Equations of two perpendicular lines:

$$\begin{cases} Ax + By + C_1 = 0 \\ Bx - Ay + C_2 = 0 \end{cases} \quad \text{or} \quad \begin{cases} y = ax + b_1, \\ y = -\dfrac{x}{a} + b_2. \end{cases}$$

2.108 Equation of line through x_1, y_1 and parallel to the line:

$$Ax + By + C = 0 \quad \text{or} \quad y = ax + b,$$
$$A(x - x_1) + B(y - y_1) = 0 \quad \text{or} \quad y - y_1 = a(x - x_1).$$

2.109 Equation of line through x_1, y_1 and perpendicular to the line

$$Ax + By + C = 0 \quad \text{or} \quad y = ax + b,$$
$$B(x - x_1) - A(y - y_1) = 0 \quad \text{or} \quad y - y_1 = -\frac{x - x_1}{a}.$$

2.110 Equation of line through x_1, y_1 making an angle ϕ with the line $y = ax + b$:

$$y - y_1 = \frac{a + \tan \phi}{1 - a \tan \phi}(x - x_1).$$

2.111 Equation of line through the two points, x_1, y_1, and x_2, y_2:

$$y - y_1 = \frac{y_2 - y_1}{x_2 - x_1}(x - x_1).$$

2.112 Perpendicular distance from the point x_1, y_1 to the line

$$Ax + By + C = 0 \quad \text{or} \quad y = ax + b,$$

$$p = \frac{Ax_1 + By_1 + C}{\sqrt{A_2 + B_2}} \quad \text{or} \quad p = \frac{y_1 - ax_1 - b}{\sqrt{1 + a^2}}.$$

2.113 Polar equation of the line $y = ax + b$:

$$r = \frac{b \cos \alpha}{\sin (\theta - \alpha)},$$

where

$$\tan \alpha = a.$$

2.114 If p, the perpendicular to the line from the origin, makes an angle β with the axis:

$$p = r \cos(\theta - \beta).$$

2.130 Area of polygon whose vertices are at $x_1, y_1;\ x_2, y_2;\ \ldots\ldots\ldots\ x_n, y_n = A$.

$$2A = y_1(x_n - x_2) + y_2(x_1 - x_3) + y_3(x_2 - x_4) + \ldots\ldots + y_n(x_{n-1} - x_1).$$

PLANE CURVES

2.200 The equation of a plane curve in rectangular coördinates may be given in the forms:

(a) $y = f(x)$.

(b) $x = f_1(t),\ y = f_2(t)$. The parametric form.

(c) $F(x,y) = 0$.

2.201 If τ is the angle between the tangent to the curve and the x-axis:

(a) $\tan \tau = \dfrac{dy}{dx} = y'$.

(b) $\tan \tau = \dfrac{\dfrac{df_2(t)}{dt}}{\dfrac{df_1(t)}{dt}}$.

(c) $\tan \tau = -\dfrac{\dfrac{\partial F(x,y)}{\partial x}}{\dfrac{\partial F(x,y)}{\partial y}}$.

In the following formulas,

$$y' = \frac{dy}{dx} = \tan \tau \ \textbf{(2.201)}.$$

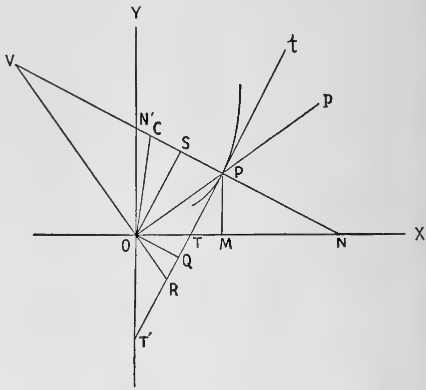

FIG. 2

2.202 $OM = x,\ MP = y$, angle $XTP = \tau$.

$$TP = y \csc \tau = \frac{y\sqrt{1 + y'^2}}{y'} = \text{tangent},$$

$$TM = y \cot \tau = \frac{y}{y'} = \text{subtangent},$$

$$PN = y \sec \tau = y\sqrt{1 + y'^2} = \text{normal},$$

$$MN = y \tan \tau = yy' = \text{subnormal}.$$

2.203 $OT = x - \dfrac{y}{y'}$ = intercept of tangent on x-axis,

$OT' = y - xy'$ = intercept of tangent on y-axis,

$ON = x + yy'$ = intercept of normal on x-axis,

$ON' = y + \dfrac{x}{y'}$ = intercept of normal on y-axis.

2.204 $OQ = \dfrac{y - xy'}{\sqrt{1 + y'^2}}$ = distance of tangent from origin = PS = projection of radius vector on normal.

Coördinates of Q: $\dfrac{y'(xy' - y)}{1 + y'^2}, \dfrac{y - xy'}{1 + y'^2}$.

2.205 $OS = \dfrac{x + yy'}{\sqrt{1 + y'^2}}$ = distance of normal from origin = PQ = projection of radius vector on tangent.

Coördinates of S: $\dfrac{x + yy'}{1 + y'^2}, \dfrac{(x + yy')y'}{1 + y'^2}$.

2.206 $OR = \dfrac{\sqrt{x^2 + y^2}\,(y - xy')}{x + yy'}$ = polar subtangent,

$PR = \dfrac{(x^2 + y^2)\sqrt{1 + y'^2}}{x + yy'}$ = polar tangent,

Coördinates of R: $\dfrac{y(xy' - y)}{x + yy'}, \dfrac{x(y - xy')}{x + yy'}$.

2.207 $OV = \dfrac{\sqrt{x^2 + y^2}\,(x + yy')}{y - xy'}$ = polar subnormal,

$PV = \dfrac{(x^2 + y^2)\sqrt{1 + y'^2}}{y - xy'}$ = polar normal,

Coördinates of V: $\dfrac{y(x + yy')}{y - xy'}, -\dfrac{x(x + yy')}{y - xy'}$.

2.210 The equations of the tangent at x_1, y_1 to the curve in the three forms of **2.200** are:

(a) $$y - y_1 = f'(x_1)\,(x - x_1).$$

(b) $$(y - y_1)f_1'(t_1) = (x - x_1)f_2'(t_1).$$

(c) $$(x - x_1)\left(\frac{\partial F}{\partial x}\right)_{\substack{x=x_1\\y=y_1}} + (y - y_1)\left(\frac{\partial F}{\partial y}\right)_{\substack{x=x_1\\y=y_1}} = 0.$$

2.211 The equations of the normal at x_1, y_1 to the curve in the three forms of **2.200** are:

(a) $$f'(x_1)\,(y - y_1) + (x - x_1) = 0.$$

(b) $$(y - y_1)f_2'(t_1) + (x - x_1)f_1'(t_1) = 0.$$

(c) $$(x - x_1)\left(\frac{\partial F}{\partial y}\right)_{\substack{x=x_1\\y=y_1}} = (y - y_1)\left(\frac{\partial F}{\partial x}\right)_{\substack{x=x_1\\y=y_1}}.$$

2.212 The perpendicular from the origin upon the tangent to the curve $F(x, y) = 0$ at the point x, y is:

$$p = \frac{x\frac{\partial F}{\partial x} + y\frac{\partial F}{\partial y}}{\sqrt{\left(\frac{\partial F}{\partial x}\right)^2 + \left(\frac{\partial F}{\partial y}\right)^2}}.$$

2.213 Concavity and Convexity. If in the neighborhood of a point P a curve lies entirely on one side of the tangent, it is concave or convex upwards according as $y'' = \frac{d^2y}{dx^2}$ is positive or negative. The positive direction of the axes are shown in figure 2.

2.220 Convention as to signs. The positive direction of the normal is related to the positive direction of the tangent as the positive y-axis is related to the positive x-axis. The angle τ is measured positively in the counter-clockwise direction from the positive x-axis to the positive tangent.

2.221 Radius of curvature $= \rho$; curvature $= 1/\rho$.

$$\frac{1}{\rho} = \frac{d\tau}{ds},$$

where s is the arc drawn from a fixed point of the curve in the direction of the positive tangent.

2.222 Formulas for the radius of curvature of curves given in the three forms of **2.200**.

(a)
$$\rho = \frac{\left\{1 + \left(\frac{dy}{dx}\right)^2\right\}^{\frac{3}{2}}}{\frac{d^2y}{dx^2}} = \frac{(1 + y'^2)^{\frac{3}{2}}}{y''}$$

(b)
$$\rho = \frac{\left\{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2\right\}^{\frac{3}{2}}}{\frac{dx}{dt}\frac{d^2y}{dt^2} - \frac{dy}{dt}\frac{d^2x}{dt^2}} = \frac{\left(\frac{ds}{dt}\right)^2}{\left\{\left(\frac{d^2x}{dt^2}\right)^2 + \left(\frac{d^2y}{dt^2}\right)^2 - \left(\frac{d^2s}{dt^2}\right)^2\right\}^{\frac{1}{2}}}$$

If s is taken as the parameter t:

(b′)
$$\frac{1}{\rho} = \frac{dx}{ds}\frac{d^2y}{ds^2} - \frac{dy}{ds}\frac{d^2x}{ds^2} = \left\{\left(\frac{d^2x}{ds^2}\right)^2 + \left(\frac{d^2y}{ds^2}\right)^2\right\}^{\frac{1}{2}}$$

(c)
$$\rho = -\frac{\left\{\left(\frac{\partial F}{\partial x}\right)^2 + \left(\frac{\partial F}{\partial y}\right)^2\right\}^{\frac{3}{2}}}{\frac{\partial^2 F}{\partial x^2}\left(\frac{\partial F}{\partial y}\right)^2 - 2\frac{\partial^2 F}{\partial x \partial y}\frac{\partial F}{\partial x}\frac{\partial F}{\partial y} + \frac{\partial^2 F}{\partial y^2}\left(\frac{\partial F}{\partial x}\right)^2}$$

2.223 The center of curvature is a point C (fig. 2) on the normal at P such that $PC = \rho$. If ρ is positive C lies on the positive normal (**2.213**); if negative, on the negative normal.

2.224 The circle of curvature is a circle with C as center and radius $= \rho$.

2.225 The chord of curvature is the chord of the circle of curvature passing through the origin and the point P.

2.226 The coördinates of the center of curvature at the point x, y are ξ, η:

$$\xi = x - \rho \sin \tau \qquad\qquad \tan \tau = \frac{dy}{dx}$$

$$\eta = y + \rho \cos \tau$$

If l', m' are the direction cosines of the positive normal,

$$\xi = x + l'\rho$$
$$\eta = y + m'\rho.$$

2.227 If l, m are the direction cosines of the positive tangent and l', m' those of the positive normal,

$$\frac{dl}{ds} = \frac{l'}{\rho}, \quad \frac{dm}{ds} = \frac{m'}{\rho}.$$

$$l' = m, \quad m' = -l,$$

$$\frac{dl'}{ds} = -\frac{l}{\rho}, \quad \frac{dm'}{ds} = -\frac{m}{\rho}$$

2.228 If the tangent and normal at P are taken as the x- and y- axes, then

$$\rho = \underset{x \to 0}{\text{limit}} \; \frac{x^2}{2y}$$

2.229 Points of Inflexion. For a curve given in the form (a) of **2.200** a point of inflexion is a point at which one at least of $\dfrac{d^2y}{dx^2}$ and $\dfrac{d^2x}{dy^2}$ exists and is continuous and at which one at least of $\dfrac{d^2y}{dx^2}$ and $\dfrac{d^2x}{dy^2}$ vanishes and changes sign.

If the curve is given in the form (b) a point of inflexion, t_1, is a point at which the determinant:

$$\begin{vmatrix} f_1''(t_1) & f_2''(t_1) \\ f_1'(t_1) & f_2'(t_1) \end{vmatrix}$$

vanishes and changes sign.

2.230 Eliminating x and y between the coördinates of the center of curvature (**2.226**) and the corresponding equations of the curve (**2.200**) gives the equation of the evolute of the curve – the locus of the center of curvature. A curve which has a given curve for evolute is called an involute of the given curve.

2.231 The envelope to a family of curves,

1. $$F(x, y, \alpha) = 0,$$

where α is a parameter, is obtained by eliminating α between (1) and

2. $$\frac{\partial F}{\partial \alpha} = 0.$$

2.232 If the curve is given in the form,

1. $$x = f_1(t, \alpha)$$

2. $$y = f_2(t, \alpha),$$

the envelope is obtained by eliminating t and α between (1), (2) and the functional determinant,

3. $$\frac{\partial(f_1, f_2)}{\partial(t, \alpha)} = 0 \quad \text{(see } \mathbf{1.370}\text{)}$$

2.233 Pedal Curves. The locus of the foot of the perpendicular from a fixed point upon the tangent to a given curve is the pedal of the given curve with reference to the fixed point.

2.240 Asymptotes. The line

$$y = ax + b$$

is an asymptote to the curve $y = f(x)$ if

$$a = \lim_{x \to \infty} f'(x)$$

$$b = \lim_{x \to \infty} [f(x) - xf'(x)]$$

2.241 If the curve is

$$x = f_1(t), \ y = f_2(t),$$

and if for a value of t, t_1, f_1 or f_2 becomes infinite, there will be an asymptote if for that value of t the direction of the tangent to the curve approaches a limit and the distance of the tangent from a fixed point approaches a limit.

2.242 An asymptote may sometimes be determined by expanding the equation of the curve in a series,

$$y = \sum_{k=0}^{n} a_k x^k + \sum_{k=1}^{\infty} \frac{b_k}{x^k}.$$

If

$$\lim_{x \to \infty} \sum_{k=1}^{\infty} \frac{b_k}{x^k} = 0,$$

the equation of the asymptote is

$$y = \sum_{k=0}^{n} a_k x^k$$

If of the first degree in x, this represents a rectilinear asymptote; if of a higher degree, a curvilinear asymptote.

2.250 Singular Points. If the equation of the curve is $F(x, y) = 0$, singular points are those for which

$$\frac{\partial F}{\partial x} = \frac{\partial F}{\partial y} = 0.$$

Put,

$$\Delta = \frac{\partial^2 F}{\partial x^2}\,\frac{\partial^2 F}{\partial y^2} - \left(\frac{\partial^2 F}{\partial x\,\partial y}\right)^2$$

If $\Delta < 0$ the singular point is a double point with two distinct tangents.

$\Delta > 0$ the singular point is an isolated point with no real branch of the curve through it.

$\Delta = 0$ the singular point is an osculating point, or a cusp. The curve has two branches, with a common tangent, which meet at the singular point.

If $\frac{\partial F}{\partial x}, \frac{\partial F}{\partial y}, \frac{\partial^2 F}{\partial x^2}, \frac{\partial^2 F}{\partial y^2}, \frac{\partial^2 F}{\partial x\,\partial y}$ simultaneously vanish at a point the singular point is one of higher order.

PLANE CURVES, POLAR COÖRDINATES

2.270 The equation of the curve is given in the form,

$$r = f(\theta).$$

In figure 2, $OP = r$, angle $XOP = \theta$, angle $XTP = \tau$, angle $pPt = \phi$.

2.271 θ is measured in the counter-clockwise direction from the initial line, OX, and s, the arc, is so chosen as to increase with θ. The angle ϕ is measured in the counter-clockwise direction from the positive radius vector to the positive tangent. Then,

$$\tau = \theta + \phi.$$

2.272

$$\tan\phi = \frac{r\,d\theta}{dr}$$

$$\sin\phi = \frac{r\,d\theta}{ds}$$

$$\cos\phi = \frac{dr}{ds}$$

2.273

$$\tan \tau = \frac{\sin\theta \dfrac{dr}{d\theta} + r\cos\theta}{\cos\theta \dfrac{dr}{d\theta} - r\sin\theta}$$

$$ds = \left\{ r^2 + \left(\frac{dr}{d\theta}\right)^2 \right\}^{\frac{1}{2}} d\theta$$

2.274

$$PR = r\sqrt{1 + \left(\frac{r\,d\theta}{dr}\right)^2} = \text{polar tangent}$$

$$PV = \sqrt{r^2 + \left(\frac{dr}{d\theta}\right)^2} = \text{polar normal}$$

$$OR = r^2\frac{d\theta}{dr} = \text{polar subtangent}$$

$$OV = \frac{dr}{d\theta} = \text{polar subnormal.}$$

2.275 $$OQ = \frac{r^2}{\sqrt{r^2 + \left(\dfrac{dr}{d\theta}\right)^2}} = p = \text{distance of tangent from origin.}$$

$$OS = \frac{r\dfrac{dr}{d\theta}}{\sqrt{r^2 + \left(\dfrac{dr}{d\theta}\right)^2}} = \text{distance of normal from origin.}$$

2.276 If $u = \dfrac{1}{r}$, the curve $r = f(\theta)$ is concave or convex to the origin according as

$$u + \frac{d^2u}{d\theta^2}$$

is positive or negative. At a point of inflexion this quantity vanishes and changes sign.

2.280 The radius of curvature is,

$$\rho = \frac{\left\{ r^2 + \left(\dfrac{dr}{d\theta}\right)^2 \right\}^{\frac{3}{2}}}{r^2 + 2\left(\dfrac{dr}{d\theta}\right)^2 - r\dfrac{d^2r}{d\theta^2}}.$$

2.281 If $u = \dfrac{1}{r}$ the radius of curvature is

$$\rho = \frac{\left\{ u^2 + \left(\dfrac{du}{d\theta}\right)^2 \right\}^{\frac{3}{2}}}{u^3\left(u + \dfrac{d^2u}{d\theta^2}\right)}.$$

2.282 If the equation of the curve is given in the form,

$$r = f(s)$$

where s is the arc measured from a fixed point of the curve,

$$\rho = \frac{r\sqrt{1 - \left(\frac{dr}{ds}\right)^2}}{r\frac{d^2r}{ds^2} + \left(\frac{dr}{ds}\right)^2 - 1}.$$

2.283 If p is the perpendicular from the origin upon the tangent to the curve,

1. $$\rho = r\frac{dr}{dp}$$ 2. $$\rho = p + \frac{d^2p}{d\tau^2}$$

2.284 If $u = \frac{1}{r}$

$$\frac{1}{p^2} = u^2 + \left(\frac{du}{d\theta}\right)^2$$

2.285
$$\frac{d^2u}{d\theta^2} + u = \frac{r^2}{p^3}\left(\frac{dp}{dr}\right)$$

2.286 Polar coördinates of the center of curvature, r_1, θ_1:

$$r_1^2 = \frac{r^2\left\{\left(\frac{dr}{d\theta}\right)^2 - r\frac{d^2r}{d\theta^2}\right\}^2 + \left(\frac{dr}{d\theta}\right)^2\left\{\left(\frac{dr}{d\theta}\right)^2 + r^2\right\}^2}{\left\{r^2 + 2\left(\frac{dr}{d\theta}\right)^2 - r\frac{d^2r}{d\theta^2}\right\}^2}$$

$$\theta_1 = \theta + \chi,$$

$$\tan\chi = \frac{\left(\frac{dr}{d\theta}\right)^3 + r^2\frac{dr}{d\theta}}{r\left(\frac{dr}{d\theta}\right)^2 - r^2\frac{d^2r}{d\theta^2}}.$$

2.287 If $2c$ is the chord of curvature (**2.225**):

$$2c = 2p\frac{dr}{dp} = 2\rho\frac{p}{r},$$

$$= 2\frac{u^2 + \left(\frac{du}{d\theta}\right)^2}{u^2\left(u + \frac{d^2u}{d\theta^2}\right)}.$$

2.290 Rectilinear Asymptotes. If r approaches ∞ as θ approaches an angle α, and if $r(\alpha - \theta)$ approaches a limit, b, then the straight line

$$r\sin(\alpha - \theta) = b$$

is an asymptote to the curve $r = f(\theta)$.

2.295 Intrinsic Equation of a plane curve. An intrinsic equation of a plane curve is one giving the radius of curvature, ρ, as a function of the arc, s,

$$\rho = f(s)$$

If τ is the angle between the x-axis and the positive tangent (**2.271**):

$$d\tau = \frac{ds}{f(s)} \qquad x = x_0 + \int_{s_0}^{s} \cos \tau \cdot ds$$

$$\tau = \tau_0 + \int_{s_0}^{s} \frac{ds}{f(s)} \qquad y = y_0 + \int_{s_0}^{s} \sin \tau \cdot ds.$$

2.300 The general equation of the second degree:

$$a_{11}x^2 + 2a_{12}xy + a_{22}y^2 + 2a_{13}x + 2a_{23}y + a_{33} = 0$$

$$A = \begin{vmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{vmatrix}; \qquad a_{hk} = a_{kh}$$

$$A_{hk} = \text{Minor of } a_{hk}.$$

Criterion giving the nature of the curve:

<table>
<tr><td></td><td colspan="3">$A_{33} \neq 0$</td><td colspan="3">$A_{33} = 0$</td></tr>
<tr><td rowspan="4">$A \neq 0$</td><td>$A_{33}<0$</td><td colspan="2">$A_{33}>0$</td><td colspan="3" rowspan="4">Parabola</td></tr>
<tr><td rowspan="3">Hyperbola</td><td colspan="2">$a_{11}A$ or $a_{22}A$</td></tr>
<tr><td><0</td><td>>0</td></tr>
<tr><td>Ellipse</td><td>Imaginary Curve</td></tr>
<tr><td rowspan="4">$A = 0$</td><td rowspan="2">$A_{33}<0$</td><td colspan="2" rowspan="2">$A_{33}>0$</td><td colspan="2">A_{11} or A_{22}</td><td rowspan="2">$A_{11} = A_{22} = 0$</td></tr>
<tr><td><0</td><td>>0</td></tr>
<tr><td>Pair of Real Straight Lines</td><td colspan="2">Pair of Imaginary Lines</td><td>Real</td><td>Imaginary</td><td rowspan="2">Double Line</td></tr>
<tr><td colspan="3">Intersection Finite</td><td colspan="2">Pair of Parallel Lines</td></tr>
</table>

(Pascal: Repertorium der höheren Mathematik, II, 1, p. 228)

2.400 Parabola (Fig. 3).

2.401 O, Vertex; F, Focus; ordinate through D, Directrix.

Equation of parabola, origin at O,

$$y^2 = 4ax$$
$$x = OM, \ y = MP,$$
$$OF = OD = a$$
$$FL = 2a = \text{semi latus rectum.}$$
$$FP = D'P.$$

2.402 $FP = FT = MD = x + a.$

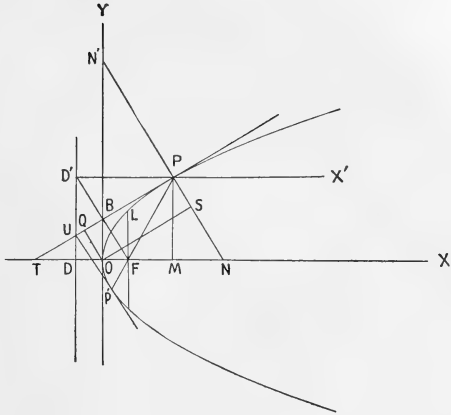

Fig. 3

$$NP = 2\sqrt{a(a+x)}, \ TM = 2x, \ MN = 2a, \ ON = x + 2a.$$

$$ON' = \sqrt{\frac{x}{a}}(x + 2a), \ OQ = x\sqrt{\frac{a}{a+x}}, \ OS = (x + 2a)\sqrt{\frac{x}{a+x}}.$$

FB perpendicular to tangent TP.

$$FB = \sqrt{a(a+x)}, \ TP = 2TB = 2\sqrt{x(a+x)}.$$

$$\overline{FB}^2 = FT \times FO = FP \times FO.$$

The tangents TP and UP' at the extremities of a focal chord PFP' meet on the directrix at U at right angles.

$$\tau = \text{angle } XTP.$$

$$\tan \tau = \sqrt{\frac{a}{x}}.$$

The tangent at P bisects the angles FPD' and FUD'.

2.403 Radius of curvature:

$$\rho = \frac{2(x+a)^{\frac{3}{2}}}{\sqrt{a}} = \frac{1}{4}\frac{\overline{NP}^3}{a^2}.$$

Coördinates of center of curvature:

$$\xi = 3x + 2a, \ \eta = -2x\sqrt{\frac{x}{a}}.$$

Equation of Evolute:

$$27ay^2 = 4(x - 2a)^3.$$

2.404 Length of arc of parabola measured from vertex,

$$s = \sqrt{x(x+a)} + a \log\left(\sqrt{1+\frac{x}{a}} + \sqrt{\frac{x}{a}}\right).$$

Area $OPMO = \frac{1}{3}xy$.

2.405 Polar equation of parabola:

$$r = FP,$$
$$\theta = \text{angle } XFP,$$
$$r = \frac{2a}{1 - \cos\theta}.$$

2.406 Equation of Parabola in terms of p, the perpendicular from F upon the tangent, and r, the radius vector FP:

$$\frac{l}{p^2} = \frac{2}{r}$$

l = semi latus rectum.

2.410 Ellipse (Fig. 4).

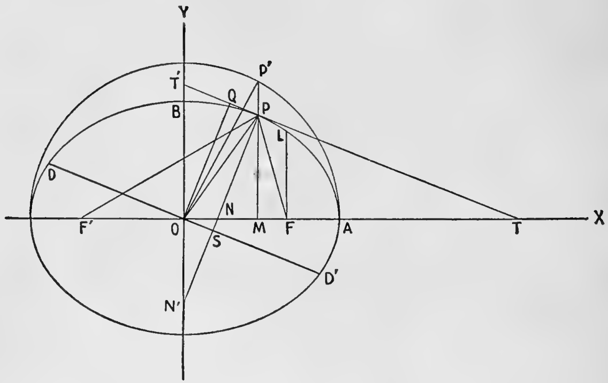

FIG. 4

2.411 O, Centre; F, F', Foci.

Equation of Ellipse origin at O:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$$

$$x = OM,\ y = MP,\ a = OA,\ b = OB.$$

2.412 Parametric Equations of Ellipse,

$$x = a \cos \phi, \qquad y = b \sin \phi.$$

ϕ = angle XOP', where P' is the point where the ordinate at P meets the eccentric circle, drawn with O as center and radius a.

2.413 $OF = OF' = ea$

$$e = \text{eccentricity} = \frac{\sqrt{a^2 - b^2}}{a},$$

$$FL = \frac{b^2}{a} = a(1 - e^2) = \text{semi latus rectum.}$$

$$F'P = a + ex,\ FP = a - ex,\ FP + F'P = 2a.$$

$$\tau = \text{angle } XTT'.$$

$$\tan \tau = -\frac{bx}{a\sqrt{a^2 - x^2}}.$$

$$NM = \frac{b^2x}{a^2},\ ON = e^2x,\ OT = \frac{a^2}{x},\ OT' = \frac{b^2}{y},\ MT = \frac{a^2 - x^2}{x},$$

$$PT = \frac{\sqrt{a^2 - x^2}\sqrt{a^2 - e^2x^2}}{x},\ ON' = \frac{e^2a}{b}\sqrt{a^2 - x^2},\ PS = \frac{ab}{\sqrt{a^2 - e^2x^2}},$$

$$OS = \frac{e^2x\sqrt{a^2 - x^2}}{\sqrt{a^2 - e^2x^2}}.$$

2.414 DD' parallel to $T'T$; DD' and PP' are conjugate diameters:

$$OD^2 = a^2 - e^2x^2 = FP \times F'P.$$

$$OP^2 + OD^2 = a^2 + b^2.$$

$$PS \times OD = ab.$$

Equation of Ellipse referred to conjugate diameters as axes:

$$\frac{x^2}{a'^2} + \frac{y^2}{b'^2} = 1 \qquad \alpha = \text{angle } XOP, \quad \beta = \text{angle } XOD$$

$$a' = OD' \qquad a'^2 = \frac{a^2b^2}{a^2 \sin^2 \alpha + b^2 \cos^2 \alpha} \qquad \tan \alpha \tan \beta = -\frac{b^2}{a^2}$$

$$b' = OP \qquad b'^2 = \frac{a^2b^2}{a^2 \sin^2 \beta + b^2 \cos^2 \beta}$$

2.415 Radius of curvature of Ellipse:

$$\rho = \frac{(a^4y^2 + b^4x^2)^{\frac{3}{2}}}{a^4b^4} = \frac{(a^2 - e^2x^2)^{\frac{3}{2}}}{ab}.$$

$$\text{angle } FPN = \text{angle } F'PN = \omega,$$

$$\tan \omega = \frac{eay}{b^2},$$

$$\frac{2}{\rho \cos \omega} = \frac{1}{FP} + \frac{1}{F'P}.$$

Coördinates of center of curvature:

$$\xi = \frac{c^2x^3}{a^2}, \ \eta = -\frac{a^2c^2y^3}{b^4}.$$

Equation of Evolute of Ellipse,

$$\left(\frac{ax}{c^2}\right)^{\frac{2}{3}} + \left(\frac{by}{c^2}\right)^{\frac{2}{3}} = 1.$$

2.416 Area of Ellipse, πab.

Length of arc of Ellipse,

$$s = a\int_0^\phi \sqrt{1 - e^2 \sin^2 \phi}\, d\phi.$$

2.417 Polar Equation of Ellipse,

$$r = F'P, \ \theta = \text{angle } XF'P,$$

$$r = \frac{a(1 - e^2)}{1 - e \cos \theta}$$

2.418

$$r = OP, \ \theta = \text{angle } XOP,$$

$$r = \frac{b}{\sqrt{1 - e^2 \cos^2 \theta}}$$

2.419 Equation of Ellipse in terms of p, the perpendicular from F upon the tangent at P, and r, the radius vector FP:

$$\frac{l}{p^2} = \frac{2}{r} - \frac{1}{a}.$$

l = semi latus rectum.

2.420 Hyperbola (Fig. 5).

2.421 O, Center; F, F', Foci.

Equation of hyperbola, origin at O,

$$\frac{x^2}{a^2} - \frac{y^2}{b^2} = 1$$

$$x = OM, \ y = MP, \ a = OA = OA'.$$

2.422 Parametric Equations of hyperbola,

$$x = a \cosh u, \ y = b \sinh u.$$

or

$$x = a \sec \phi, \ y = b \tan \phi.$$

ϕ = angle XOP', where P' is the point where the ordinate at T meets the circle of radius a, center O.

2.423 $OF = OF' = ea.$

$$e = \text{eccentricity} = \frac{\sqrt{a^2 + b^2}}{a}.$$

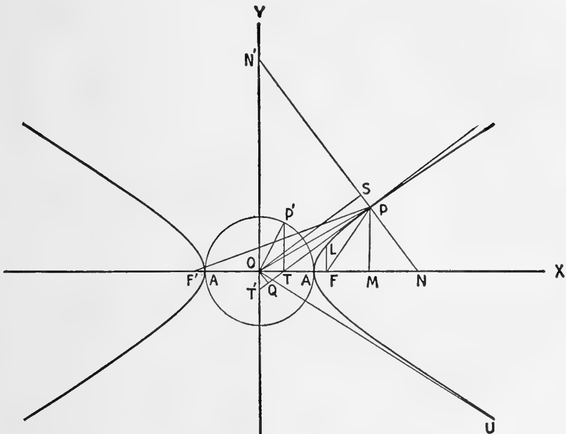

FIG. 5

$$FL = \frac{b^2}{a} = a(e^2 - 1) = \text{semi latus rectum.}$$

$$F'P = ex + a,\ FP = ex - a,\ F'P - FP = 2a.$$

$$\tau = \text{angle } XTP.$$

$$\tan \tau = \frac{bx}{a\sqrt{x^2 - a^2}}.$$

$$NM = \frac{b^2x}{a^2},\ ON = e^2x,\ OT = \frac{a^2}{x},\ OT' = \frac{b^2}{y},$$

$$MT = \frac{x^2 - a^2}{x},\ PT = \frac{\sqrt{x^2 - a^2}\sqrt{e^2x^2 - a^2}}{x},\quad ON' = \frac{e^2a}{b}\sqrt{x^2 - a^2},$$

$$PS = \frac{ab}{\sqrt{e^2x^2 - a^2}},\ OS = \frac{e^2x\sqrt{x^2 - a^2}}{\sqrt{e^2x^2 - a^2}}.$$

2.424 OU = Asymptote.

$$\tan XOU = \frac{b}{a}\cdot$$

b = distance of vertex A from asymptote.

2.425 Radius of curvature of hyperbola,

$$\rho = \frac{(e^2x^2 - a^2)^{\frac{3}{2}}}{ab}.$$

$$\text{angle } F'PT = \text{angle } FPT.$$

$$\text{angle } FPN = \omega = \frac{\pi}{2} - FPT.$$

$$\text{angle } F'PN = \omega' = \frac{\pi}{2} + F'PT.$$

$$\tan\ \omega = \frac{aey}{b^2}.$$

$$\cos\ \omega = \frac{b}{\sqrt{e^2x^2 - a^2}}$$

$$\frac{2}{\rho\ \cos\ \omega} = \frac{1}{FP} - \frac{1}{F'P}.$$

Coördinates of center of curvature,

$$\xi = \frac{e^2x^3}{a^2},\ \eta = -\frac{a^2e^2y^3}{b^4}.$$

Equation of Evolute of hyperbola,

$$\left(\frac{ax}{e^2}\right)^{\frac{2}{3}} - \left(\frac{by}{e^2}\right)^{\frac{2}{3}} = 1.$$

2.426 In a rectangular hyperbola $b = a$; the asymptotes are perpendicular to each other. Equation of rectangular hyperbola with asymptotes as axes and origin at O:

$$xy = \frac{a^2}{2}.$$

2.427 Length of arc of hyperbola,

$$s = \frac{b^2}{ae}\int_0^{\phi} \frac{\sec^2 \phi\ d\phi}{\sqrt{1 - k^2 \sin^2 \phi}},\quad k = \frac{1}{e},\quad \tan \phi = \frac{aey}{b^2}.$$

2.428 Polar Equation of hyperbola:

$$r = F'P,\quad \theta = XF'P,\quad r = a\,\frac{e^2 - 1}{e\ \cos\ \theta - 1},$$

$$r = OP,\quad \theta = XOP,\quad r^2 = \frac{b^2}{e^2\ \cos^2\ \theta - 1}.$$

2.429 Equation of right-hand branch of hyperbola in terms of p, the perpendicular from F upon the tangent at P and r, the radius vector FP,

$$\frac{l}{p^2} = \frac{2}{r} + \frac{1}{a}.$$

$$l = \text{semi latus rectum}.$$

2.450 Cycloids and Trochoids.

If a circle of radius a rolls on a straight line as base the extremity of any radius, a, describes a cycloid. The rectangular equation of a cycloid is:

$$x = a(\phi - \sin\phi),$$
$$y = a(1 - \cos\phi),$$

where the x-axis is the base with the origin at the initial point of contact. ϕ is the angle turned through by the moving circle. (Fig. 6.)

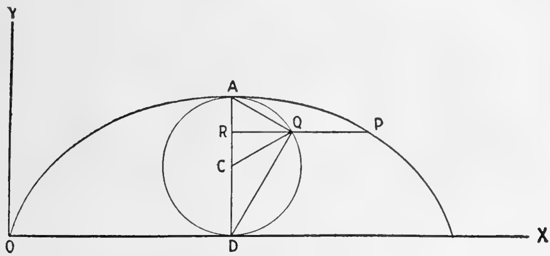

FIG. 6

A = vertex of cycloid.

C = center of generating circle, drawn tangent at A.

The tangent to the cycloid at P is parallel to the chord AQ.

Arc $AP = 2 \times$ chord AQ.

The radius of curvature at P is parallel to the chord QD and equal to $2 \times$ chord QD.

$PQ =$ circular arc AQ.

Length of cycloid: $s = 8a$; $a = CA$.

Area of cycloid: $S = 3\pi a^2$.

2.451 A point on the radius, $b>a$, describes a prolate trochoid. A point, $b<a$, describes a curtate trochoid. The general equation of trochoids and cycloids is

$$x = a\phi - (a+d)\sin\phi,$$
$$y = (a+d)(1-\cos\phi),$$
$$d = 0 \text{ Cycloid},$$
$$d>0 \text{ Prolate trochoid},$$
$$d<0 \text{ Curtate trochoid}.$$

Radius of curvature:

$$\rho = \frac{(2ay + d^2)^{\frac{3}{2}}}{ay + ad + d^2}.$$

2.452 Epi- and Hypocycloids. An epicycloid is described by a point on a circle of radius a that rolls on the convex side o a fixed circle of radius b. An hypocycloid is described by a point on a circle of radius a that rolls on the concave side of a fixed circle of radius b.

Equations of epi- and hypocycloids.

Upper sign: Epicycloid,
Lower sign: Hypocycloid.

$$x = (b \pm a) \cos \phi \mp \cos \frac{b \pm a}{a} \phi,$$

$$y = (b \pm a) \sin \phi - a \sin \frac{b \pm a}{a} \phi.$$

The origin is at the center of the fixed circle. The x-axis is the line joining the centers of the two circles in the initial position and ϕ is the angle turned through by the moving circle.

Radius of curvature:

$$\rho = \frac{2a(b \pm a)}{b \pm 2a} \sin \frac{a}{2b} \phi.$$

2.453 In the epicycloid put $b = a$. The curve becomes a Cardioid:

$$(x^2 + y^2)^2 - 6a^2(x^2 + y^2) + 8a^3x = 3a^4.$$

2.454 Catenary. The equation may be written:

1. $$y = \frac{1}{2} a(e^{\frac{x}{a}} + e^{-\frac{x}{a}}).$$

2. $$y = a \cosh \frac{x}{a}.$$

3. $$x = a \log \frac{y \pm \sqrt{y^2 - a^2}}{a}.$$

The radius of curvature, which is equal to the length of the normal, is:

$$\rho = a \cosh^2 \frac{x}{a}.$$

2.455 Spiral of Archimedes. A point moving uniformly along a line which rotates uniformly about a fixed point describes a spiral of Archimedes. The equation is:

$$r = a\theta,$$

or

$$\sqrt{x^2 + y^2} = a \tan^{-1} \frac{y}{x}.$$

The polar subtangent = polar subnormal = a.

Radius of curvature:

$$\rho = \frac{r(1 + \theta^2)^{\frac{3}{2}}}{\theta(2 + \theta^2)} = \frac{(r^2 + a^2)^{\frac{3}{2}}}{r^2 + 2a^2}.$$

2.456 Hyperbolic spiral:

$$r\theta = a.$$

2.457 Parabolic spiral:

$$r^2 = a^2\theta.$$

2.458 Logarithmic or equiangular spiral:

$r = ae^{n\theta}$,

$n = \cot\alpha = \text{const.}$,

α = angle tangent to curve makes with the radius vector.

2.459 Lituus:

$$r\sqrt{\theta} = a.$$

2.460 Neoid:

$$r = a + b\theta.$$

2.461 Cissoid:

$$(x^2 + y^2)x = 2ay^2,$$
$$r = 2a \tan\theta \sin\theta.$$

2.462 Cassinoid:

$$(x^2 + y^2 + a^2)^2 = 4a^2x^2 + b^4,$$
$$r^4 - 2a^2r^2 \cos 2\theta = b^4 - a^4.$$

2.463 Lemniscate ($b = a$ in Cassinoid):

$$(x^2 + y^2)^2 = 2a^2(x^2 - y^2),$$
$$r^2 = 2a^2 \cos 2\theta.$$

2.464 Conchoid:

$$x^2y^2 = (b + y)^2(a^2 - y^2).$$

2.465 Witch of Agnesi:

$$x^2y = 4a^2(2a - y).$$

2.466 Tractrix:

$$x = \tfrac{1}{2}a \log \frac{a + \sqrt{a^2 - y^2}}{a - \sqrt{a^2 - y^2}} - \sqrt{a^2 - y^2},$$

$$\frac{dy}{dx} = -\frac{y}{\sqrt{a^2 - y^2}},$$

$$\rho = \frac{a\sqrt{a^2 - y^2}}{y}.$$

SOLID GEOMETRY

2.600 The Plane. The general equation of the plane is:

$$Ax + By + Cz + D = 0.$$

2.601 l, m, n are the direction cosines of the normal to the plane and p is the perpendicular distance from the origin upon the plane.

$$l, m, n = \frac{A, B, C}{\sqrt{A^2 + B^2 + C^2}},$$

$$p = lx + my + nz,$$

$$p = -\frac{D}{\sqrt{A^2 + B^2 + C^2}}.$$

2.602 The perpendicular from the point x_1, y_1, z_1 upon the plane $Ax + By + Cz + D = 0$ is:

$$d = \frac{Ax_1 + By_1 + Cz_1 + D}{\sqrt{A^2 + B^2 + C^2}}.$$

2.603 θ is the angle between the two planes:

$$A_1x + B_1y + C_1z + D_1 = 0,$$
$$A_2x + B_2y + C_2z + D_2 = 0,$$

$$\cos\theta = \frac{A_1A_2 + B_1B_2 + C_1C_2}{\sqrt{A_1^2 + B_1^2 + C_1^2}\ \sqrt{A_2^2 + B_2^2 + C_2^2}}.$$

2.604 Equation of the plane passing through the three points (x_1, y_1, z_1) (x_2, y_2, z_2) (x_3, y_3, z_3):

$$x\begin{vmatrix} y_1 & z_1 & 1 \\ y_2 & z_2 & 1 \\ y_3 & z_3 & 1 \end{vmatrix} + y\begin{vmatrix} z_1 & x_1 & 1 \\ z_2 & x_2 & 1 \\ z_3 & x_3 & 1 \end{vmatrix} + z\begin{vmatrix} x_1 & y_1 & 1 \\ x_2 & y_2 & 1 \\ x_3 & y_3 & 1 \end{vmatrix} = \begin{vmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x_3 & y_3 & z_3 \end{vmatrix}$$

THE RIGHT LINE

2.620 The equations of a right line passing through the point x_1, y_1, z_1, and whose direction cosines are l, m, n are:

$$\frac{x - x_1}{l} = \frac{y - y_1}{m} = \frac{z - z_1}{n}.$$

2.621 θ is the angle between the two lines whose direction cosines are l_1, m_1, n_1 and l_2, m_2, n_2:

$$\cos\theta = l_1l_2 + m_1m_2 + n_1n_2,$$
$$\sin^2\theta = (l_1m_2 - l_2m_1)^2 + (m_1n_2 - m_2n_1)^2 + (n_1l_2 - n_2l_1)^2.$$

2.622 The direction cosines of the normal to the plane defined by the two lines whose direction cosines are l_1, m_1, n_1 and l_2, m_2n_2 are:

$$\frac{m_1n_2 - m_2n_1}{\sin\theta}, \quad \frac{n_1l_2 - n_2l_1}{\sin\theta}, \quad \frac{l_1m_2 - l_2m_1}{\sin\theta}.$$

2.623 The shortest distance between the two lines:

$$\frac{x - x_1}{l_1} = \frac{y - y_1}{m_1} = \frac{z - z_1}{n_1} \quad \text{and} \quad \frac{x - x_2}{l_2} = \frac{y - y_2}{m_2} = \frac{z - z_2}{n_2},$$

is:

$$d = \frac{(x_1 - x_2)(m_1n_2 - m_2n_1) + (y_1 - y_2)(n_1l_2 - n_2l_1) + (z_1 - z_2)(l_1m_2 - l_2m_1)}{\{(m_1n_2 - m_2n_1)^2 + (n_1l_2 - n_2l_1)^2 + (l_1m_2 - l_2m_1)^2\}^{\frac{1}{2}}},$$

2.624 The direction cosines of the shortest distance between the two lines are:

$$\frac{(m_1n_2 - n_2m_1),\ (n_1l_2 - n_2l_1),\ (l_1m_2 - l_2m_1)}{\{(m_1n_2 - m_2n_1)^2 + (n_1l_2 - n_2l_1)^2 + (l_1m_2 - l_2m_1)^2\}^{\frac{1}{2}}}.$$

2.625 The perpendicular distance from the point x_2, y_2, z_2 to the line:

$$\frac{x - x_1}{l_1} = \frac{y - y_1}{m_1} = \frac{z - z_1}{n_1}$$

is:

$$d = \{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2\}^{\frac{1}{2}} - \{l_1(x_2 - x_1) + m_1(y_2 - y_1) + n_1(z_2 - z_1)\}.$$

2.626 The direction cosines of the line passing through the two points x_1, y_1, z_1 and x_2, y_2, z_2 are:

$$\frac{(x_2 - x_1), \quad (y_2 - y_1), \quad (z_2 - z_1)}{\{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2\}^{\frac{1}{2}}}.$$

2.627 The two lines:

$$\begin{aligned} x &= m_1 z + p_1, \\ y &= n_1 z + q_1, \end{aligned} \quad \text{and} \quad \begin{aligned} x &= m_2 z + p_2, \\ y &= n_2 z + q_2, \end{aligned}$$

intersect at a point if,

$$(m_1 - m_2)(q_1 - q_2) - (n_1 - n_2)(p_1 - p_2) = 0.$$

The coördinates of the point of intersection are:

$$x = \frac{m_1 p_2 - m_2 p_1}{m_1 - m_2}, \quad y = \frac{n_1 q_2 - n_2 q_1}{n_1 - n_2}, \quad z = \frac{p_2 - p_1}{m_1 - m_2} = \frac{q_2 - q_1}{n_1 - n_2}.$$

The equation of the plane containing the two lines is then

$$(n_1 - n_2)(x - m_1 z - p_1) = (m_1 - m_2)(y - n_1 z - q_1).$$

SURFACES

2.640 A single equation in x, y, z represents a surface:

$$F(x, y, z) = 0.$$

2.641 The direction cosines of the normal to the surface are:

$$l, m, n = \frac{\dfrac{\partial F}{\partial x}, \quad \dfrac{\partial F}{\partial y}, \quad \dfrac{\partial F}{\partial z}}{\left\{\left(\dfrac{\partial F}{\partial x}\right)^2 + \left(\dfrac{\partial F}{\partial y}\right)^2 + \left(\dfrac{\partial F}{\partial z}\right)^2\right\}^{\frac{1}{2}}}.$$

2.642 The perpendicular from the origin upon the tangent plane at x, y, z is:

$$p = lx + my + nz.$$

2.643 The two principal radii of curvature of the surface $F(x, y, z) = 0$ are given by the two roots of:

$$\begin{vmatrix} \frac{k}{\rho} + \frac{\partial^2 F}{\partial x^2} & \frac{\partial^2 F}{\partial x \partial y} & \frac{\partial^2 F}{\partial x \partial z} & \frac{\partial F}{\partial x} \\ \frac{\partial^2 F}{\partial x \partial y} & \frac{k}{\rho} + \frac{\partial^2 F}{\partial y^2} & \frac{\partial^2 F}{\partial y \partial z} & \frac{\partial F}{\partial y} \\ \frac{\partial^2 F}{\partial x \partial z} & \frac{\partial^2 F}{\partial y \partial z} & \frac{k}{\rho} + \frac{\partial^2 F}{\partial z^2} & \frac{\partial F}{\partial z} \\ \frac{\partial F}{\partial x} & \frac{\partial F}{\partial y} & \frac{\partial F}{\partial z} & 0 \end{vmatrix} = 0,$$

where:

$$k^2 = \left(\frac{\partial F}{\partial x}\right)^2 + \left(\frac{\partial F}{\partial y}\right)^2 + \left(\frac{\partial F}{\partial z}\right)^2.$$

2.644 The coördinates of each center of curvature are:

$$\xi = x + \frac{\rho}{k}\frac{\partial F}{\partial x}, \qquad \eta = y + \frac{\rho}{k}\frac{\partial F}{\partial y}, \qquad \zeta = z + \frac{\rho}{k}\frac{\partial F}{\partial z}.$$

2.645 The envelope of a family of surfaces:

1. $$F(x, y, z, \alpha) = 0$$

is found by eliminating α between (1) and

2. $$\frac{\partial F}{\partial \alpha} = 0.$$

2.646 The characteristic of a surface is a curve defined by the two equations (1) and (2) in **2.645**.

2.647 The envelope of a family of surfaces with two variable parameters, α, β, is obtained by eliminating α and β between:

1. $$F(x, y, z, \alpha, \beta) = 0.$$

2. $$\frac{\partial F}{\partial \alpha} = 0.$$

3. $$\frac{\partial F}{\partial \beta} = 0.$$

2.648 The equations of a surface may be given in the parametric form:

$$x = f_1(u, v), \quad y = f_2(u, v), \quad z = f_3(u, v).$$

The equation of a tangent plane at x_1, y_1, z_1 is:

$$(x - x_1)\frac{\partial(f_2, f_3)}{\partial(u, v)} + (y - y_1)\frac{\partial(f_3, f_1)}{\partial(u, v)} + (z - z_1)\frac{\partial(f_1, f_2)}{\partial(u, v)} = 0,$$

where

$$\frac{\partial(f_2, f_3)}{\partial(u, v)} = \begin{vmatrix} \frac{\partial f_2}{\partial u} & \frac{\partial f_2}{\partial v} \\ \frac{\partial f_3}{\partial u} & \frac{\partial f_3}{\partial v} \end{vmatrix}, \text{ etc.}$$ See **1.370**.

2.649 The direction cosines to the normal to the surface in the form **2.648** are:

$$l,\ m,\ n = \frac{\dfrac{\partial(f_2, f_3)}{\partial(u, v)},\ \dfrac{\partial(f_3, f_1)}{\partial(u, v)},\ \dfrac{\partial(f_1, f_2)}{\partial(u, v)}}{\left\{\left(\dfrac{\partial(f_2, f_3)}{\partial(u, v)}\right)^2 + \left(\dfrac{\partial(f_3, f_1)}{\partial(u, v)}\right)^2 + \left(\dfrac{\partial(f_1, f_2)}{\partial(u, v)}\right)^2\right\}^{\frac{1}{2}}}.$$

2.650 If the equation of the surface is:

$$z = f(x, y),$$

the equation of the tangent plane at x_1, y_1, z_1 is:

$$z - z_1 = \left(\frac{\partial f}{\partial x}\right)_1 (x - x_1) + \left(\frac{\partial f}{\partial y}\right)_1 (y - y_1).$$

2.651 The direction cosines of the normal to the surface in the form **2.650** are:

$$l,\ m,\ n = \frac{-\left(\dfrac{\partial f}{\partial x}\right),\ -\left(\dfrac{\partial f}{\partial y}\right),\ +1}{\left\{1 + \left(\dfrac{\partial f}{\partial x}\right)^2 + \left(\dfrac{\partial f}{\partial y}\right)^2\right\}^{\frac{1}{2}}}.$$

2.652 The two principal radii of curvature of the surface in the form **2.650** are given by the two roots of:

$$(rt - s^2)\rho^2 - \{(1 + q^2)r - 2pqs + (1 + p^2)t\}\sqrt{1 + p^2 + q^2}\,\rho + (1 + p^2 + q^2)^2 = 0,$$

where

$$p = \frac{\partial f}{\partial x},\quad q = \frac{\partial f}{\partial y},\quad r = \frac{\partial^2 f}{\partial x^2},\quad s = \frac{\partial^2 f}{\partial x \partial y},\quad t = \frac{\partial^2 f}{\partial y^2}.$$

2.653 If ρ_1 and ρ_2 are the two principal radii of curvature of a surface, and ρ is the radius of curvature in a plane making an angle ϕ with the plane of ρ_1,

$$\frac{1}{\rho} = \frac{\cos^2\phi}{\rho_1} + \frac{\sin^2\phi}{\rho_2}.$$

2.654 If ρ and ρ' are the radii of curvature in any two mutually perpendicular planes, and ρ_1 and ρ_2 the two principal radii of curvature:

$$\frac{1}{\rho} + \frac{1}{\rho'} = \frac{1}{\rho_1} + \frac{1}{\rho_2}.$$

2.655 Gauss's measure of the curvature of a surface is:

$$\frac{1}{\rho} = \frac{1}{\rho_1\rho_2}.$$

SPACE CURVES

2.670 The equations of a space curve may be given in the forms:

(a) $F_1(x, y, z) = 0, \quad F_2(x, y, z) = 0.$

(b) $x = f_1(t), \quad y = f_2(t), \quad z = f_3(t).$

(c) $y = \phi(x), \quad z = \psi(x).$

2.671 The direction cosines of the tangent to a space curve in the form (a) are:

$$l = \frac{\dfrac{\partial F_1}{\partial y}\dfrac{\partial F_2}{\partial z} - \dfrac{\partial F_1}{\partial z}\dfrac{\partial F_2}{\partial y}}{T},$$

$$m = \frac{\dfrac{\partial F_1}{\partial z}\dfrac{\partial F_2}{\partial x} - \dfrac{\partial F_1}{\partial x}\dfrac{\partial F_2}{\partial z}}{T},$$

$$n = \frac{\dfrac{\partial F_1}{\partial x}\dfrac{\partial F_2}{\partial y} - \dfrac{\partial F_1}{\partial y}\dfrac{\partial F_2}{\partial x}}{T},$$

where T is the positive root of:

$$T^2 = \left\{\left(\frac{\partial F_1}{\partial x}\right)^2 + \left(\frac{\partial F_1}{\partial y}\right)^2 + \left(\frac{\partial F_1}{\partial z}\right)^2\right\}\left\{\left(\frac{\partial F_2}{\partial x}\right)^2 + \left(\frac{\partial F_2}{\partial y}\right)^2 + \left(\frac{\partial F_2}{\partial z}\right)^2\right\}$$
$$- \left\{\frac{\partial F_1}{\partial x}\frac{\partial F_2}{\partial x} + \frac{\partial F_1}{\partial y}\frac{\partial F_2}{\partial y} + \frac{\partial F_1}{\partial z}\frac{\partial F_2}{\partial z}\right\}^2.$$

2.672 The direction cosines of the tangent to a space curve in the form (b) are:

$$l,\ m,\ n = \frac{x',\ y',\ z'}{\{x'^2 + y'^2 + z'^2\}^{\frac{1}{2}}},$$

where the accents denote differentials with respect to t.

2.673 If s, the length of arc measured from a fixed point on the curve is the parameter, t:

$$l,\ m,\ n = \frac{dx}{ds},\ \frac{dy}{ds},\ \frac{dz}{ds}.$$

2.674 The principal radius of curvature of a space curve in the form (b) is:

$$\rho = \frac{(x'^2 + y'^2 + z'^2)^{\frac{3}{2}}}{\{(y'z'' - z'y'')^2 + (z'x'' - x'z'')^2 + (x'y'' - y'x'')^2\}^{\frac{1}{2}}}$$

$$= \frac{s'^2}{(x''^2 + y''^2 + z''^2 - s''^2)^{\frac{1}{2}}}.$$

where the double accents denote second differentials with respect to t, and s, the length of arc, is a function of t.

2.675 When $t = s$:

$$\frac{1}{\rho} = \left\{\left(\frac{d^2x}{ds^2}\right)^2 + \left(\frac{d^2y}{ds^2}\right)^2 + \left(\frac{d^2z}{ds^2}\right)^2\right\}^{\frac{1}{2}}$$

2.676 The direction cosines of the principal normal to the space curve in the form (b) are:

$$l' = \frac{z'(z'x'' - x'z'') - y'(x'y'' - y'x'')}{L},$$

$$m' = \frac{x'(x'y'' - y'x'') - z'(y'z'' - z'y'')}{L},$$

$$n' = \frac{y'(y'z'' - z'y'') - x'(z'x'' - x'z'')}{L},$$

where

$$L = \{x'^2 + y'^2 + z'^2\}^{\frac{1}{2}}\{(y'z'' - z'y'')^2 + (z'x'' - x'z'')^2 + (x'y'' - y'x'')^2\}^{\frac{1}{2}}.$$

2.677 The direction cosines of the binormal to the curve in the form (b) are:

$$l'' = \frac{y'z'' - z'y''}{S},$$

$$m'' = \frac{z'x'' - x'z''}{S},$$

$$n'' = \frac{x'y'' - y'x''}{S},$$

where

$$S = \{(y'z'' - z'y'')^2 + (z'x'' - x'z'')^2 + (x'y'' - y'x'')^2\}^{\frac{1}{2}}.$$

2.678 If s, the distance measured along the curve from a fixed point on it is the parameter, t:

$$l' = \rho\frac{d^2x}{ds^2}, \quad m' = \rho\frac{d^2y}{ds^2}, \quad n' = \rho\frac{d^2z}{ds^2},$$

where ρ is the principal radius of curvature; and

$$l'' = \rho\left(\frac{dy}{ds}\frac{d^2z}{ds^2} - \frac{dz}{ds}\frac{d^2y}{ds^2}\right),$$

$$m'' = \rho\left(\frac{dz}{ds}\frac{d^2x}{ds^2} - \frac{dx}{ds}\frac{d^2z}{ds^2}\right),$$

$$n'' = \rho\left(\frac{dx}{ds}\frac{d^2y}{ds^2} - \frac{dy}{ds}\frac{d^2x}{ds^2}\right).$$

2.679 The radius of torsion, or radius of second curvature of a space curve is:

$$\tau = \frac{(x'^2 + y'^2 + z'^2)^{\frac{1}{2}}}{\left\{\left(\frac{\partial l''}{\partial t}\right)^2 + \left(\frac{\partial m''}{\partial t}\right)^2 + \left(\frac{\partial n''}{\partial t}\right)^2\right\}^{\frac{1}{2}}}$$

$$= -\frac{1}{S^2}\begin{vmatrix} x' & y' & z' \\ x'' & y'' & z'' \\ x''' & y''' & z''' \end{vmatrix},$$

where S is given in **2.677**.

2.680 When $t = s$:

$$\frac{1}{\tau} = \left\{\left(\frac{\partial l''}{\partial s}\right)^2 + \left(\frac{\partial m''}{\partial s}\right)^2 + \left(\frac{\partial n''}{\partial s}\right)^2\right\}^{\frac{1}{2}}$$

$$= -\rho^2 \begin{vmatrix} \frac{dx}{ds} & \frac{dy}{ds} & \frac{dz}{ds} \\ \frac{d^2x}{ds^2} & \frac{d^2y}{ds^2} & \frac{d^2z}{ds^2} \\ \frac{d^3x}{ds^3} & \frac{d^3y}{ds^3} & \frac{d^3z}{ds^3} \end{vmatrix}.$$

2.681 The direction cosines of the tangent to a space curve in the form (c) are:

$$l,\ m,\ n = \frac{1,\ y',\ z'}{\sqrt{1 + y'^2 + z'^2}}$$

where accents denote differentials with respect to x:

$$y' = \frac{d\phi(x)}{dx}, \quad z' = \frac{d\psi(x)}{dx}.$$

2.682 The principal radius of curvature of a space curve in the form (c) is:

$$\rho = \left\{ \frac{(1 + y'^2 + z'^2)^3}{(y'z'' - z'y'')^2 + y''^2 + z''^2} \right\}^{\frac{1}{2}}.$$

2.683 The radius of torsion of a space curve in the form (c) is:

$$\tau = \frac{(1 + y'^2 + z'^2)^3}{\rho^2(y''z''' - z''y''')}.$$

2.690 The relation between the direction cosines of the tangent, principal normal and binormal to a space curve is:

$$\begin{vmatrix} l & m & n \\ l' & m' & n' \\ l'' & m'' & n'' \end{vmatrix} = 1.$$

2.691 The tangent, principal normal and binormal all being mutually perpendicular the relations of **2.00** hold among their direction cosines.

III. TRIGONOMETRY

3.00 $\tan x = \dfrac{\sin x}{\cos x}$, $\sec x = \dfrac{1}{\cos x}$, $\csc x = \dfrac{1}{\sin x}$, $\cot x = \dfrac{1}{\tan x}$,

$\sec^2 x = 1 + \tan^2 x$, $\csc^2 x = 1 + \cot^2 x$, $\sin^2 x + \cos^2 x = 1$,

$\operatorname{versin} x = 1 - \cos x$, $\operatorname{coversin} x = 1 - \sin x$, $\operatorname{haversin} x = \sin^2 \dfrac{x}{2}$.

3.01 $$\sin x = -\sin(-x) = \sqrt{\frac{1 - \cos 2x}{2}} = 2\sqrt{\cos^2 \frac{x}{2} - \cos^4 \frac{x}{2}},$$

$$= 2 \sin \frac{x}{2} \cos \frac{x}{2} = \frac{\tan x}{\sqrt{1 + \tan^2 x}} = \frac{2 \tan \frac{x}{2}}{1 + \tan^2 \frac{x}{2}},$$

$$= \frac{1}{\sqrt{1 + \cot^2 x}} = \frac{1}{\cot \frac{x}{2} - \cot x} = \frac{1}{\tan \frac{x}{2} + \cot x},$$

$$= \cot \frac{x}{2} \cdot (1 - \cos x) = \tan \frac{x}{2} \cdot (1 + \cos x),$$

$$= \sin y \cos(x - y) + \cos y \sin(x - y),$$

$$= \cos y \sin(x + y) - \sin y \cos(x + y),$$

$$= -\tfrac{1}{2} i\,(e^{ix} - e^{-ix}).$$

3.02 $$\cos x = \cos(-x) = \sqrt{\frac{1 + \cos 2x}{2}} = 1 - 2 \sin^2 \frac{x}{2},$$

$$= \cos^2 \frac{x}{2} - \sin^2 \frac{x}{2} = 2 \cos^2 \frac{x}{2} - 1 = \frac{1}{\sqrt{1 + \tan^2 x}},$$

$$= \frac{1 - \tan^2 \frac{x}{2}}{1 + \tan^2 \frac{x}{2}} = \frac{1}{1 + \tan x \tan \frac{x}{2}} = \frac{1}{\tan x \cot \frac{x}{2} - 1},$$

$$= \frac{\cot \frac{x}{2} - \tan \frac{x}{2}}{\cot \frac{x}{2} + \tan \frac{x}{2}} = \frac{\cot x}{\sqrt{1 + \cot^2 x}} = \frac{\sin 2x}{2 \sin x},$$

$$= \cos y \cos(x + y) + \sin y \sin(x + y),$$

$$= \cos y \cos(x - y) - \sin y \sin(x - y),$$

$$= \tfrac{1}{2}(e^{ix} + e^{-ix}).$$

3.03 $\tan x = -\tan(-x) = \dfrac{\sin 2x}{1+\cos 2x} = \dfrac{1-\cos 2x}{\sin 2x}, =$

$$\sqrt{\frac{1-\cos 2x}{1+\cos 2x}} = \frac{\sin(x+y)+\sin(x-y)}{\cos(x+y)+\cos(x-y)},$$

$$= \frac{\cos(x-y)-\cos(x+y)}{\sin(x+y)-\sin(x-y)} = \cot x - 2\cot 2x,$$

$$= \frac{\tan\frac{x}{2}}{1-\tan\frac{x}{2}} + \frac{\tan\frac{x}{2}}{1+\tan\frac{x}{2}} = \frac{2\tan\frac{x}{2}}{1-\tan^2\frac{x}{2}},$$

$$= \frac{1}{1-\tan\frac{x}{2}} - \frac{1}{1+\tan\frac{x}{2}},$$

$$= i\,\frac{1-e^{2ix}}{1+e^{2ix}}.$$

3.04 The values of five trigonometric functions in terms of the sixth are given in the following table. (For signs, see **3.05**.)

	$\sin x = a$	$\cos x = a$	$\tan x = a$	$\cot x = a$	$\sec x = a$	$\csc x = a$
$\sin x =$	a	$\sqrt{1-a^2}$	$\frac{a}{\sqrt{1+a^2}}$	$\frac{1}{\sqrt{1+a^2}}$	$\frac{\sqrt{a^2-1}}{a}$	$\frac{1}{a}$
$\cos x =$	$\sqrt{1-a^2}$	a	$\frac{1}{\sqrt{1+a^2}}$	$\frac{a}{\sqrt{1+a^2}}$	$\frac{1}{a}$	$\frac{\sqrt{a^2-1}}{a}$
$\tan x =$	$\frac{a}{\sqrt{1-a^2}}$	$\frac{\sqrt{1-a^2}}{a}$	a	$\frac{1}{a}$	$\sqrt{a^2-1}$	$\frac{1}{\sqrt{a^2-1}}$
$\cot x =$	$\frac{\sqrt{1-a^2}}{a}$	$\frac{a}{\sqrt{1-a^2}}$	$\frac{1}{a}$	a	$\frac{1}{\sqrt{a^2-1}}$	$\sqrt{a^2-1}$
$\sec x =$	$\frac{1}{\sqrt{1-a^2}}$	$\frac{1}{a}$	$\sqrt{1+a^2}$	$\frac{\sqrt{1+a^2}}{a}$	a	$\frac{a}{\sqrt{a^2-1}}$
$\csc x =$	$\frac{1}{a}$	$\frac{1}{\sqrt{1-a^2}}$	$\frac{\sqrt{1+a^2}}{a}$	$\sqrt{1+a^2}$	$\frac{a}{\sqrt{a^2-1}}$	a

3.05 The trigonometric functions are periodic, the periods of the sin, cos, sec, csc being 2π, and those of the tan and cot, π. Their signs may be determined from the following table. In using formulas giving any of the trigonometric functions by the root of some quantity, the proper sign may be taken from this table.

	$0°$	$0-\frac{\pi}{2}$ $0-90°$	$\frac{\pi}{2}$ $90°$	$\frac{\pi}{2}-\pi$ $90°-180°$	π $180°$	$\pi-\frac{3}{2}\pi$ $180°-270°$	$\frac{3}{2}\pi$ $270°$	$\frac{3}{2}\pi-2\pi$ $270°-360°$	2π $360°$
sin	0	+	1	+	0	−	−1	−	0
cos	1	+	0	−	−1	−	0	+	1
tan	0	+	$\pm\infty$	−	0	+	$\pm\infty$	−	0
cot	$\mp\infty$	+	0	−	$\mp\infty$	+	0	−	$\mp\infty$
sec	1	+	$\pm\infty$	−	−1	−	$\pm\infty$	+	1
csc	$\mp\infty$	+	1	+	$\pm\infty$	−	−1	−	$\mp\infty$

3.10 Functions of Half an Angle. (See **3.05** for signs.)

3.101

$$\sin\frac{1}{2}x=\pm\sqrt{\frac{1-\cos x}{2}},$$

$$=\frac{1}{2}\left\{\pm\sqrt{1+\sin x}\mp\sqrt{1-\sin x}\right\}$$

$$=\pm\sqrt{\frac{1}{2}\left(1-\frac{1}{\pm\sqrt{1+\tan^2 x}}\right)}$$

3.102

$$\cos\frac{1}{2}x=\pm\sqrt{\frac{1+\cos x}{2}},$$

$$=\frac{1}{2}\left\{\pm\sqrt{1+\sin x}\pm\sqrt{1-\sin x}\right\},$$

$$=\pm\sqrt{\frac{1}{2}\left(1+\frac{1}{\pm\sqrt{1+\tan^2 x}}\right)}.$$

3.103

$$\tan\frac{1}{2}x=\pm\sqrt{\frac{1-\cos x}{1+\cos x}},$$

$$= \frac{\sin x}{1 + \cos x} = \frac{1 - \cos x}{\sin x},$$

$$= \frac{\pm\sqrt{1 + \tan^2 x} - 1}{\tan x}.$$

3.11 Functions of the Sum and Difference of Two Angles.

3.111

$$\sin (x \pm y) = \sin x \cos y \pm \cos x \sin y,$$
$$= \cos x \cos y (\tan x \pm \tan y),$$
$$= \frac{\tan x \pm \tan y}{\tan x \mp \tan y} \sin (x \mp y),$$
$$= \frac{1}{2}\left\{ \cos (x + y) + \cos (x - y) \right\} (\tan x \pm \tan y).$$

3.112

$$\cos (x \pm y) = \cos x \cos y \mp \sin x \sin y,$$
$$= \cos x \cos y (1 \mp \tan x \tan y),$$
$$= \frac{\cot x \mp \tan y}{\cot x \pm \tan y} \cos (x \mp y),$$
$$= \frac{\cot y \mp \tan x}{\cot y \tan x \mp 1} \sin (x \mp y),$$
$$= \cos x \sin y (\cot y \mp \tan x).$$

3.113

$$\tan (x \pm y) = \frac{\tan x \pm \tan y}{1 \mp \tan x \tan y},$$
$$= \frac{\cot y \pm \cot x}{\cot x \cot y \mp 1},$$
$$= \frac{\sin 2x \pm \sin 2y}{\cos 2x + \cos 2y}.$$

3.114

$$\cot (x \pm y) = \frac{\cot x \cot y \mp 1}{\cot y \pm \cot x},$$
$$= -\frac{\sin 2x \mp \sin 2y}{\cos 2x - \cos 2y}.$$

3.115 The cosine and sine of the sum of any number of angles in terms of the sine and cosine of the angles are given by the real and imaginary parts of

$$\cos (x_1 + x_2 + \ldots + x_n) + i \sin (x_1 + x_2 + \ldots + x_n)$$
$$= (\cos x_1 + i \sin x_1)(\cos x_2 + i \sin x_2) \ldots\ldots (\cos x_n + i \sin x_n)$$

3.12 Sums and Differences of Trigonometric Functions.

3.121
$$\sin x \pm \sin y = 2 \sin \tfrac{1}{2}(x \pm y) \cos \tfrac{1}{2}(x \mp y),$$
$$= (\cos x + \cos y) \tan \tfrac{1}{2}(x \pm y),$$
$$= (\cos y - \cos x) \cot \tfrac{1}{2}(x \mp y),$$
$$= \frac{\tan \frac{1}{2}(x \pm y)}{\tan \frac{1}{2}(x \mp y)} (\sin x \mp \sin y).$$

3.122
$$\cos x + \cos y = 2 \cos \tfrac{1}{2}(x + y) \cos \tfrac{1}{2}(x - y),$$
$$= \frac{\sin x \pm \sin y}{\tan \frac{1}{2}(x \pm y)},$$
$$= \frac{\cot \frac{1}{2}(x + y)}{\tan \frac{1}{2}(x - y)} (\cos y - \cos x).$$

3.123
$$\cos x - \cos y = 2 \sin \tfrac{1}{2}(y + x) \sin \tfrac{1}{2}(y - x)$$
$$= -(\sin x \pm \sin y) \tan \tfrac{1}{2}(x \mp y).$$

3.124
$$\tan x \pm \tan y = \frac{\sin (x \pm y)}{\cos x \cdot \cos y}.$$
$$= \frac{\sin (x \pm y)}{\sin (x \mp y)} (\tan x \mp \tan y),$$
$$= \tan y \tan (x \pm y)(\cot y \mp \tan x),$$
$$= \frac{1 \mp \tan x \tan y}{\cot (x \pm y)},$$
$$= (1 \mp \tan x \tan y) \tan (x \pm y).$$

3.125
$$\cot x \pm \cot y = \pm \frac{\sin (x \pm y)}{\sin x \sin y}.$$

3.130

1. $$\frac{\sin x \pm \sin y}{\cos x + \cos y} = \tan \tfrac{1}{2}(x \pm y).$$

2. $$\frac{\sin x \pm \sin y}{\cos x - \cos y} = -\cot \tfrac{1}{2}(x \mp y).$$

3. $$\frac{\sin x + \sin y}{\sin x - \sin y} = \frac{\tan \frac{1}{2}(x + y)}{\tan \frac{1}{2}(x - y)}.$$

3.140

1. $$\sin^2 x + \sin^2 y = 1 - \cos(x+y)\cos(x-y).$$

2. $$\sin^2 x - \sin^2 y = \cos^2 y - \cos^2 x = \sin(x+y)\sin(x-y).$$

3. $$\cos^2 x - \sin^2 y = \cos(x+y)\cos(x-y).$$

4. $$\sin^2(x+y) + \sin^2(x-y) = 1 - \cos 2x \cos 2y.$$

5. $$\sin^2(x+y) - \sin^2(x-y) = \sin 2x \sin 2y.$$

6. $$\cos^2(x+y) + \cos^2(x-y) = 1 + \cos 2x \cos 2y.$$

7. $$\cos^2(x+y) - \cos^2(x-y) = -\sin 2x \sin 2y.$$

3.150

1. $$\cos nx \cos mx = \tfrac{1}{2}\cos(n-m)x + \tfrac{1}{2}\cos(n+m)x.$$

2. $$\sin nx \sin mx = \tfrac{1}{2}\cos(n-m)x - \tfrac{1}{2}\cos(n+m)x.$$

3. $$\cos nx \sin mx = \tfrac{1}{2}\sin(n+m)x - \tfrac{1}{2}\sin(n-m)x.$$

3.160

1. $$e^{x+iy} = e^x(\cos y + i \sin y).$$

2. $$a^{x+iy} = a^x\{\cos(y\log a) + i\sin(y\log a)\}.$$

3. $$(\cos x \pm i\sin x)^n = \cos nx \pm i \sin nx$$
[De Moivre's Theorem].

4. $$\sin(x \pm iy) = \sin x \cosh y \pm i \cos x \sinh y.$$

5. $$\cos(x \pm iy) = \cos x \cosh y \mp i \sin x \sinh y.$$

6. $$\cos x = \tfrac{1}{2}(e^{ix} + e^{-ix}).$$

7. $$\sin x = -\frac{i}{2}(e^{ix} - e^{-ix}).$$

8. $$e^{ix} = \cos x + i \sin x.$$

9. $$e^{-ix} = \cos x - i \sin x.$$

3.170 Sines and Cosines of Multiple Angles.

3.171 n an even integer:

$$\sin nx = n\cos x\left\{\sin x - \frac{(n^2-2^2)}{3!}\sin^3 x + \frac{(n^2-2^2)(n^2-4^2)}{5!}\sin^5 x - \ldots\right\}.$$

$$\cos nx = 1 - \frac{n^2}{2!}\sin^2 x + \frac{n^2(n^2-2^2)}{4!}\sin^4 x - \frac{n^2(n^2-2^2)(n^2-4^2)}{6!}\sin^6 x + \ldots$$

3.172 n an odd integer:

$$\sin nx = n\left\{\sin x - \frac{(n^2-1^2)}{3!}\sin^3 x + \frac{(n^2-1^2)(n^2-3^2)}{5!}\sin^5 x - \ldots\right\}.$$

$$\cos nx = \cos x\left\{1 - \frac{(n^2-1^2)}{2!}\sin^2 x + \frac{(n^2-1^2)(n^2-3^2)}{4!}\sin^4 x - \ldots\right\}.$$

3.173 n an even integer:

$$\sin nx = (-1)^{\frac{n}{2}-1}\cos x\left\{2^{n-1}\sin^{n-1} x - \frac{(n-2)}{1!}2^{n-3}\sin^{n-3} x + \frac{(n-3)(n-4)}{2!}2^{n-5}\sin^{n-5} x - \frac{(n-4)(n-5)(n-6)}{3!}2^{n-7}\sin^{n-7} x + \ldots\right\}.$$

$$\cos nx = (-1)^{\frac{n}{2}}\left\{2^{n-1}\sin^n x - \frac{n}{1!}2^{n-3}\sin^{n-2} x + \frac{n(n-3)}{2!}2^{n-5}\sin^{n-4} x - \frac{n(n-3)(n-5)}{3!}2^{n-7}\sin^{n-6} x + \ldots\right\}.$$

3.174 n an odd integer:

$$\sin nx = (-1)^{\frac{n-1}{2}}\left\{2^{n-1}\sin^n x - \frac{n}{1!}2^{n-3}\sin^{n-2} x + \frac{n(n-3)}{2!}2^{n-5}\sin^{n-4} x - \frac{n(n-3)(n-5)}{3!}2^{n-7}\sin^{n-6} x + \ldots\right\}.$$

$$\cos nx = (-1)^{\frac{n-1}{2}}\cos x\left\{2^{n-1}\sin^{n-1} x - \frac{n-2}{1!}2^{n-3}\sin^{n-3} x + \frac{(n-3)(n-4)}{2!}2^{n-5}\sin^{n-5} x - \frac{(n-4)(n-5)(n-6)}{3!}2^{n-7}\sin^{n-7} x + \ldots\right\}.$$

3.175 n any integer:

$$\sin nx = \sin x\left\{2^{n-1}\cos^{n-1} x - \frac{n-2}{1!}2^{n-3}\cos^{n-3} x + \frac{(n-3)(n-4)}{2!}2^{n-5}\cos^{n-5} x - \frac{(n-4)(n-5)(n-6)}{3!}2^{n-7}\cos^{n-7} x + \ldots\right\}.$$

$$\cos nx = 2^{n-1}\cos^n x - \frac{n}{1!}2^{n-3}\cos^{n-2} x + \frac{n(n-3)}{2!}2^{n-5}\cos^{n-4} x - \frac{n(n-4)(n-5)}{3!}2^{n-7}\cos^{n-6} x + \ldots.$$

3.176

$$\sin 2x = 2 \sin x \cos x.$$

$$\begin{aligned} \sin 3x &= \sin x(3 - 4 \sin^2 x) \\ &= \sin x(4 \cos^2 x - 1). \end{aligned}$$

$$\sin 4x = \sin x(8 \cos^3 x - 4 \cdot \cos x).$$

$$\begin{aligned} \sin 5x &= \sin x(5 - 20 \sin^2 x + 16 \sin^4 x) \\ &= \sin x(16 \cos^4 x - 12 \cos^2 x + 1). \end{aligned}$$

$$\sin 6x = \sin x(32 \cos^5 x - 32 \cos^3 x + 6 \cos x).$$

3.177

$$\begin{aligned} \cos 2x &= \cos^2 x - \sin^2 x \\ &= 1 - 2 \sin^2 x \\ &= 2 \cos^2 x - 1. \end{aligned}$$

$$\begin{aligned} \cos 3x &= \cos x(4 \cos^2 x - 3) \\ &= \cos x(1 - 4 \sin^2 x). \end{aligned}$$

$$\cos 4x = 8 \cos^4 x - 8 \cos^2 x + 1.$$

$$\begin{aligned} \cos 5x &= \cos x(16 \cos^4 x - 20 \cos^2 x + 5) \\ &= \cos x(16 \sin^4 x - 12 \sin^2 x + 1). \end{aligned}$$

$$\cos 6x = 32 \cos^6 x - 48 \cos^4 x + 18 \cos^2 x - 1.$$

3.178

$$\tan 2x = \frac{2 \tan x}{1 - \tan^2 x}$$

$$\cot 2x = \frac{\cot^2 x - 1}{2 \cot x}.$$

3.180 Integral Powers of Sine and Cosine.

3.181 n an even integer:

$$\sin^n x = \frac{(-1)^{\frac{n}{2}}}{2^{n-1}} \left\{ \cos nx - n \cos (n-2)x + \frac{n(n-1)}{2!} \cos (n-4)x \right.$$
$$\left. - \frac{n(n-1)(n-2)}{3!} \cos (n-6)x + \ldots\ldots + (-1)^{\frac{n}{2}} \frac{1}{2} \frac{n!}{\left(\frac{n}{2}\right)! \left(\frac{n}{2}\right)!} \right\}$$

$$\cos^n x = \frac{1}{2^{n-1}} \left\{ \cos nx + n \cos (n-2)x + \frac{n(n-1)}{2!} \cos (n-4)x \right.$$
$$\left. + \frac{n(n-1)(n-2)}{3!} \cos (n-6)x + \ldots + \frac{1}{2} \frac{n!}{\left(\frac{n}{2}\right)! \left(\frac{n}{2}\right)!} \cdot \right\}$$

3.182 n an odd integer:

$$\sin^n x = \frac{(-1)^{\frac{n-1}{2}}}{2^{n-1}}\left\{\sin nx - n\sin(n-2)x + \frac{n(n-1)}{2!}\sin(n-4)x\right.$$

$$\left. - \frac{n(n-1)(n-2)}{3!}\sin(n-6)x + \ldots + (-1)^{\frac{n-1}{2}}\frac{n!}{\left(\frac{n-1}{2}\right)!\left(\frac{n+1}{2}\right)!}\sin x\right\}.$$

$$\cos^n x = \frac{1}{2^{n-1}}\left\{\cos nx + n\cos(n-2)x + \frac{n(n-1)}{2!}\cos(n-4)x\right.$$

$$\left. + \frac{n(n-1)(n-2)}{3!}\cos(n-6)x + \ldots + \frac{n!}{\left(\frac{n-1}{2}\right)!\left(\frac{n+1}{2}\right)!}\cos x\right\}.$$

3.183

$$\sin^2 x = \tfrac{1}{2}(1 - \cos 2x).$$

$$\sin^3 x = \tfrac{1}{4}(3\sin x - \sin 3x).$$

$$\sin^4 x = \tfrac{1}{8}(\cos 4x - 4\cos 2x + 3).$$

$$\sin^5 x = \tfrac{1}{16}(\sin 5x - 5\sin 3x + 10\sin x).$$

$$\sin^6 x = -\tfrac{1}{32}(\cos 6x - 6\cos 4x + 15\cos 2x - 10).$$

3.184

$$\cos^2 x = \tfrac{1}{2}(1 + \cos 2x).$$

$$\cos^3 x = \tfrac{1}{4}(3\cos x + \cos 3x).$$

$$\cos^4 x = \tfrac{1}{8}(3 + 4\cos 2x + \cos 4x).$$

$$\cos^5 x = \tfrac{1}{16}(10\cos x + 5\cos 3x + \cos 5x).$$

$$\cos^6 x = \tfrac{1}{32}(10 + 15\cos 2x + 6\cos 4x + \cos 6x).$$

INVERSE CIRCULAR FUNCTIONS

3.20 The inverse circular and logarithmic functions are multiple valued; i.e., if

$$0 < \sin^{-1} x < \frac{\pi}{2},$$

the solution of $x = \sin\theta$ is:

$$\theta = 2n\pi + \sin^{-1} x,$$

where n is a positive integer. In the following formulas the cyclic constants are omitted.

3.21

$$\sin^{-1} x = -\sin^{-1}(-x) = \frac{\pi}{2} - \cos^{-1}x = \cos^{-1}\sqrt{1-x^2}$$

$$= \frac{\pi}{2} - \sin^{-1}\sqrt{1-x^2} = \frac{\pi}{4} + \frac{1}{2}\sin^{-1}(2x^2-1)$$

$$= \frac{1}{2}\cos^{-1}(1-2x^2) = \tan^{-1}\frac{x}{\sqrt{1-x^2}}$$

$$= 2\tan^{-1}\left\{\frac{1-\sqrt{1-x^2}}{x}\right\} = \frac{1}{2}\tan^{-1}\left\{\frac{2x\sqrt{1-x^2}}{1-2x^2}\right\}$$

$$= \cot^{-1}\frac{\sqrt{1-x^2}}{x} = \frac{\pi}{2} - i\log(x+\sqrt{x^2-1}).$$

3.22

$$\cos^{-1} x = \pi - \cos^{-1}(-x) = \frac{\pi}{2} - \sin^{-1} x = \frac{1}{2}\cos^{-1}(2x^2-1)$$

$$= 2\cos^{-1}\sqrt{\frac{1+x}{2}} = \sin^{-1}\sqrt{1-x^2} = \tan^{-1}\frac{\sqrt{1-x^2}}{x}$$

$$= 2\tan^{-1}\sqrt{\frac{1-x}{1+x}} = \frac{1}{2}\tan^{-1}\left\{\frac{2x\sqrt{1-x^2}}{2x^2-1}\right\} = \cot^{-1}\frac{x}{\sqrt{1-x^2}}$$

$$= i\log(x+\sqrt{x^2-1}) = \pi - i\log(\sqrt{x^2-1}-x).$$

3.23

$$\tan^{-1} x = -\tan^{-1}(-x) = \sin^{-1}\frac{x}{\sqrt{1+x^2}} = \cos^{-1}\frac{1}{\sqrt{1+x^2}}$$

$$= \frac{1}{2}\sin^{-1}\frac{2x}{1+x^2} = \frac{\pi}{2} - \cot^{-1} x = \sec^{-1}\sqrt{1+x^2}$$

$$= \frac{\pi}{2} - \tan^{-1}\frac{1}{x} = \frac{1}{2}\cos^{-1}\frac{1-x^2}{1+x^2}$$

$$= 2\cos^{-1}\left\{\frac{1+\sqrt{1+x^2}}{2\sqrt{1+x^2}}\right\}^{\frac{1}{2}} = 2\sin^{-1}\left\{\frac{\sqrt{1+x^2}-1}{2\sqrt{1+x^2}}\right\}^{\frac{1}{2}}$$

$$= \frac{1}{2}\tan^{-1}\frac{2x}{1-x^2} = 2\tan^{-1}\left\{\frac{\sqrt{1+x^2}-1}{x}\right\}$$

$$= -\tan^{-1} c + \tan^{-1}\frac{x+c}{1-cx}$$

$$= \frac{1}{2}i\log\frac{1-ix}{1+ix} = \frac{1}{2}i\log\frac{i+x}{i-x} = -\frac{1}{2}i\log\frac{1+ix}{1-ix}.$$

3.25

1. $$\sin^{-1} x \pm \sin^{-1} y = \sin^{-1}\{x\sqrt{1 - y^2} \pm y\sqrt{1 - x^2}\}.$$

2. $$\cos^{-1} x \pm \cos^{-1} y = \cos^{-1}\{xy \mp \sqrt{(1 - x^2)(1 - y^2)}\}.$$

3. $$\sin^{-1} x \pm \cos^{-1} y = \sin^{-1}\{xy \pm \sqrt{(1 - x^2)(1 - y^2)}\} = \cos^{-1}\{y\sqrt{1 - x^2} \mp x\sqrt{1 - y^2}\}.$$

4. $$\tan^{-1} x \pm \tan^{-1} y = \tan^{-1} \frac{x \pm y}{1 \mp xy}.$$

5. $$\tan^{-1} x \pm \cot^{-1} y = \tan^{-1} \frac{xy \pm 1}{y \mp x} = \cot^{-1} \frac{y \mp x}{xy \pm 1}.$$

HYPERBOLIC FUNCTIONS

3.30 Formulas for the hyperbolic functions may be obtained from the corresponding formulas for the circular functions by replacing x by ix and using the following relations:

1. $$\sin ix = \tfrac{1}{2}i(e^x - e^{-x}) = i \sinh x.$$

2. $$\cos ix = \tfrac{1}{2}(e^x + e^{-x}) = \cosh x.$$

3. $$\tan ix = \frac{i(e^{2x} - 1)}{e^{2x} + 1} = i \tanh x.$$

4. $$\cot ix = -i\frac{e^{2x} + 1}{e^{2x} - 1} = -i \coth x.$$

5. $$\sec ix = \frac{2}{e^x + e^{-x}} = \operatorname{sech} x.$$

6. $$\csc ix = -\frac{2i}{e^x - e^{-x}} = -i \operatorname{csch} x.$$

7. $$\sin^{-1} ix = i \sinh^{-1} x = i \log (x + \sqrt{1 + x^2}).$$

8. $$\cos^{-1} ix = -i \cosh^{-1} x = \frac{\pi}{2} - i \log (x + \sqrt{1 + x^2}).$$

9. $$\tan^{-1} ix = i \tanh^{-1} x = i \log \sqrt{\frac{1 + x}{1 - x}}.$$

10. $$\cot^{-1} ix = -i \coth^{-1} x = -i \log \sqrt{\frac{x + 1}{x - 1}}.$$

3.310 The values of five hyperbolic functions in terms of the sixth are given in the following table:

	$\sinh x = a$	$\cosh x = a$	$\tanh x = a$	$\coth x = a$	$\operatorname{sech} x = a$	$\operatorname{csch} x = a$
$\sinh x =$	a	$\sqrt{a^2 - 1}$	$\frac{a}{\sqrt{1 - a^2}}$	$\frac{1}{\sqrt{a^2 - 1}}$	$\frac{\sqrt{1 - a^2}}{a}$	$\frac{1}{a}$
$\cosh x =$	$\sqrt{1 + a^2}$	a	$\frac{1}{\sqrt{1 - a^2}}$	$\frac{a}{\sqrt{a^2 - 1}}$	$\frac{1}{a}$	$\frac{\sqrt{1 + a^2}}{a}$
$\tanh x =$	$\frac{a}{\sqrt{1 + a^2}}$	$\frac{\sqrt{a^2 - 1}}{a}$	a	$\frac{1}{a}$	$\sqrt{1 - a^2}$	$\frac{1}{\sqrt{1 + a^2}}$
$\coth x =$	$\frac{\sqrt{a^2 + 1}}{a}$	$\frac{a}{\sqrt{a^2 - 1}}$	$\frac{1}{a}$	a	$\frac{1}{\sqrt{1 - a^2}}$	$\sqrt{1 + a^2}$
$\operatorname{sech} x =$	$\frac{1}{\sqrt{1 + a^2}}$	$\frac{1}{a}$	$\sqrt{1 - a^2}$	$\frac{\sqrt{a^2 - 1}}{a}$	a	$\frac{a}{\sqrt{1 + a^2}}$
$\operatorname{csch} x =$	$\frac{1}{a}$	$\frac{1}{\sqrt{a^2 - 1}}$	$\frac{\sqrt{1 - a^2}}{a}$	$\sqrt{a^2 - 1}$	$\frac{a}{\sqrt{1 - a^2}}$	a

3.311 Periodicity of the Hyperbolic Functions.

The functions $\sinh x$, $\cosh x$, $\operatorname{sech} x$, $\operatorname{csch} x$ have an imaginary period $2\pi i$, e.g.:

$$\cosh x = \cosh (x + 2\pi i n),$$

where n is any integer. The functions $\tanh x$, $\coth x$ have an imaginary period πi.

The values of the hyperbolic functions for the argument 0, $\frac{\pi}{2}i$, πi, $\frac{3\pi i}{2}$, are given in the following table:

	0	$\frac{\pi}{2} i$	πi	$3 \frac{\pi}{2} i$
sinh	0	i	0	$-i$
cosh	1	0	-1	0
tanh	0	$\infty \cdot i$	0	$\infty \cdot i$
coth	∞	0	∞	0
sech	1	∞	-1	∞
csch	∞	$-i$	∞	i

3.320

1. $$\sinh \frac{1}{2}x = \sqrt{\frac{\cosh x - 1}{2}}$$

2. $$\cosh \frac{1}{2}x = \sqrt{\frac{\cosh x + 1}{2}}$$

3. $$\tanh \frac{1}{2}x = \frac{\cosh x - 1}{\sinh x} = \frac{\sinh x}{\cosh x + 1} = \sqrt{\frac{\cosh x - 1}{\cosh x + 1}}.$$

3.33

1. $$\sinh (x \pm y) = \sinh x \cosh y \pm \cosh x \sinh y.$$

2. $$\cosh (x \pm y) = \cosh x \cosh y \pm \sinh x \sinh y.$$

3. $$\tanh (x \pm y) = \frac{\tanh x \pm \tanh y}{1 \pm \tanh x \tanh y}.$$

4. $$\coth (x \pm y) = \frac{\coth x \coth y \pm 1}{\coth y \pm \coth x}.$$

3.34

1. $$\sinh x + \sinh y = 2 \sinh \tfrac{1}{2}(x + y) \cosh \tfrac{1}{2}(x - y).$$

2. $$\sinh x - \sinh y = 2 \cosh \tfrac{1}{2}(x + y) \sinh \tfrac{1}{2}(x - y).$$

3. $$\cosh x + \cosh y = 2 \cosh \tfrac{1}{2}(x + y) \cosh \tfrac{1}{2}(x - y).$$

4. $$\cosh x - \cosh y = 2 \sinh \tfrac{1}{2}(x + y) \sinh \tfrac{1}{2}(x - y).$$

5. $$\tanh x + \tanh y = \frac{\sinh (x + y)}{\cosh x \cosh y}.$$

6. $$\tanh x - \tanh y = \frac{\sinh (x - y)}{\cosh x \cosh y}.$$

7. $$\coth x + \coth y = \frac{\sinh (x + y)}{\sinh x \sinh y}.$$

8. $$\coth x - \coth y = -\frac{\sinh (x - y)}{\sinh x \sinh y}.$$

3.35

1. $$\sinh(x+y) + \sinh(x-y) = 2\sinh x \cosh y.$$

2. $$\sinh(x+y) - \sinh(x-y) = 2\cosh x \sinh y.$$

3. $$\cosh(x+y) + \cosh(x-y) = 2\cosh x \cosh y.$$

4. $$\cosh(x+y) - \cosh(x-y) = 2\sinh x \sinh y.$$

5. $$\tanh \tfrac{1}{2}(x \pm y) = \frac{\sinh x \pm \sinh y}{\cosh x + \cosh y}.$$

6. $$\coth \tfrac{1}{2}(x \pm y) = \frac{\sinh x \mp \sinh y}{\cosh x - \cosh y}.$$

7. $$\frac{\tanh x + \tanh y}{\tanh x - \tanh y} = \frac{\sinh(x+y).}{\sinh(x-y).}$$

8. $$\frac{\coth x + \coth y}{\coth x - \coth y} = -\frac{\sinh(x+y)}{\sinh(x-y)}.$$

3.36

1. $$\sinh(x+y) + \cosh(x+y) = (\cosh x + \sinh x)(\cosh y + \sinh y).$$

2. $$\sinh(x+y)\sinh(x-y) = \sinh^2 x - \sinh^2 y$$
$$= \cosh^2 x - \cosh^2 y.$$

3. $$\cosh(x+y)\cosh(x-y) = \cosh^2 x + \sinh^2 y$$
$$= \sinh^2 x + \cosh^2 y.$$

4. $$\sinh x + \cosh x = \frac{1 + \tanh \frac{1}{2}x}{1 - \tanh \frac{1}{2}x}.$$

5. $$(\sinh x + \cosh x)^n = \cosh nx + \sinh nx.$$

3.37

1. $$e^x = \cosh x + \sinh x.$$

2. $$e^{-x} = \cosh x - \sinh x.$$

3. $$\sinh x = \tfrac{1}{2}(e^x - e^{-x}).$$

4. $$\cosh x = \tfrac{1}{2}(e^x + e^{-x}).$$

3.38

1. $$\sinh 2x = 2 \sinh x \cosh x, \quad = \frac{2 \tanh x}{1 - \tanh^2 x}.$$

2. $$\cosh 2x = \cosh^2 x + \sinh^2 x = 2 \cosh^2 x - 1, \quad = 1 + 2 \sinh^2 x, \quad = \frac{1 + \tanh^2 x}{1 - \tanh^2 x}.$$

3. $$\tanh 2x = \frac{2 \tanh x}{1 + \tanh^2 x}.$$

4. $$\sinh 3x = 3 \sinh x + 4 \sinh^3 x.$$

5. $$\cosh 3x = 4 \cosh^3 x - 3 \cosh x.$$

6. $$\tanh 3x = \frac{3 \tanh x + \tanh^3 x}{1 + 3 \tanh^2 x}.$$

3.40 Inverse Hyperbolic Functions.

The hyperbolic functions being periodic, the inverse functions are multiple valued (**3.311**). In the following formulas the periodic constants are omitted, the principal values only being given.

1. $$\sinh^{-1} x = \log (x + \sqrt{x^2 + 1}) = \cosh^{-1} \sqrt{x^2 + 1}.$$

2. $$\cosh^{-1} x = \log (x + \sqrt{x^2 - 1}) = \sinh^{-1} \sqrt{x^2 - 1}.$$

3. $$\tanh^{-1} x = \log \sqrt{\frac{1 + x}{1 - x}}.$$

4. $$\coth^{-1} x = \log \sqrt{\frac{x + 1}{x - 1}} = \tanh^{-1} \frac{1}{x}.$$

5. $$\operatorname{sech}^{-1} x = \log \left(\frac{1}{x} + \sqrt{\frac{1}{x^2} - 1} \right) = \cosh^{-1} \frac{1}{x}.$$

6. $$\operatorname{csch}^{-1} x = \log \left(\frac{1}{x} + \sqrt{\frac{1}{x^2} + 1} \right) = \sinh^{-1} \frac{1}{x}.$$

3.41

1. $$\sinh^{-1} x \pm \sinh^{-1} y = \sinh^{-1}(x\sqrt{1 + y^2} \pm y\sqrt{1 + x^2}).$$

2. $$\cosh^{-1} x \pm \cosh^{-1} y = \cosh^{-1} (xy \pm \sqrt{(x^2 - 1)(y^2 - 1)}).$$

3. $$\tanh^{-1} x \pm \tanh^{-1} y = \tanh^{-1} \frac{x \pm y}{1 \pm xy}.$$

3.42

1. $$\cosh^{-1} \frac{1}{2}\left(x + \frac{1}{x}\right) = \sinh^{-1} \frac{1}{2}\left(x - \frac{1}{x}\right),$$

$$= \tanh^{-1} \frac{x^2 - 1}{x^2 + 1} = 2 \tanh^{-1} \frac{x - 1}{x + 1},$$

$$= \log x.$$

2. $$\cosh^{-1} \csc 2x = -\sinh^{-1} \cot 2x = -\tanh^{-1} \cos 2x,$$

$$= \log \tan x.$$

3. $$\tanh^{-1} \tan^2 \left(\frac{\pi}{4} + \frac{x}{2}\right) = \frac{1}{1} \log \csc x.$$

4. $$\tanh^{-1} \tan^2 \frac{x}{2} = \frac{1}{2} \log \sec x.$$

3.43 The Gudermannian.

If,

1. $$\cosh x = \sec \theta.$$

2. $$\sinh x = \tan \theta.$$

3. $$e^x = \sec \theta + \tan \theta = \tan \left(\frac{\pi}{4} + \frac{\theta}{2}\right).$$

4. $$x = \log \tan \left(\frac{\pi}{4} + \frac{\theta}{2}\right).$$

5. $$\theta = \operatorname{gd} x.$$

3.44

1. $$\sinh x = \tan \operatorname{gd} x.$$

2. $$\cosh x = \sec \operatorname{gd} x.$$

3. $$\tanh x = \sin \operatorname{gd} x.$$

4. $$\tanh \frac{x}{2} = \tan \frac{1}{2} \operatorname{gd} x.$$

5. $$c^x = \frac{1 + \sin \operatorname{gd} x}{\cos \operatorname{gd} x} = \frac{1 - \cos\left(\frac{\pi}{2} + \operatorname{gd} x\right)}{\sin\left(\frac{\pi}{2} + \operatorname{gd} x\right)}.$$

6. $\tanh^{-1} \tan x = \frac{1}{2} \operatorname{gd} 2x.$

7. $\tan^{-1} \tanh x = \frac{1}{2} \operatorname{gd}^{-1} 2x.$

SOLUTION OF OBLIQUE PLANE TRIANGLES

3.50

a, b, c = Sides of triangle,

α, β, γ = angles opposite to a, b, c, respectively,

A = area of triangle,

$s = \frac{1}{2}(a + b + c).$

Given	*Sought*	*Formula*
a, b, c	α	$\sin \frac{1}{2} \alpha = \sqrt{\frac{(s-b)(s-c)}{bc}}.$
		$\cos \frac{1}{2} \alpha = \sqrt{\frac{s(s-a)}{bc}}.$
		$\tan \frac{1}{2} \alpha = \sqrt{\frac{(s-b)(s-c)}{s(s-a)}}.$
		$\cos \alpha = \frac{c^2 + b^2 - a^2}{2bc}.$
	A	$A = \sqrt{s(s-a)(s-b)(s-c)}.$
a, b, α	β	$\sin \beta = \frac{b \sin \alpha}{a}.$ When $a>b$, $\beta<\frac{\pi}{2}$ and but one value results. When $b>a$ β has two values.
	γ	$\gamma = 180^\circ - (\alpha + \beta).$
	c	$c = \frac{a \sin \gamma}{\sin \alpha}.$
	A	$A = \frac{1}{2} ab \sin \gamma.$
a, α, β	b	$b = \frac{a \sin \beta}{\sin \alpha}$
	γ	$\gamma = 180^\circ - (\alpha + \beta).$
	c	$c = \frac{a \sin \gamma}{\sin \alpha} = \frac{a \sin (\alpha + \beta)}{\sin \alpha}.$

Given	Sought	Formula
	A	$A = \frac{1}{2} ab \sin \gamma = \frac{1}{2} a^2 \frac{\sin \beta \sin \gamma}{\sin \alpha}.$
a, b, γ	α	$\tan \alpha = \frac{a \sin \gamma}{b - a \cos \gamma}.$
	α, β	$\frac{1}{2}(\alpha + \beta) = 90° - \frac{1}{2}\gamma.$
		$\tan \frac{1}{2}(\alpha - \beta) = \frac{a - b}{a + b} \cot \frac{1}{2}\gamma$
	c	$c = (a^2 + b^2 - 2ab \cos \gamma)^{\frac{1}{2}}.$
		$= \{(a + b)^2 - 4ab \cos^2 \frac{1}{2}\gamma\}^{\frac{1}{2}}$
		$= \{(a - b)^2 + 4ab \sin^2 \frac{1}{2}\gamma\}^{\frac{1}{2}}.$
		$= \frac{a - b}{\cos \phi}$ where $\tan \phi = 2\sqrt{ab} \frac{\sin \frac{1}{2}\gamma}{a - b}$
		$= \frac{a \sin \gamma}{\sin \alpha}.$
	A	$A = \frac{1}{2} ab \sin \gamma.$

SOLUTION OF SPHERICAL TRIANGLES

3.51 Right-angled spherical triangles.

a, b, c = sides of triangle, c the side opposite γ, the right angle.

α, β, γ = angles opposite a, b, c, respectively.

3.511 Napier's Rules:

The five parts are a, b, *co* c, *co* α, *co* β, where *co* $c = \frac{\pi}{2} - c$. The right angle γ is omitted.

The sine of the middle part is equal to the product of the tangents of the adjacent parts.

The sine of the middle part is equal to the product of the cosines of opposite parts.

From these rules the following equations follow:

$$\sin a = \sin c \sin \alpha,$$
$$\tan a = \tan c \cos \beta = \sin b \tan \alpha,$$
$$\sin b = \sin c \sin \beta,$$
$$\tan b = \tan c \cos \alpha = \sin a \tan \beta,$$
$$\cos \alpha = \cos a \sin \beta,$$
$$\cos \beta = \cos b \sin \alpha,$$
$$\cos c = \cot \alpha \cot \beta = \cos a \cos b.$$

3.52 Oblique-angled spherical triangles.

$a,\ b,\ c$ = sides of triangle.

$\alpha,\ \beta,\ \gamma$ = angles opposite to a, b, c, respectively.

$s = \frac{1}{2}(a + b + c)$,

$\sigma = \frac{1}{2}(\alpha + \beta + \gamma)$,

$\epsilon = \alpha + \beta + \gamma - 180$ = spherical excess,

S = surface of triangle on sphere of radius r.

Given	*Sought*	*Formula*
$a,\ b,\ c$	α	$\sin^2 \frac{1}{2}\alpha = \text{haversin}\ \alpha, = \dfrac{\sin(s-b)\sin(s-c)}{\sin b \sin c}$
		$\tan^2 \frac{1}{2}\alpha = \dfrac{\sin(s-b)\sin(s-c)}{\sin s \sin(s-a)}.$
		$\cos^2 \frac{1}{2}\alpha = \dfrac{\sin s \sin(s-a)}{\sin b \sin c}.$
		$\text{haversin}\ \alpha = \dfrac{\text{hav}\ a - \text{hav}\ (b-c)}{\sin b \sin c}.$
$\alpha,\ \beta,\ \gamma$	a	$\sin^2 \frac{1}{2}a = \text{haversin}\ a, = \dfrac{-\cos\sigma \cos(\sigma-\alpha)}{\sin\beta \sin\gamma}$
		$\tan^2 \frac{1}{2}a = \dfrac{-\cos\sigma \cos(\sigma-\alpha)}{\cos(\sigma-\beta)\cos(\sigma-\gamma)}.$
		$\cos^2 \frac{1}{2}a = \dfrac{\cos(\sigma-\beta)\cos(\sigma-\gamma)}{\sin\beta \sin\gamma}.$
$a,\ c,\ \alpha$ Ambiguous case. Two solutions possible.	γ	$\sin\gamma = \dfrac{\sin\alpha \sin c}{\sin a}.$
	β	$\left\{\begin{aligned} \tan\theta &= \tan\alpha \cos c. \\ \sin(\beta+\theta) &= \sin\theta \tan c \cot a \end{aligned}\right.$
	b	$\left\{\begin{aligned} \cot\phi &= \tan c \cos\alpha. \\ \sin(b+\phi) &= \dfrac{\cos a \sin\phi}{\cos c}. \end{aligned}\right.$
$\alpha,\ \gamma,\ c$ Ambiguous case. Two solutions possible.	c	$\sin c = \dfrac{\sin a \sin\gamma}{\sin\alpha}.$

Given	*Sought*	*Formula*
	b	$\tan\theta = \tan a \cos\gamma.$ $\sin(b-\theta) = \cot\alpha \tan\gamma \sin\theta.$
	b	$\tan\frac{1}{2}b = \frac{\sin\frac{1}{2}(\alpha+\gamma)}{\sin\frac{1}{2}(\alpha-\gamma)}\tan\frac{1}{2}(a-c)$ $= \frac{\cos\frac{1}{2}(\alpha+\gamma)}{\cos\frac{1}{2}(\alpha-\gamma)}\tan\frac{1}{2}(a+c).$
	β	$\cot\phi = \cos a \tan\gamma$ $\sin(\beta-\phi) = \frac{\cos\alpha\sin\phi}{\cos\gamma}.$
	β	$\cot\frac{1}{2}\beta = \frac{\sin\frac{1}{2}(a+c)}{\sin\frac{1}{2}(a-c)}\tan\frac{1}{2}(\alpha-\gamma).$ $= \frac{\cos\frac{1}{2}(a+c)}{\cos\frac{1}{2}(a-c)}\tan\frac{1}{2}(\alpha+\gamma).$
a, b, γ	c	$\cos c = \cos a\cos b + \sin a\sin b\cos\gamma.$
$\tan\theta = \tan a\cos\gamma$ $\tan\phi = \tan b\cos\gamma$	c	$\cos c = \frac{\cos a\cos(b-\theta)}{\cos\theta}$ $= \frac{\cos b\cos(a-\phi)}{\cos\phi}.$
		$\operatorname{hav} c = \operatorname{hav}(a-b) + \sin a\sin b \operatorname{hav}\gamma$
	α	$\tan\alpha = \frac{\sin\theta\tan\gamma}{\sin(b-\theta)}.$
	β	$\sin\beta = \frac{\sin\gamma\sin b}{\sin c}.$ $= \frac{\sin\alpha\sin b}{\sin a}.$ $\tan\beta = \frac{\sin\phi\tan\gamma}{\sin(a-\phi)}.$
	α, β	$\tan\frac{1}{2}(\alpha+\beta) = \frac{\cos\frac{1}{2}(a-b)\cot\frac{1}{2}\gamma}{\cos\frac{1}{2}(a+b)}$ $\tan\frac{1}{2}(\alpha-\beta) = \frac{\sin\frac{1}{2}(a-b)\cot\frac{1}{2}\gamma}{\sin\frac{1}{2}(a+b)}.$
c, α, β	γ	$\cos\gamma = -\cos\alpha\cos\beta + \sin\alpha\sin\beta\cos c.$
$\tan\theta = \cos c\tan\alpha$ $\tan\phi = \cos c\tan\beta$		$\cos\gamma = \frac{\cos\alpha\cos(\beta+\theta)}{\cos\theta}.$ $= \frac{\cos\beta\cos(\alpha+\phi)}{\cos\phi}.$
	a	$\tan a = \frac{\tan c\sin\theta}{\sin(\beta+\theta)}.$

Given	*Sought*	*Formula*
	b	$\tan b = \dfrac{\tan c \sin \phi}{\sin (\alpha + \phi)}.$
	a, b	$\begin{cases} \tan \frac{1}{2}(a+b) = \dfrac{\cos \frac{1}{2}(\alpha - \beta) \tan \frac{1}{2}c}{\cos \frac{1}{2}(\alpha + \beta)} \\ \tan \frac{1}{2}(a-b) = \dfrac{\sin \frac{1}{2}(\alpha - \beta) \tan \frac{1}{2}c}{\sin \frac{1}{2}(\alpha + \beta)}. \end{cases}$
a, b, γ	ϵ	$\cot \frac{1}{2}\epsilon = \dfrac{\cot \frac{1}{2}a \cot \frac{1}{2}b + \cos \gamma}{\sin \gamma}.$
a, b, c	ϵ	$\tan^2 \frac{1}{4}\epsilon = \tan \frac{1}{2}s \tan \frac{1}{2}(s-a) \tan \frac{1}{2}(s-b) \tan \frac{1}{2}(s-c).$
ϵ, γ	S	$S = \dfrac{\epsilon}{180°} \pi r^2.$

FINITE SERIES OF CIRCULAR FUNCTIONS

3.60 If the sum, $f(r)$, of the finite or infinite series:

$$f(r) = a_0 + a_1 r + a_2 r^2 + \ldots\ldots$$

is known, the sums of the series:

$$S_1 = a_0 \cos x + a_1 r \cos (x + y) + a_2 r^2 \cos (x + 2y) + \ldots\ldots$$

$$S_2 = a_0 \sin x + a_1 r \sin (x + y) + a_2 r^2 \sin (x + 2y) + \ldots\ldots$$

are:

$$S_1 = \tfrac{1}{2}\{e^{ix} f(re^{iy}) + e^{-ix} f(re^{-iy})\},$$

$$S_2 = -\frac{i}{2}\{e^{ix} f(re^{iy}) - e^{-ix} f(re^{-iy})\}.$$

3.61 Special Finite Series.

1. $$\sum_{k=1}^{n} \sin kx = \frac{\sin \dfrac{nx}{2} \sin \dfrac{n+1}{2} x}{\sin \dfrac{x}{2}}.$$

2. $$\sum_{k=0}^{n} \cos kx = \frac{\cos \dfrac{nx}{2} \sin \dfrac{n+1}{2} x}{\sin \dfrac{x}{2}}.$$

3. $$\sum_{k=1}^{n} \sin^2 kx = \frac{n}{2} - \frac{\cos (n+1)x \cdot \sin nx}{2 \sin x}.$$

4. $$\sum_{k=0}^{n} \cos^2 kx = \frac{n+2}{2} + \frac{\cos (n+1)x \cdot \sin nx}{2 \sin x}.$$

5. $$\sum_{k=1}^{n-1} k \sin kx = \frac{\sin nx}{4 \sin^2 \frac{x}{2}} - \frac{n \cos \left(\frac{2n-1}{2}\right)x}{2 \sin \frac{x}{2}}.$$

6. $$\sum_{k=1}^{n-1} k \cos kx = \frac{n \sin \left(\frac{2n-1}{2}\right)x}{2 \sin \frac{x}{2}} - \frac{1 - \cos nx}{4 \sin^2 \frac{x}{2}}.$$

7. $$\sum_{k=1}^{n} \sin (2k-1)x = \frac{\sin^2 nx}{\sin x}.$$

8. $$\sum_{k=0}^{n} \sin (x + ky) = \frac{\sin \left(x + \frac{ny}{2}\right) \sin \left(\frac{n+1}{2} y\right)}{\sin \frac{y}{2}}.$$

9. $$\sum_{k=0}^{n} \cos (x + ky) = \frac{\cos \left(x + \frac{n}{2} y\right) \sin \left(\frac{n+1}{2} y\right)}{\sin \frac{y}{2}}.$$

10. $$\sum_{k=1}^{n+1} (-1)^{k-1} \sin (2k-1)x = (-1)^n \frac{\sin (2n+2)x}{2 \cos x}.$$

11. $$\sum_{k=1}^{n} (-1)^k \cos kx = -\frac{1}{2} + (-1)^n \frac{\cos \left(\frac{2n+1}{2} x\right)}{2 \cos \frac{x}{2}}.$$

12. $$\sum_{k=1}^{n-1} r^k \sin kx = \frac{r \sin x(1 - r^n \cos nx) - (1 - r \cos x)r^n \sin nx}{1 - 2r \cos x + r^2}.$$

13. $$\sum_{k=0}^{n-1} r^k \cos kx = \frac{(1 - r \cos x)(1 - r^n \cos nx) + r^{n+1} \sin x \sin nx}{1 - 2r \cos x + r^2}.$$

14. $$\sum_{k=1}^{n} \left(\frac{1}{2^k} \sec \frac{x}{2^k}\right)^2 = \csc^2 x - \left(\frac{1}{2^n} \csc \frac{x}{2^n}\right)^2.$$

15. $$\sum_{k=1}^{n} \left(2^k \sin^2 \frac{x}{2^k}\right)^2 = \left(2^n \sin \frac{x}{2^n}\right)^2 - \sin^2 x.$$

16. $$\sum_{k=0}^{n} \frac{1}{2^k} \tan \frac{x}{2^k} = \frac{1}{2^n} \cot \frac{x}{2^n} - 2 \cot 2x.$$

17. $$\sum_{k=0}^{n-1} \cos \frac{k^2 2\pi}{n} = \frac{\sqrt{n}}{2}\left(1 + \cos \frac{n\pi}{2} + \sin \frac{n\pi}{2}\right).$$

18. $$\sum_{k=1}^{n-1} \sin \frac{k^2\, 2\pi}{n} = \frac{\sqrt{n}}{2}\left(1 + \cos \frac{n\pi}{2} - \sin \frac{n\pi}{2}\right).$$

19. $$\sum_{k=1}^{n-1} \sin \frac{k\pi}{n} = \cot \frac{\pi}{2n}.$$

20. $$\sum_{k-0}^{n} \frac{1}{2^{2k}} \tan^2 \frac{x}{2^k} = \frac{2^{2n+2} - 1}{3 \cdot 2^{2n-1}} + 4 \cot^2 2x - \frac{1}{2^{2n}} \cot \frac{x}{2^n}.$$

3.62

$$S_n = \sum_{k=1}^{n-1} \csc \frac{k\pi}{n}.$$

Watson (Phil. Mag. 31, p. 111, 1916) has obtained an asymptotic expansion for this sum, and has given the following approximation:

$$S_n = 2n\{0.7329355992 \log_{10}(2n) - 0.1806453871\} - \frac{0.087266}{n} + \frac{0.01035}{n^3} - \frac{0.004}{n^5} + \frac{0.005}{n^7} - \dots$$

Values of S_n are tabulated by integers from $n = 2$ to $n = 30$, and from $n = 30$ to $n = 100$ at intervals of 5.

The expansion of

$$T_n = \sum_{k=1}^{n-1} \csc \left(\frac{k\pi}{n} - \frac{\beta}{2}\right),$$

where

$$-\frac{2\pi}{n} < \beta < \frac{2\pi}{n},$$

is also obtained.

3.70 Finite Products.

1. $$\sin nx = n \sin x \cos x \prod_{k=1}^{\frac{n}{2}-1} \left(1 - \frac{\sin^2 x}{\sin^2 \frac{k\pi}{n}} \right) \quad n \text{ even.}$$

2. $$\cos nx = \prod_{k=1}^{\frac{n}{2}} \left(1 - \frac{\sin^2 x}{\sin^2 \frac{2k-1}{2n}\pi} \right) \quad n \text{ even.}$$

3. $$\sin nx = n \sin x \prod_{k=1}^{\frac{n-1}{2}} \left(1 - \frac{\sin^2 x}{\sin^2 \frac{k\pi}{n}} \right) \quad n \text{ odd.}$$

4. $$\cos nx = \cos x \prod_{k=1}^{\frac{n-1}{2}} \left(1 - \frac{\sin^2 x}{\sin^2 \frac{2k-1}{2n}\pi} \right) \quad n \text{ odd.}$$

5. $$\cos nx - \cos ny = 2^{n-1} \prod_{k=0}^{n-1} \left\{ \cos x - \cos\left(y + \frac{2k\pi}{n} \right) \right\}.$$

6. $$a^{2n} - 2a^n b^n \cos nx + b^{2n} = \prod_{k=0}^{n-1} \left\{ a^2 - 2ab \cos\left(x + \frac{2k\pi}{n} \right) + b^2 \right\}.$$

ROOTS OF TRANSCENDENTAL EQUATIONS

3.800 $\tan x = x$.

The first 17 roots, and the corresponding maxima and minima of $\frac{\sin x}{x}$ are given in the following table (Lommel, Abh. Munch. Akad. (2) 15, 123, 1886):

n	x_n	Max / Min $\frac{\sin x}{x}$
1	0	1
2	4.4934	−0.2172
3	7.7253	+0.1284
4	10.9041	−0.0913
5	14.0662	+0.0709
6	17.2208	−0.0580
7	20.3713	+0.0490
8	23.5195	−0.0425
9	26.6661	+0.0375
10	29.8116	−0.0335
11	32.9564	+0.0303
12	36.1006	−0.0277
13	39.2444	+0.0255
14	42.3879	−0.0236
15	45.5311	+0.0220
16	48.6741	−0.0205
17	51.8170	+0.0193

3.801

$$\tan x = \frac{2x}{2 - x^2}.$$

The first three roots are:

$$x_1 = 0,$$

$$x_2 = 119.26 \frac{\pi}{180},$$

$$x_3 = 340.35 \frac{\pi}{180}.$$

If x is large

$$x_n = n\pi - \frac{2}{n\pi} - \frac{16}{3n^3\pi^3} + \ldots .$$

(Rayleigh, Theory of Sound, II, p. 265.)

3.802

$$\tan x = \frac{x^3 - 9x}{4x^2 - 9}.$$

The first two roots are:

$$x_1 = 0,$$

$$x_2 = 3.3422.$$

(Rayleigh, l. c. p. 266.)

3.803

$$\tan x = \frac{x}{1 - x^2}.$$

The first two roots are:

$$x_1 = 0,$$

$$x_2 = 2.744.$$

(J. J. Thomson, Recent Researches, p. 373.)

3.804

$$\tan x = \frac{3x}{3 - x^2}.$$

The first seven roots are:

$$x_1 = 0,$$

$$x_2 = 1.8346\pi,$$

$$x_3 = 2.8950\pi,$$

$$x_4 = 3.9225\pi,$$

$$x_5 = 4.9385\pi,$$

$$x_6 = 5.9489\pi,$$

$$x_7 = 6.9563\pi.$$

(Lamb, London Math. Soc. Proc. 13, 1882.)

3.805

$$\tan x = \frac{4x}{4 - 3x^2}.$$

The first seven roots are:

$$x_1 = 0,$$
$$x_2 = 0.8160\pi,$$
$$x_3 = 1.9285\pi,$$
$$x_4 = 2.9359\pi,$$
$$x_5 = 3.9658\pi,$$
$$x_6 = 4.9728\pi,$$
$$x_7 = 5.9774\pi.$$

(Lamb, l. c.)

3.806

$$\cos x \cosh x = 1.$$

The roots are:

$$x_1 = 4.7300408,$$
$$x_2 = 7.8532046,$$
$$x_3 = 10.9956078,$$
$$x_4 = 14.1371655,$$
$$x_5 = 17.2787596,$$
$$x_n = \tfrac{1}{2}(2n + 1)\pi \quad n > 5.$$

(Rayleigh, Theory of Sound, I, p. 278.)

3.807

$$\cos x \cosh x = -1.$$

The roots are:

$$x_1 = 1.875104,$$
$$x_2 = 4.694098,$$
$$x_3 = 7.854757,$$
$$x_4 = 10.995541,$$
$$x_5 = 14.137168,$$
$$x_6 = 17.278759,$$
$$x_n = \tfrac{1}{2}(2n - 1)\pi \quad n > 6.$$

3.808

$$1 - (1 + x^2) \cos x = 0.$$

The roots are:

$$x_1 = 1.102506,$$
$$x_2 = 4.754761,$$
$$x_3 = 7.837964,$$
$$x_4 = 11.003766,$$
$$x_5 = 14.132185,$$
$$x_6 = 17.282097.$$

(Schlömilch: Ubungsbuch, I, p. 354.)

3.809 The smallest root of

$$\theta - \cot \theta = 0,$$

is

$$\theta = 49^\circ\ 17'\ 36''.5.$$

(l. c. p. 355.)

3.810 The smallest root of

$$\theta - \cos\theta = 0,$$

is

$$\theta = 42^\circ\, 20'\, 47''.3.$$

(l. c. p. 353.)

3.811 The smallest root of

$$xe^x - 2 = 0,$$

is

$$x = 0.8526.$$

(l. c. p. 353.)

3.812 The smallest root of

$$\log(1 + x) - \tfrac{3}{4}x = 0,$$

is

$$x = 0.73360.$$

(l. c. p. 353.)

3.813

$$\tan x - x + \frac{1}{x} = 0.$$

The first roots are:

$$x_1 = 4.480,$$
$$x_2 = 7.723,$$
$$x_3 = 10.90,$$
$$x_4 = 14.07.$$

(Collo, Annalen der Physik, 65, p. 45, 1921.)

3.814

$$\cot x + x - \frac{1}{x} = 0.$$

The first roots are:

$$x_1 = 0,$$
$$x_2 = 2.744,$$
$$x_3 = 6.117,$$
$$x_4 = 9.317,$$
$$x_5 = 12.48,$$
$$x_6 = 15.64,$$
$$x_7 = 18.80.$$

(Collo, l. c.)

3.90 Special Tables.

$\sin\theta$, $\cos\theta$: The British Association Report for 1916 contains the following tables:

Table I, p. 60. $\sin\theta$, $\cos\theta$, θ expressed in radians from $\theta = 0$ to $\theta = 1.600$, interval 0.001, 10 decimal places.

Table II, p. 88. $\theta - \sin\theta$, $1 - \cos\theta$, $\theta = 0.00001$ to $\theta = 0.00100$, interval 0.00001, 10 decimal places.

Table III, p. 90. $\sin \theta$, $\cos \theta$; $\theta = 0.1$ to $\theta = 10.0$, interval 0.1, 15 decimal places.

J. Peters (Abh. d. K. P. Akad. der Wissen., Berlin, 1911) has given sines and cosines for every sexagesimal second to 21 places.

hav θ, $\log_{10}$ hav θ: Bowditch, American Practical Navigator, five-place tables, $0° - 180°$, for $15''$ intervals.

Tables for Solution of Spherical Triangles.

Aquino's Altitude and Azimuth Tables, London, 1918. Reprinted in Hydrographic Office Publication, No. 200, Washington, 1918.

Hyperbolic Functions.

The Smithsonian Mathematical Tables: Hyperbolic Functions, contain the most complete five-place tables of Hyperbolic Functions.

Table I. The common logarithms (base 10) of $\sinh u$, $\cosh u$, $\tanh u$, $\coth u$:

$u = 0.0001$ to $u = 0.1000$ interval 0.0001,
$u = 0.001$ to $u = 3.000$ interval 0.001,
$u = 3.00$ to $u = 6.00$ interval 0.01.

Table II. $\sinh u$, $\cosh u$, $\tanh u$, $\coth u$. Same ranges and intervals.

Table III. $\sin u$, $\cos u$, $\log_{10} \sin u$, $\log_{10} \cos u$:

$u = 0.0001$ to $u = 0.1000$ interval 0.0001,
$u = 0.100$ to $u = 1.600$ interval 0.001.

Table IV. $\log_{10} e^u$ (7 places), e^u and e^{-u} (7 significant figures):

$u = 0.001$ to $u = 2.950$ interval 0.001,
$u = 3.00$ to $u = 6.00$ interval 0.01,
$u = 1.0$ to $u = 100$ interval 1.0 (9–10 figures).

Table V. five-place table of natural logarithms, $\log u$.

$u = 1.0$ to $u = 1000$ interval 1.0,
$u = 1000$ to $u = 10{,}000$ varying intervals.

Table VI. $gd\, u$ (7 places); u expressed in radians, $u = 0.001$ to $u = 3.000$, interval 0.001, and the corresponding angular measure. $u = 3.00$ to $u = 6.00$, interval 0.01.

Table VII. $gd^{-1}u$, to $0'.01$, in terms of $gd\, u$ in degrees and minutes from $0°\ 1'$ to $89°\ 59'$.

Table VIII. Table for conversion of radians into angular measure.

Kennelly: Tables of Complex Hyperbolic and Circular Functions. Cambridge, Harvard University Press, 1914.

The complex argument, $x + iq = \rho e^{i\delta}$. In the tables this is denoted $\rho\angle\delta$. $\rho = \sqrt{x^2 + q^2}$, $\tan\,\delta = q/x$.

Tables I, II, III give the hyperbolic sine, cosine and tangent of $(\rho\angle\delta)$ expressed as $r\angle\gamma$:

$$\delta = 45^\circ \text{ to } \delta = 90^\circ \quad \text{interval } 1^\circ$$
$$\rho = 0.01 \text{ to } \rho = 3.0 \quad \text{interval } 0.1.$$

Tables IV and V give $\dfrac{\sinh\theta}{\theta}, \dfrac{\tanh\theta}{\theta}$ expressed as $r\angle\gamma$, $\theta = \rho\angle\delta$,

$$\rho = 0.1 \text{ to } \rho = 3.0 \quad \text{interval } 0.1,$$
$$\delta = 45^\circ \text{ to } \delta = 90^\circ \quad \text{interval } 1^\circ.$$

Table VI gives $\sinh\,(\rho\angle 45^\circ)$, $\cosh\,(\rho\angle 45^\circ)$, $\tanh\,(\rho\angle 45^\circ)$, $\coth\,(\rho\angle 45^\circ)$, $\text{sech}\,(\rho\angle 45^\circ)$, $\text{csch}\,(\rho\angle 45^\circ)$ expressed as $r\angle\gamma$:

$$\rho = 0 \text{ to } \rho = 6.0 \quad \text{interval } 0.1,$$
$$\rho = 6.05 \text{ to } \rho = 20.50 \quad \text{interval } 0.05.$$

Tables VII, VIII and IX give $\sinh\,(x + iq)$, $\cosh\,(x + iq)$, $\tanh\,(x + iq)$, expressed as $u + iv$:

$$x = 0 \text{ to } x = 3.95 \quad \text{interval } 0.05,$$
$$q = 0 \text{ to } q = 2.0 \quad \text{interval } 0.05.$$

Tables X, XI, XII give $\sinh\,(x + iq)$, $\cosh\,(x + iq)$, $\tanh\,(x + iq)$ expressed as $r\angle\gamma$:

$$x = 0 \text{ to } x = 3.95 \quad \text{interval } 0.05,$$
$$q = 0 \text{ to } q = 2.0 \quad \text{interval } 0.05.$$

Table XIII gives $\sinh\,(4 + iq)$, $\cosh\,(4 + iq)$, $\tanh\,(4 + iq)$ expressed both as $u + iv$ and $r\angle\gamma$:

$$q = 0 \text{ to } q = 2.0 \quad \text{interval } 0.05.$$

Table XIV gives $\dfrac{e^x}{2}$ and $\log_{10}\dfrac{e^x}{2}$.

$$x = 4.00 \text{ to } x = 10.00 \quad \text{interval } 0.01.$$

Table XV gives the real hyperbolic functions: $\sinh\theta$, $\cosh\theta$, $\tanh\theta$, $\coth\theta$, $\text{sech}\,\theta$, $\text{csch}\,\theta$.

$$\theta = 0 \text{ to } \theta = 2.5 \quad \text{interval } 0.01,$$
$$\theta = 2.5 \text{ to } \theta = 7.5 \quad \text{interval } 0.1.$$

Pernot and Woods: Logarithms of Hyperbolic Functions to 12 Significant Figures. Berkeley, University of California Press, 1918.

Table I. $\log_{10} \sinh x$, with the first three differences.

$x = .0000$ to $x = 2\ 018$ nterval 0.001.

Table II. $\log_{10} \cosh x$.

$x = 0.000$ to $x = 2.032$ interval 0.001.

Table III. $\log_{10} \tanh x$.

$x = 0.000$ to $x = 2.018$ interval 0.001.

Table IV. $\log_{10} \dfrac{\sinh x}{x}$.

$x = 0.00$ to $x = 0.506$ interval 0.001.

Table V. $\log_{10} \dfrac{\tanh x}{x}$.

$x = 0.000$ to $x = 0.506$ interval 0.001.

Van Orstrand, Memoirs of the National Academy of Sciences, Vol. XIV, fifth memoir, Washington, 1921.

Tables of $\frac{1}{n!}$, e^x, e^{-x}, $e^{n\pi}$, $e^{-n\pi}$, $e^{\pm\frac{n\pi}{360}}$, $\sin x$, $\cos x$, to 23–62 decimal places or significant figures.

IV. VECTOR ANALYSIS

4.000 A vector **A** has components along the three rectangular axes, x, y, z: A_x, A_y, A_z.

$$A = \text{length of vector.}$$

$$A = \sqrt{A_x^2 + A_y^2 + A_z^2}.$$

Direction cosines of **A**, $\dfrac{A_x}{A}, \dfrac{A_y}{A}, \dfrac{A_z}{A}$.

4.001 Addition of vectors.

$$\mathbf{A} + \mathbf{B} = \mathbf{C}.$$

C is a vector with components.

$$C_x = A_x + B_x.$$

$$C_y = A_y + B_y.$$

$$C_z = A_z + B_z.$$

4.002 θ = angle between **A** and **B**.

$$C = \sqrt{A^2 + B^2 + 2AB\cos\theta}.$$

$$\cos\theta = \frac{A_xB_x + A_yB_y + A_zB_z}{AB}.$$

4.003 If **a**, **b**, **c** are any three non-coplanar vectors of unit length, any vector, **R**, may be expressed:

$$\mathbf{R} = a\mathbf{a} + b\mathbf{b} + c\mathbf{c},$$

where a, b, c are the lengths of the projections of **R** upon **a**, **b**, **c** respectively.

4.004 Scalar product of two vectors:

$$S\mathbf{AB} = (\mathbf{AB}) = \mathbf{AB}$$

are equivalent notations.

$$\mathbf{AB} = AB\cos\widehat{AB}.$$

4.005 Vector product of two vectors:

$$V\mathbf{AB} = \mathbf{A} \times \mathbf{B} = [\mathbf{AB}] = \mathbf{C}.$$

C is a vector whose length is

$$C = AB\sin\widehat{AB}.$$

The direction of **C** is perpendicular to both **A** and **B** such that a right-handed rotation about **C** through the angle $\widehat{AB}$ turns **A** into **B**.

4.006 **i**, **j**, **k** are three unit vectors perpendicular to each other. If their directions coincide with the axes x, y, z of a rectangular system of coördinates:

$$\mathbf{A} = A_x\mathbf{i} + A_y\mathbf{j} + A_z\mathbf{k}.$$

4.007

$$\mathbf{ii} = \mathbf{i}^2 = \mathbf{jj} = \mathbf{j}^2 = \mathbf{kk} = \mathbf{k}^2 = 1,$$
$$\mathbf{ij} = \mathbf{ji} = \mathbf{jk} = \mathbf{kj} = \mathbf{ki} = \mathbf{ik} = 0.$$

4.008

$$V\mathbf{ij} = -V\mathbf{ji} = \mathbf{k},$$
$$V\mathbf{jk} = -V\mathbf{kj} = \mathbf{i},$$
$$V\mathbf{ki} = -V\mathbf{ik} = \mathbf{j}.$$

4.009

$$\mathbf{AB} = \mathbf{BA} = AB\cos\widehat{AB} = A_xB_x + A_yB_y + A_zB_z.$$

4.010

$$V\mathbf{AB} = -V\mathbf{BA} = \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ A_x & A_y & A_z \\ B_x & B_y & B_z \end{vmatrix}$$
$$= (A_yB_z - A_zB_y)\mathbf{i} + (A_zB_x - A_xB_z)\mathbf{j} + (A_xB_y - A_yB_x)\mathbf{k}.$$

4.10 If **A**, **B**, **C**, are any three vectors:

$$\mathbf{A}V\mathbf{BC} = \mathbf{B}V\mathbf{CA} = \mathbf{C}V\mathbf{AB}$$

= Volume of parallelepipedon having **A**, **B**, **C** as edges

$$= \begin{vmatrix} A_x & A_y & A_z \\ B_x & B_y & B_z \\ C_x & C_y & C_z \end{vmatrix}$$

4.11

1. $V\mathbf{A}(\mathbf{B} + \mathbf{C}) = V\mathbf{AB} + V\mathbf{AC}.$
2. $V(\mathbf{A} + \mathbf{B})(\mathbf{C} + \mathbf{D}) = V\mathbf{A}(\mathbf{C} + \mathbf{D}) + V\mathbf{B}(\mathbf{C} + \mathbf{D}).$
3. $V\mathbf{A}V\mathbf{BC} = \mathbf{B}S\mathbf{AC} - \mathbf{C}S\mathbf{AB}.$
4. $V\mathbf{A}V\mathbf{BC} + V\mathbf{B}V\mathbf{CA} + V\mathbf{C}V\mathbf{AB} = 0.$
5. $V\mathbf{AB}\cdot V\mathbf{CD} = \mathbf{AC}\cdot\mathbf{BD} - \mathbf{BC}\cdot\mathbf{AD}.$
6. $V(V\mathbf{AB}\cdot V\mathbf{CD}) = \mathbf{C}S(\mathbf{D}V\mathbf{AB}) - \mathbf{D}S(\mathbf{C}V\mathbf{AB})$

$$= \mathbf{C}S(\mathbf{A}V\mathbf{BD}) - \mathbf{D}S(\mathbf{A}V\mathbf{BC})$$
$$= \mathbf{B}S(\mathbf{A}V\mathbf{CD}) - \mathbf{A}S(\mathbf{B}V\mathbf{CD})$$
$$= \mathbf{B}S(\mathbf{C}V\mathbf{DA}) - \mathbf{A}S(\mathbf{C}V\mathbf{DB}).$$

4.20

1. $$d\mathbf{AB} = \mathbf{A}d\,\mathbf{B} + \mathbf{B}d\mathbf{A}.$$

2. $$dV\mathbf{AB} = V\mathbf{A}d\mathbf{B} + Vd\mathbf{AB}$$
$$= V\mathbf{A}d\mathbf{B} - V\mathbf{B}d\mathbf{A}.$$

4.21

1. $$\nabla = \mathbf{i}\frac{\partial}{\partial x} + \mathbf{j}\frac{\partial}{\partial y} + \mathbf{k}\frac{\partial}{\partial z}.$$

2. $$\nabla\mathbf{A} = \text{div } \mathbf{A} = \frac{\partial A_x}{\partial x} + \frac{\partial A_y}{\partial y} + \frac{\partial A_z}{\partial z}.$$

3. $$\nabla\phi = \text{grad } \phi = \mathbf{i}\frac{\partial\phi}{\partial x} + \mathbf{j}\frac{\partial\phi}{\partial y} + \mathbf{k}\frac{\partial\phi}{\partial z}.$$

4. $$V\nabla\mathbf{A} = \text{curl } \mathbf{A} = \text{rot } \mathbf{A}$$
$$= \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ \dfrac{\partial}{\partial x} & \dfrac{\partial}{\partial y} & \dfrac{\partial}{\partial z} \\ A_x & A_y & A_z \end{vmatrix}$$
$$= \mathbf{i}\left(\frac{\partial A_z}{\partial y} - \frac{\partial A_y}{\partial z}\right) + \mathbf{j}\left(\frac{\partial A_x}{\partial z} - \frac{\partial A_z}{\partial x}\right) + \mathbf{k}\left(\frac{\partial A_y}{\partial x} - \frac{\partial A_x}{\partial y}\right).$$

5. $$\nabla\nabla = \nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}.$$

4.22

1. curl grad ϕ = curl $\nabla\phi = V\nabla\nabla\phi = 0.$

2. div grad $\phi = \nabla\nabla\phi = \overline{\nabla}^2\phi = \dfrac{\partial^2\phi}{\partial x^2} + \dfrac{\partial^2\phi}{\partial y^2} + \dfrac{\partial^2\phi}{\partial z^2}.$

3. div curl $\mathbf{A} = 0.$

4. curl curl $\mathbf{A} = \text{curl}^2\,\mathbf{A} = \nabla\text{ div }\mathbf{A} - \overline{\nabla}^2\mathbf{A}.$

5. $$\overline{\nabla}^2\mathbf{A} = \mathbf{i}\overline{\nabla}^2\mathbf{A}_x + \mathbf{j}\overline{\nabla}^2 A_y + \mathbf{k}\overline{\nabla}^2 A_z.$$

6. $$\mathbf{A}\nabla = A_x\frac{\partial}{\partial x} + A_y\frac{\partial}{\partial y} + A_z\frac{\partial}{\partial z}.$$

4.23

1. $\nabla \mathbf{AB} = \text{grad } \mathbf{AB} = (\mathbf{A}\nabla)\mathbf{B} + (\mathbf{B}\nabla)\mathbf{A} + V.\mathbf{A} \text{ curl } \mathbf{B} + V.\mathbf{B} \text{ curl } \mathbf{A}.$
2. $\nabla V\mathbf{AB} = \text{div } V\mathbf{AB} = \mathbf{B} \text{ curl } \mathbf{A} - \mathbf{A} \text{ curl } \mathbf{B}.$
3. $V\nabla V\mathbf{AB} = (\mathbf{B}\nabla)\mathbf{A} - (\mathbf{A}\nabla)\mathbf{B} + \mathbf{A} \text{ div } B - \mathbf{B} \text{ div } \mathbf{A}.$
4. $\text{div } \phi\mathbf{A} = \phi \text{ div } \mathbf{A} + \mathbf{A}\nabla\phi.$
5. $\text{curl } \phi\mathbf{A} = V\cdot\nabla\phi\mathbf{A} + \phi \text{ curl } \mathbf{A} = V\cdot\text{grad } \phi.\mathbf{A} + \phi \text{ curl } \mathbf{A}.$
6. $\nabla \mathbf{A}^2 = 2(\mathbf{A}\nabla)\mathbf{A} + 2V\mathbf{A} \text{ curl } \mathbf{A}.$
7. $\mathbf{C}(\mathbf{A}\nabla)\mathbf{B} = \mathbf{A}(\mathbf{C}\nabla)\mathbf{B} + \mathbf{A}V\mathbf{C} \text{ curl } \mathbf{B}.$
8. $\mathbf{B}\nabla\mathbf{A}^2 = 2\mathbf{A}(\mathbf{B}\nabla)\mathbf{A}.$

4.24 $\mathbf{R}$ is a radius vector of length r and $\mathbf{r}$ a unit vector in the direction of $\mathbf{R}$.

$$\mathbf{R} = r\mathbf{r},$$
$$r^2 = x^2 + y^2 + z^2.$$

1. $$\nabla \frac{1}{r} = -\frac{1}{r^3}\mathbf{R} = -\frac{1}{r^2}\mathbf{r}.$$
2. $$\nabla^2 \frac{1}{r} = 0.$$
3. $$\nabla r = \frac{1}{r}\mathbf{R} = \mathbf{r} = \text{grad } r.$$
4. $$\nabla^2 r = \frac{2}{r}.$$
5. $$V\nabla\mathbf{R} = \text{curl } \mathbf{R} = 0.$$
6. $$\nabla\mathbf{R} = \text{div } \mathbf{R} = 3.$$
7. $$\frac{d\phi}{dr} = \mathbf{r}\nabla\phi.$$
8. $$(\mathbf{R}\nabla)\mathbf{A} = r\frac{d\mathbf{A}}{dr}.$$
9. $$(\mathbf{r}\nabla)\mathbf{A} = \frac{d\mathbf{A}}{dr}.$$
10. $$(\mathbf{A}\nabla)\mathbf{R} = \mathbf{A}.$$

4.30 $d\mathbf{S}$ = an element of area of a surface regarded as a vector whose direction is that of the positive normal to the surface.

dV = an element of volume — a scalar.

$d\mathbf{s}$ = an element of arc of a curve regarded as a vector whose direction is that of the positive tangent to the curve.

4.31 Gauss's Theorem:

$$\int\int\int \operatorname{div} \mathbf{A} dV = \int\int \mathbf{A} d\mathbf{S}.$$

4.32 Green's Theorem:

1. $\int\int\int \phi\nabla^2\psi dV + \int\int\int \nabla\phi\nabla\psi dV = \int\int \phi\nabla\psi d\mathbf{S}$
2. $\int\int\int (\phi\nabla^2\psi - \psi\nabla^2\phi) dV = \int\int (\phi\nabla\psi - \psi\nabla\phi) d\mathbf{S}.$

4.33 Stokes's Theorem:

$$\int\int \operatorname{curl} \mathbf{A} d\mathbf{S} = \int \mathbf{A} d\mathbf{s}.$$

4.40 A polar vector is one whose components, referred to a rectangular system of axes, all change in sign when the three axes are reversed.

4.401 An axial vector is one whose components are unchanged when the axes are reversed.

4.402 The vector product of two polar or of two axial vectors is an axial vector.

4.403 The vector product of a polar and an axial vector is a polar vector.

4.404 The curl of a polar vector is an axial vector and the curl of an axial vector is a polar vector.

4.405 The scalar product of two polar or of two axial vectors is a true scalar, i.e., it keeps its sign if the axes to which the vectors are referred are reversed.

4.406 The scalar product of an axial vector and a polar vector is a pseudo-scalar, i.e., it changes in sign when the axes of reference are reversed.

4.407 The product or quotient of a polar vector and a true scalar is a polar vector; of an axial vector and a true scalar an axial vector; of a polar vector and a pseudo-scalar an axial vector; of an axial vector and a pseudo-scalar a polar vector.

4.408 The gradient of a true scalar is a polar vector; the gradient of a pseudo-scalar is an axial vector.

4.409 The divergence of a polar vector is a true scalar; of an axial vector a pseudo-scalar.

4.6 Linear Vector Functions.

4.610 A vector **Q** is a linear vector function of a vector **R** if its components, Q_1, Q_2, Q_3, along any three non-coplanar axes are linear functions of the components R_1, R_2, R_3 of **R** along the same axes.

4.611 Linear Vector Operator. If $\hat{\omega}$ is the linear vector operator,

$$\mathbf{Q} = \hat{\omega}\mathbf{R}.$$

This is equivalent to the three scalar equations,

$$\begin{aligned} Q_1 &= \omega_{11}R_1 + \omega_{12}R_2 + \omega_{13}R_3, \\ Q_2 &= \omega_{21}R_1 + \omega_{22}R_2 + \omega_{23}R_3, \\ Q_3 &= \omega_{31}R_1 + \omega_{32}R_2 + \omega_{33}R_3. \end{aligned}$$

4.612 If **a, b, c** are the three non-coplanar unit axes,

$$\begin{aligned} &\omega_{11} = S.\mathbf{a}\hat{\omega}\mathbf{a}, \quad &\omega_{21} = S.\mathbf{b}\hat{\omega}\mathbf{a}, \quad &\omega_{31} = S.\mathbf{c}\hat{\omega}\mathbf{a}, \\ &\omega_{12} = S.\mathbf{a}\hat{\omega}\mathbf{b}, \quad &\omega_{22} = S.\mathbf{b}\hat{\omega}\mathbf{b}, \quad &\omega_{32} = S.\mathbf{c}\hat{\omega}\mathbf{b}, \\ &\omega_{13} = S.\mathbf{a}\hat{\omega}\mathbf{c}, \quad &\omega_{23} = S.\mathbf{b}\hat{\omega}\mathbf{c} \quad &\omega_{33} = S.\mathbf{c}\hat{\omega}\mathbf{c}. \end{aligned}$$

4.613 The conjugate linear vector operator $\hat{\omega}'$ is obtained from $\hat{\omega}$ by replacing ω_{hk} by ω_{kh}; $h, k = 1, 2, 3$.

4.614 In the symmetrical, or self-conjugate linear vector operator, denoted by ω,

$$\omega = \tfrac{1}{2}(\hat{\omega} + \hat{\omega}').$$

Hence by **4.612**

$$S.\mathbf{a}\omega\mathbf{b} = S.\mathbf{b}\omega\mathbf{a}, \text{ etc.}$$

4.615 The general linear vector function $\hat{\omega}\mathbf{R}$ may always be resolved into the sum of a self-conjugate linear vector function of **R** and the vector product of **R** by a vector **c**:

$$\hat{\omega}\mathbf{R} = \omega\mathbf{R} + V.\mathbf{cR},$$

where

$$\omega = \tfrac{1}{2}(\hat{\omega} + \hat{\omega}'),$$

and

$$\mathbf{c} = \tfrac{1}{2}(\omega_{32} - \omega_{23})\mathbf{i} + \tfrac{1}{2}(\omega_{13} - \omega_{31})\mathbf{j} + \tfrac{1}{2}(\omega_{21} - \omega_{12})\mathbf{k},$$

if **i, j, k** are three mutually perpendicular unit vectors.

4.616 The general linear vector operator $\hat{\omega}$ may be determined by three non-coplanar vectors, **A, B, C,** where,

$$\mathbf{A} = \mathbf{a}\omega_{11} + \mathbf{b}\omega_{12} + \mathbf{c}\omega_{13},$$
$$\mathbf{B} = \mathbf{a}\omega_{21} + \mathbf{b}\omega_{22} + \mathbf{c}\omega_{23},$$
$$\mathbf{C} = \mathbf{a}\omega_{31} + \mathbf{b}\omega_{32} + \mathbf{c}\omega_{33},$$

and

$$\hat{\omega} = \mathbf{a}S.\mathbf{A} + \mathbf{b}S.\mathbf{B} + \mathbf{c}S.\mathbf{C}.$$

4.617 If $\hat{\omega}$ is the general linear vector operator and $\hat{\omega}'$ its conjugate,

$$\hat{\omega}\mathbf{R} = \mathbf{R}\hat{\omega}',$$
$$\hat{\omega}'\mathbf{R} = \mathbf{R}\hat{\omega}$$

4.620 The symmetrical or self-conjugate linear vector operator has three mutually perpendicular axes. If these be taken along **i, j, k,**

$$\omega = \mathbf{i}S.\omega_1\mathbf{i} + \mathbf{j}S.\omega_2\mathbf{j} + \mathbf{k}S.\omega_3\mathbf{k},$$

where ω_1, ω_2, ω_3 are scalar quantities, the principal values of ω.

4.621 Referred to any system of three mutually perpendicular unit vectors, **a, b, c,** the self-conjugate operator, ω, is determined by the three vectors (**4.616**):

$$\mathbf{A} = \omega\mathbf{a} = \mathbf{a}\omega_{11} + \mathbf{b}\omega_{12} + \mathbf{c}\omega_{13},$$
$$\mathbf{B} = \omega\mathbf{b} = \mathbf{a}\omega_{21} + \mathbf{b}\omega_{22} + \mathbf{c}\omega_{23},$$
$$\mathbf{C} = \omega\mathbf{c} = \mathbf{a}\omega_{31} + \mathbf{b}\omega_{32} + \mathbf{c}\omega_{33},$$

where

$$\omega_{hk} = \omega_{kh},$$
$$\omega = \mathbf{a}S.\mathbf{A} + \mathbf{b}S.\mathbf{B} + \mathbf{c}S.\mathbf{C}.$$

4.622 If n is one of the principal values, ω_1, ω_2, ω_3, these are given by the roots of the cubic,

$$n^3 - n^2(S.\mathbf{Aa} + S.\mathbf{Bb} + S.\mathbf{Cc}) + n(S.\mathbf{a}V\mathbf{BC} + S.\mathbf{b}V\mathbf{CA} + \mathrm{S}.\mathbf{c}V\mathbf{A}B)$$
$$- S.\mathbf{A}V\mathbf{BC} = 0.$$

4.623 In transforming from one to another system of rectangular axes the following are invariant:

$$S.\mathbf{Aa} + S.\mathbf{Bb} + S.\mathbf{Cc} = \omega_1 + \omega_2 + \omega_3.$$
$$S\mathbf{a}V\mathbf{BC} + S.\mathbf{b}V\mathbf{CA} + S.\mathbf{c}V\mathbf{AB} = \omega_2\omega_3 + \omega_3\omega_1 + \omega_1\omega_2.$$
$$S.\mathbf{A}V\mathbf{BC} = \omega_1\omega_2\omega_3.$$

4.624

$$\omega_1 + \omega_2 + \omega_3 = \omega_{11} + \omega_{22} + \omega_{33},$$
$$\omega_2\omega_3 + \omega_3\omega_1 + \omega_1\omega_2 = \omega_{22}\omega_{33} + \omega_{33}\omega_{11} + \omega_{11}\omega_{22} - \omega^2{}_{23} - \omega^2{}_{31} + \omega^2{}_{12},$$
$$\omega_1\omega_2\omega_3 = \omega_{11}\omega_{22}\omega_{33} + 2\omega_{23}\omega_{31}\omega_{12} - \omega_{11}\omega^2{}_{23} - \omega_{22}\omega^2{}_{31} - \omega_{33}\omega^2{}_{12}.$$

4.625 The principal axes of the self-conjugate operator, ω, are those of the quadric:

$$\omega_{11}x^2 + \omega_{22}y^2 + \omega_{33}z^2 + 2\omega_{23}yz + 2\omega_{31}zx + 2\omega_{12}xy = \text{const.},$$

where x, y, z are rectangular axes in the direction of **a, b, c** respectively.

4.626 Referred to its principal axes the equation of the quadric is,

$$\omega_1 x^2 + \omega_2 y^2 + \omega_3 z^2 = \text{const.}$$

4.627 Applying the self-conjugate operator, ω, successively,

$$\omega\mathbf{R} = \mathbf{i}\omega_1 R_1 + \mathbf{j}\omega_2 R_2 + \mathbf{k}\omega_3 R_3,$$
$$\omega\omega\mathbf{R} = \omega^2\mathbf{R} = \omega_1{}^2 R_1 + \mathbf{j}\omega_2{}^2 R_2 + \mathbf{k}\omega_3{}^2 R_3,$$
$$\omega\omega^2\mathbf{R} = \omega^3\mathbf{R} = \mathbf{i}\omega_1{}^3 R_1 + \mathbf{j}\omega_2{}^3 R_2 + \mathbf{k}\omega_3{}^3 R_3,$$

. . .

. . .

$$\omega^{-1}\mathbf{R} = \mathbf{i}\frac{R_1}{\omega_1} + \mathbf{j}\frac{R_2}{\omega_2} + \mathbf{k}\frac{R_3}{\omega_3}.$$

. . .

. . .

4.628 Applying a number of self-conjugate operators, α, β, ..., all with the same axes but with different principal values $(\alpha_1\alpha_2\alpha_3)$, $(\beta_1\beta_2\beta_3)$, ...

$$\alpha\mathbf{R} = \mathbf{i}\alpha\ R_1 + \mathbf{j}\alpha_2 R_2 + \mathbf{k}\alpha_3 R_3,$$
$$\beta\alpha\mathbf{R} = \alpha\beta\mathbf{R} = \mathbf{i}\alpha_1\beta_1 R_1 + \mathbf{j}\alpha_2\beta_2 R_2 + \mathbf{k}\alpha_3\beta_3 R_3.$$

. . .

4.629

$$S.\mathbf{Q}\omega\mathbf{R} = S.\mathbf{R}\omega Q,$$
$$= \omega_1 Q_1 R_1 + \omega_2 Q_2 R_2 + \omega_3 Q_3 R_3.$$

V. CURVILINEAR COÖRDINATES

5.00 Given three surfaces.

1.
$$\begin{cases} u = f_1(x, y, z), \\ v = f_2(x, y, z), \\ w = f_3(x, y, z). \end{cases}$$

2.
$$\begin{cases} x = \phi_1(u, v, w), \\ y = \phi_2(u, v, w), \\ z = \phi_3(u, v, w). \end{cases}$$

3.
$$\begin{cases} \dfrac{1}{h_1^2} = \left(\dfrac{\partial \phi_1}{\partial u}\right)^2 + \left(\dfrac{\partial \phi_2}{\partial u}\right)^2 + \left(\dfrac{\partial \phi_3}{\partial u}\right)^2, \\ \dfrac{1}{h_2^2} = \left(\dfrac{\partial \phi_1}{\partial v}\right)^2 + \left(\dfrac{\partial \phi_2}{\partial v}\right)^2 + \left(\dfrac{\partial \phi_3}{\partial v}\right)^2, \\ \dfrac{1}{h_3^2} = \left(\dfrac{\partial \phi_1}{\partial w}\right)^2 + \left(\dfrac{\partial \phi_2}{\partial w}\right)^2 + \left(\dfrac{\partial \phi_3}{\partial w}\right)^2. \end{cases}$$

4.
$$\begin{cases} g_1 = \dfrac{\partial \phi_1}{\partial v}\dfrac{\partial \phi_1}{\partial w} + \dfrac{\partial \phi_2}{\partial v}\dfrac{\partial \phi_2}{\partial w} + \dfrac{\partial \phi_3}{\partial v}\dfrac{\partial \phi_3}{\partial w}, \\ g_2 = \dfrac{\partial \phi_1}{\partial w}\dfrac{\partial \phi_1}{\partial u} + \dfrac{\partial \phi_2}{\partial w}\dfrac{\partial \phi_2}{\partial u} + \dfrac{\partial \phi_3}{\partial w}\dfrac{\partial \phi_3}{\partial u}, \\ g_3 = \dfrac{\partial \phi_1}{\partial u}\dfrac{\partial \phi_1}{\partial v} + \dfrac{\partial \phi_2}{\partial u}\dfrac{\partial \phi_2}{\partial v} + \dfrac{\partial \phi_3}{\partial u}\dfrac{\partial \phi_3}{\partial v}. \end{cases}$$

5.01 The linear element of arc, ds, is given by:

$$ds^2 = dx^2 + dy^2 + dz^2 = \frac{du^2}{h_1^2} + \frac{dv^2}{h_2^2} + \frac{dw^2}{h_3^2} + 2g_1\, dv\, dw + 2g_2\, dw\, du + 2g_3\, du\, dv.$$

5.02 The surface elements, areas of parallelograms on the three surfaces, are:

$$dS_u = \frac{dv\, dw}{h_2 h_3}\sqrt{1 - h_2^2 h_3^2 g_1^2},$$

$$dS_v = \frac{dw\, du}{h_3 h_1}\sqrt{1 - h_3^2 h_1^2 g_2^2},$$

$$dS_w = \frac{du\, dv}{h_1 h_2}\sqrt{1 - h_1^2 h_2^2 g_3^2}.$$

5.03 The volume of an elementary parallelepipedon is:

$$d\tau = \frac{du\,dv\,dw}{h_1h_2h_3}\left\{1 - h_1^2h_2^2g_3^2 - h_2^2h_3^2g_1^2 - h_3^2h_1^2g_2^2 + h_1^2h_2^2h_3^2g_1g_2g_3\right\}^{\frac{1}{2}}$$

5.04 ω_1, ω_2, ω_3 are the angles between the normals to the surface f_2, f_3; f_3, f_1; f_1, f_2 respectively:

$$\cos\omega_1 = h_2h_3g_1,$$
$$\cos\omega_2 = h_3h_1g_2,$$
$$\cos\omega_3 = h_1h_2g_3.$$

5.05 Orthogonal Curvilinear Coördinates.

$$g_1 = g_2 = g_3 = 0,$$
$$ds^2 = \frac{du^2}{h_1^2} + \frac{dv^2}{h_2^2} + \frac{dw^2}{h_3^2},$$
$$dS_u = \frac{dv\ dw}{h_2h_3},\quad dS_v = \frac{dw\ du}{h_3h_1},\quad dS_w = \frac{du\ dv}{h_1h_2},$$
$$d\tau = \frac{du\ dv\ dw}{h_1h_2h_3}.$$

5.06 h_1^2, h_2^2, h_3^2 are given by **5.00** (3) and also by:

$$h_1^2 = \left(\frac{\partial f_1}{\partial x}\right)^2 + \left(\frac{\partial f_1}{\partial y}\right)^2 + \left(\frac{\partial f_1}{\partial z}\right)^2,$$
$$h_2^2 = \left(\frac{\partial f_2}{\partial x}\right)^2 + \left(\frac{\partial f_2}{\partial y}\right)^2 + \left(\frac{\partial f_2}{\partial z}\right)^2,$$
$$h_3^2 = \left(\frac{\partial f_3}{\partial x}\right)^2 + \left(\frac{\partial f_3}{\partial y}\right)^2 + \left(\frac{\partial f_3}{\partial z}\right)^2.$$

5.07 A vector, **A,** will have three components in the directions of the normals to the orthogonal surfaces u, v, w:

$$A = \sqrt{A_u^2 + A_v^2 + A_w^2}.$$

5.08

1. $$\operatorname{div} \mathbf{A} = h_1 h_2 h_3 \left\{ \frac{\partial}{\partial u}\left(\frac{A_u}{h_2 h_3}\right) + \frac{\partial}{\partial v}\left(\frac{A_v}{h_3 h_1}\right) + \frac{\partial}{\partial w}\left(\frac{A_w}{h_1 h_2}\right) \right\}.$$

2. $$\nabla^2 = h_1 h_2 h_3 \left\{ \frac{\partial}{\partial u}\left(\frac{h_1}{h_2 h_3}\frac{\partial}{\partial u}\right) + \frac{\partial}{\partial v}\left(\frac{h_2}{h_3 h_1}\frac{\partial}{\partial v}\right) + \frac{\partial}{\partial w}\left(\frac{h_3}{h_1 h_2}\frac{\partial}{\partial w}\right) \right\}.$$

3. $$\begin{cases} \operatorname{curl}_u \mathbf{A} = h_2 h_3 \left\{ \dfrac{\partial}{\partial v}\left(\dfrac{A_w}{h_3}\right) - \dfrac{\partial}{\partial w}\left(\dfrac{A_v}{h_2}\right) \right\}, \\ \operatorname{curl}_v \mathbf{A} = h_3 h_1 \left\{ \dfrac{\partial}{\partial w}\left(\dfrac{A_u}{h_1}\right) - \dfrac{\partial}{\partial u}\left(\dfrac{A_w}{h_3}\right) \right\}, \\ \operatorname{curl}_w \mathbf{A} = h_1 h_2 \left\{ \dfrac{\partial}{\partial u}\left(\dfrac{A_v}{h_2}\right) - \dfrac{\partial}{\partial v}\left(\dfrac{A_u}{h_1}\right) \right\}. \end{cases}$$

5.09 The gradient of a scalar function, ψ, has three components in the directions of the normals to the three orthogonal surfaces:

$$h_1 \frac{\partial \psi}{\partial u},\ h_2 \frac{\partial \psi}{\partial v},\ h_3 \frac{\partial \psi}{\partial w}.$$

5.20 Spherical Polar Coördinates.

1. $$\begin{cases} u = r, \\ v = \theta, \\ w = \phi. \end{cases}$$

2. $$\begin{cases} x = r \sin\theta \cos\phi. \\ y = r \sin\theta \sin\phi, \\ z = r \cos\theta. \end{cases}$$

3. $$h_1 = 1,\ h_2 = \frac{1}{r},\ h_3 = \frac{1}{r \sin\theta}.$$

4. $$\begin{cases} dS_r = r^2 \sin\theta \, d\theta \, d\phi, \\ dS_\theta = r \sin\theta \, dr \, d\phi, \\ dS_\phi = r \, dr \, d\theta. \end{cases}$$

5. $$d\tau = r^2 \sin\theta \, dr \, d\theta \, d\phi.$$

6. $$\operatorname{div} \mathbf{A} = \frac{1}{r^2 \sin\theta} \left\{ \sin\theta \frac{\partial}{\partial r}\left(r^2 A_r\right) + r \frac{\partial}{\partial \theta}\left(\sin\theta \, A_\theta\right) + r \frac{\partial A_\phi}{\partial \phi} \right\}.$$

7. $$\nabla^2 = \frac{1}{r^2 \sin\theta} \left\{ \sin\theta \frac{\partial}{\partial r}\left(r^2 \frac{\partial}{\partial r}\right) + \frac{\partial}{\partial \theta}\left(\sin\theta \frac{\partial}{\partial \theta}\right) + \frac{1}{\sin\theta}\frac{\partial^2}{\partial \phi^2} \right\}.$$

8.
$$\begin{cases} \operatorname{curl}_r \mathbf{A} = \dfrac{1}{r \sin\theta}\left\{\dfrac{\partial}{\partial\theta}\left(\sin\theta\, A_\phi\right) - \dfrac{\partial A_\phi}{\partial\phi}\right\}, \\ \operatorname{curl}_\theta \mathbf{A} = \dfrac{1}{r \sin\theta}\left\{\dfrac{\partial A_r}{\partial\phi} - \sin\theta\dfrac{\partial(rA_\phi)}{\partial r}\right\}, \\ \operatorname{curl}_\phi \mathbf{A} = \dfrac{1}{r}\left\{\dfrac{\partial}{\partial r}\left(r\, A_\theta\right) - \dfrac{\partial A_r}{\partial\theta}\right\}. \end{cases}$$

5.21 Cylindrical Coördinates.

1.
$$\begin{cases} u = \rho, \\ v = \theta, \\ w = z. \end{cases}$$

2.
$$\begin{cases} x = \rho\cos\theta, \\ y = \rho\sin\theta, \\ z = z. \end{cases}$$

3.
$$h_1 = 1, \quad h_2 = \frac{1}{\rho}, \quad h_3 = 1.$$

4.
$$\begin{cases} dS_r = \rho\, d\theta\, dz, \\ dS_\theta = dz\, d\rho, \\ dS_z = \rho\, d\rho\, d\theta. \end{cases}$$

5.
$$d\tau = \rho d\rho d\theta dz.$$

6.
$$\operatorname{div} \mathbf{A} = \frac{1}{\rho}\left\{\frac{\partial}{\partial\rho}\left(\rho A_\rho\right) + \frac{\partial A_\theta}{\partial\theta} + \rho\frac{\partial A_z}{\partial z}\right\}.$$

7.
$$\nabla^2 = \frac{1}{\rho}\left\{\frac{\partial}{\partial\rho}\left(\rho\frac{\partial}{\partial\rho}\right) + \frac{1}{\rho}\frac{\partial^2}{\partial\theta^2} + \rho\frac{\partial^2}{\partial z^2}\right\}.$$

8.
$$\begin{cases} \operatorname{curl}_\rho \mathbf{A} = \dfrac{1}{\rho}\dfrac{\partial A_z}{\partial\theta} - \dfrac{\partial A_\theta}{\partial z}. \\ \operatorname{curl}_\theta \mathbf{A} = \dfrac{\partial A_\rho}{\partial z} - \dfrac{\partial A_z}{\partial\rho}. \\ \operatorname{curl}_z \mathbf{A} = \dfrac{1}{\rho}\left\{\dfrac{\partial}{\partial\rho}(\rho A_\theta) - \dfrac{\partial A_\rho}{\partial\theta}\right\}. \end{cases}$$

5.22 Ellipsoidal Coördinates.

u, v, w are the three roots of the equation:

1.
$$\frac{x^2}{a^2+\theta} + \frac{y^2}{b^2+\theta} + \frac{z^2}{c^2+\theta} = 1.$$

$$a > b > c, \qquad u > v > w.$$

$\theta = u$: Ellipsoid.
$\theta = v$: Hyperboloid of one sheet.
$\theta = w$: Hyperboloid of two sheets.

2. $$\begin{cases} x^2 = \dfrac{(a^2+u)\,(a^2+v)\,(a^2+w)}{(a^2-b^2)\,(a^2-c^2)}, \\[2ex] y^2 = -\dfrac{(b^2+u)\,(b^2+v)\,(b^2+w)}{(b^2-c^2)\,(a^2-b^2)}, \\[2ex] z^2 = \dfrac{(c^2+u)\,(c^2+v)\,(c^2+w)}{(a^2-c^2)\,(b^2-c^2)}. \end{cases}$$

3. $$\begin{cases} h_1{}^2 = \dfrac{4(a^2+u)\,(b^2+u)\,(c^2+u)}{(u-v)\,(u-w)}, \\[2ex] h_2{}^2 = \dfrac{4(a^2+v)\,(b^2+v)\,(c^2+v)}{(v-w)\,(v-u)}, \\[2ex] h_3{}^2 = \dfrac{4(a^2+w)\,(b^2+w)\,(c^2+w)}{(w-u)\,(w-v)}. \end{cases}$$

4. $$\begin{aligned} \operatorname{div} \mathbf{A} = {} & 2\,\frac{\sqrt{(a^2+u)\,(b^2+u)\,(c^2+u)}}{(u-v)\,(u-w)}\,\frac{\partial}{\partial u}\left(\sqrt{(u-v)\,(u-w)}\,A_u\right) \\ & + 2\,\frac{\sqrt{(a^2+v)\,(b^2+v)\,(c^2+v)}}{(v-w)\,(u-v)}\,\frac{\partial}{\partial v}\left(\sqrt{(w-v)\,(u-v)}\,A_v\right) \\ & + 2\,\frac{\sqrt{(a^2+w)\,(b^2+w)\,(c^2+w)}}{(u-w)\,(v-w)}\,\frac{\partial}{\partial w}\left(\sqrt{(u-w)\,(v-w)}\,A_w\right). \end{aligned}$$

5. $$\begin{aligned} \nabla^2 = {} & 4\,\frac{\sqrt{(a^2+u)\,(b^2+u)\,(c^2+u)}}{(u-v)\,(u-w)}\,\frac{\partial}{\partial u}\left(\sqrt{(a^2+u)\,(b^2+u)\,(c^2+u)}\,\frac{\partial}{\partial u}\right) \\ & + 4\,\frac{\sqrt{(a^2+v)\,(^2+v)\,(bc^2+v)}}{(u-v)\,(v-w)}\,\frac{\partial}{\partial v}\left(\sqrt{(a^2+v)\,(b^2+v)\,(c^2+v)}\,\frac{\partial}{\partial v}\right) \\ & + 4\,\frac{\sqrt{(a^2+w)\,(b^2+w)\,(c^2+w)}}{(a-w)\,(v-w)}\,\frac{\partial}{\partial w}\left(\sqrt{(a^2+w)\,(b^2+w)\,(c^2+w)}\,\frac{\partial}{\delta w}\right). \end{aligned}$$

6. $$\begin{cases} \operatorname{curl}_u \mathbf{A} = \dfrac{2}{v-w}\left\{\sqrt{\dfrac{(a^2+v)\,(b^2+v)\,(c^2+v)}{u-v}}\,\dfrac{\partial}{\partial v}\left(\sqrt{w-v}\,A_w\right)\right. \\[2ex] \qquad\qquad \left. -\sqrt{\dfrac{(a^2+w)\,(b^2+w)\,(c^2+w)}{u-w}}\,\dfrac{\partial}{\partial w}\left(\sqrt{v-w}\,A_v\right)\right\}. \end{cases}$$

7. $$\begin{cases} \operatorname{curl}_v \mathbf{A} = \dfrac{2}{u-w}\left\{\sqrt{\dfrac{(a^2+w)\,(b^2+w)\,(c^2+w)}{v-w}}\,\dfrac{\partial}{\partial w}\left(\sqrt{u-w}\,A_u\right)\right. \\[2ex] \qquad\qquad \left. -\sqrt{\dfrac{(a^2+u)\,(b^2+u)\,(c^2+u)}{v-u}}\,\dfrac{\partial}{\partial u}\left(\sqrt{w-u}\,A_w\right)\right\} \\[2ex] \operatorname{curl}_w \mathbf{A} = \dfrac{2}{u-v}\left\{\sqrt{\dfrac{(a^2+u)\,(b^2+u)\,(c^2+u)}{w-u}}\,\dfrac{\partial}{\partial u}\left(\sqrt{v-u}\,A_v\right)\right. \\[2ex] \qquad\qquad \left. -\sqrt{\dfrac{(a^2+v)\,(b^2+v)\,(c^2+v)}{w-v}}\,\dfrac{\partial}{\partial v}\left(\sqrt{u-v}\,A_u\right)\right\}. \end{cases}$$

5.23 Conical Coördinates.

The three orthogonal surfaces are: the spheres,

1. $$x^2 + y^2 + z^2 = u^2,$$

the two cones:

2. $$\frac{x^2}{v^2} + \frac{y^2}{v^2 - b^2} + \frac{z^2}{v^2 - c^2} = 0.$$

3. $$\frac{x^2}{w^2} + \frac{y^2}{w^2 - b^2} + \frac{z^2}{w^2 - c^2} = 0.$$

$$c^2 > v^2 > b^2 > w^2.$$

4. $$\begin{cases} x^2 = \dfrac{u^2 v^2 w^2}{b^2 c^2}, \\[2ex] y^2 = \dfrac{u^2(v^2 - b^2)(w^2 - b^2)}{b^2(b^2 - c^2)}, \\[2ex] z^2 = \dfrac{u^2(v^2 - c^2)(w^2 - c^2)}{c^2(c^2 - b^2)}. \end{cases}$$

5. $$h_1 = 1, \quad h_2^2 = \frac{(v^2 - b^2)(c^2 - v^2)}{u^2(v^2 - w^2)}, \quad h_3^2 = \frac{(b^2 - w^2)(c^2 - w^2)}{u^2(v^2 - w^2)}.$$

6. $$\operatorname{div} \mathbf{A} = \frac{1}{u^2}\frac{\partial}{\partial u}(u^2 A_u) + \frac{\sqrt{(v^2 - b^2)(c^2 - v^2)}}{u(v^2 - w^2)}\frac{\partial}{\partial v}\left(\sqrt{v^2 - w^2}\, A_v\right)$$
$$+ \frac{\sqrt{(b^2 - w^2)(c^2 - w^2)}}{u(v^2 - w^2)}\frac{\partial}{\partial w}\left(\sqrt{v^2 - w^2}\, A_w\right).$$

7. $$\nabla^2 = \frac{1}{u^2}\frac{\partial}{\partial u}\left(u^2\frac{\partial}{\partial u}\right) + \frac{\sqrt{(v^2 - b^2)(c^2 - v^2)}}{u^2(v^2 - w^2)}\frac{\partial}{\partial v}\left(\sqrt{(v^2 - b^2)(c^2 - v^2)}\,\frac{\partial}{\partial v}\right).$$
$$+ \frac{\sqrt{(b^2 - w^2)(c^2 - w^2)}}{u^2(v^2 - w^2)}\frac{\partial}{\partial w}\left(\sqrt{(b^2 - w^2)(c^2 - w^2)}\,\frac{\partial}{\partial w}\right).$$

8. $$\begin{cases} \operatorname{curl}_u \mathbf{A} = \dfrac{1}{u(v^2 - w^2)}\left\{\sqrt{(v^2 - b^2)(c^2 - v^2)}\,\dfrac{\partial}{\partial v}\left(\sqrt{v^2 - w^2}\, A_w\right)\right. \\[2ex] \qquad\qquad \left. - \sqrt{(b^2 - w^2)(c^2 - w^2)}\,\dfrac{\partial}{\partial w}\left(\sqrt{v^2 - w^2}\;A_v\right)\right\}; \\[2ex] \operatorname{curl}_v \mathbf{A} = \dfrac{\sqrt{(b^2 - w^2)(c^2 - w^2)}}{u\sqrt{v^2 - w^2}}\,\dfrac{\partial A_u}{\partial w} - \dfrac{1}{u}\dfrac{\partial}{\partial u}\left(uA_u\right)\Big\}, \\[2ex] \operatorname{curl}_w \mathbf{A} = \dfrac{1}{u}\dfrac{\partial}{\partial u}\left(uA_v\right) - \dfrac{\sqrt{(v^2 - b^2)(c^2 - v^2)}}{u\sqrt{v^2 - w^2}}\,\dfrac{\partial A_u}{\partial v}. \end{cases}$$

5.30 Elliptic Cylinder Coördinates.

The three orthogonal surfaces are:

1. The elliptic cylinders:

$$\frac{x^2}{c^2 u^2} + \frac{y^2}{c^2(u^2 - 1)} = 1.$$

2. The hyperbolic cylinders:

$$\frac{x^2}{c^2v^2} - \frac{y^2}{c^2(1 - v^2)} = 1.$$

3. The planes: $z = w.$

$2c$ is the distance between the foci of the confocal ellipses and hyperbolas:

4. $$x = cuv.$$

5. $$y = c\sqrt{u^2 - 1}\ \sqrt{1 - v^2}.$$

6. $$\frac{1}{h_1^2} = \frac{1}{h_2^2} = c^2(u^2 - v^2), \quad h_3 = 1.$$

7. $$\operatorname{div} \mathbf{A} = \frac{1}{c(u^2 - v^2)} \left\{ \frac{\partial}{\partial u}\left(\sqrt{u^2 - v^2}\, A_u\right) + \frac{\partial}{\partial v}\left(\sqrt{u^2 - v^2}\, A_v\right) \right\} + \frac{\partial A_z}{\partial z}.$$

8. $$\nabla^2 = \frac{1}{c^2(u^2 - v^2)}\left(\frac{\partial^2}{\partial u^2} + \frac{\partial^2}{\partial v^2}\right) + \frac{\partial^2}{\partial z^2}.$$

9. $$\begin{cases} \operatorname{curl}_u \mathbf{A} = \dfrac{1}{c\sqrt{u^2 - v^2}}\, \dfrac{\partial A_z}{\partial v} - \dfrac{\partial A_v}{\partial z}, \\[2ex] \operatorname{curl}_v \mathbf{A} = \dfrac{\partial A_u}{\partial z} - \dfrac{1}{c\sqrt{u^2 - v^2}}\, \dfrac{\partial A_z}{\partial u}, \\[2ex] \operatorname{curl}_z \mathbf{A} = \dfrac{1}{c(u^2 - v^2)} \left\{ \dfrac{\partial}{\partial u}\left(\sqrt{u^2 - v^2}\, A_v\right) - \dfrac{\partial}{\partial v}\left(\sqrt{u^2 - v^2}\, A_u\right) \right\}. \end{cases}$$

5.31 Parabolic Cylinder Coördinates.

The three orthogonal surfaces are the two parabolic cylinders:

1. $$y^2 = 4cux + 4c^2u^2.$$

2. $$y^2 = -4cvx + 4c^2v^2.$$

And the planes:

3. $$z = w.$$

4. $$x = c(v - u).$$

5. $$y = 2c\sqrt{uv}.$$

6. $$\frac{1}{h_1^2} = \frac{u + v}{u}, \quad \frac{1}{h_2^2} = \frac{u + v}{v}, \quad h_3 = 1.$$

7. $$\operatorname{div} \mathbf{A} = \frac{\sqrt{uv}}{u + v} \left\{ \frac{\partial}{\partial u}\left(\sqrt{\frac{u + v}{v}}\, A_u\right) + \frac{\partial}{\partial v}\left(\sqrt{\frac{u + v}{u}}\, A_v\right) \right\} + \frac{\partial A_z}{\partial z}.$$

8. $$\nabla^2 = \frac{\sqrt{uv}}{u + v} \left\{ \frac{\partial}{\partial u}\left(\frac{u}{v}\frac{\partial}{\partial u}\right) + \frac{\partial}{\partial v}\left(\frac{v}{u}\frac{\partial}{\partial v}\right) \right\} + \frac{\partial^2}{\partial z^2}.$$

9.
$$\begin{cases} \operatorname{curl}_u \mathbf{A} = \sqrt{\dfrac{v}{u+v}}\,\dfrac{\partial A_z}{\partial v} - \dfrac{v}{u+v}\,\dfrac{\partial A_v}{\partial z}, \\ \operatorname{curl}_v \mathbf{A} = \dfrac{u}{u+v}\,\dfrac{\partial A_u}{\partial z} - \sqrt{\dfrac{u}{u+v}}\,\dfrac{\partial A_z}{\partial u}, \\ \operatorname{curl}_z \mathbf{A} = \dfrac{\sqrt{uv}}{u+v}\left\{\dfrac{\partial}{\partial u}\left(\sqrt{\dfrac{v}{u+v}}\,A_v\right) - \dfrac{\partial}{\partial v}\left(\sqrt{\dfrac{u}{u+v}}\,A_u\right)\right\}. \end{cases}$$

5.40 Helical Coördinates. (Nicholson, Phil. Mag. 19, 77, 1910.)

A cylinder of any cross-section is wound on a circular cylinder in the form of a helix of angle α. a = radius of circular cylinder on which the central line of the normal cross-sections of the helical cylinder lies. The z-axis is along the axis of the cylinder of radius a.

$u = \rho$ and $v = \phi$ are the polar coördinates in the plane of any normal section of the helical cylinder. ϕ is measured from a line perpendicular to z and to the tangent to the cylinder.

$w = \theta$ = the twist in a plane perpendicular to z of the radius in that plane measured from a line parallel to the x-axis:

1.
$$\begin{cases} x = (a + \rho\cos\phi)\cos\theta + \rho\sin\alpha\sin\theta\sin\phi, \\ y = (a + \rho\cos\phi)\sin\theta - \rho\sin\alpha\cos\theta\sin\phi, \\ z = a\,\theta\tan\alpha + \rho\cos\alpha\sin\phi. \end{cases}$$

2.
$$\begin{cases} h_1 = 1, \quad h_2 = \dfrac{1}{\rho}, \\ h_3^2 = \dfrac{1}{a^2\sec^2\alpha + 2a\rho\cos\phi + \rho^2(\cos^2\phi + \sin^2\alpha\sin^2\phi)}. \end{cases}$$

5.50 Surfaces of Revolution.

z-axis = axis of revolution.

ρ, θ = polar coördinates in any plane perpendicular to z-axis.

1.
$$ds^2 = dz^2 + d\rho^2 + \rho^2 d\theta^2$$
$$= \frac{du^2}{h_1^2} + \frac{dv^2}{h_2^2} + \frac{dw^2}{h_3^2}.$$

In any meridian plane, z, ρ, determine u, v, from:

2.
$$f(z + i\rho) = u + iv.$$

3.
$$w = \theta.$$

Then u, v, θ will form a system of orthogonal curvilinear coördinates.

5.51 Spheroidal Coördinates (Prolate Spheroids):

1. $$z + i\rho = c \cosh (u + iv).$$

2. $$\begin{cases} z = c \cosh u \cos v, \\ \rho = c \sinh u \sin v. \end{cases}$$

The three orthogonal surfaces are the ellipsoids and hyperboloids of revolution, and the planes, θ:

3. $$\begin{cases} \dfrac{z^2}{c^2 \cosh^2 u} + \dfrac{\rho^2}{c^2 \sinh^2 u} = 1, \\ \dfrac{z^2}{c^2 \cos^2 v} - \dfrac{\rho^2}{c^2 \sin^2 v} = 1. \end{cases}$$

With $\cos u = \lambda$, $\cos v = \mu$:

4. $$\begin{cases} z = c\,\lambda\,\mu, \\ \rho = c\sqrt{(\lambda^2 - 1)\,(1 - \mu^2)}. \end{cases}$$

5. $$h_1^2 = \frac{\lambda^2 - 1}{c^2(\lambda^2 - \mu^2)}, \quad h_2^2 = \frac{1 - \mu^2}{c^2\,(\lambda^2 - \mu^2)}, \quad h_3^2 = \frac{1}{c^2(\lambda^2 - 1)\,(1 - \mu^2)}.$$

5.52 Spheroidal Coördinates (Oblate Spheroids):

1. $$\rho + iz = c \cosh(u + iv).$$

2. $$z = c \sinh u \sin v.$$
$$\rho = c \cosh u \cos v.$$

3. $$\cosh u = \lambda, \quad \cos v = \mu.$$

4. $$h_1^2 = \frac{1 - \mu^2}{c^2(\lambda^2 - \mu^2)}, \quad h_2^2 = \frac{\lambda^2 - 1}{c^2(\lambda^2 - \mu^2)}, \quad h_3^2 = \frac{1}{c^2(\lambda^2 - 1)\,(1 - \mu^2)}.$$

5.53 Parabolic Coördinates:

1. $$z + i\rho = c(u + iv)^2.$$

2. $$\begin{cases} z = c(u^2 - v^2), \\ \rho = 2cuv. \end{cases}$$

3. $$u^2 = \lambda, \quad v^2 = \mu.$$

With curvilinear coördinates, λ, μ, θ:

4. $$h_1 = \frac{1}{c}\sqrt{\frac{\lambda}{\lambda+\mu}}, \quad h_2 = \frac{1}{c}\sqrt{\frac{\mu}{\lambda+\mu}}, \quad h_3 = \frac{1}{2c\sqrt{\lambda\mu}}.$$

5.54 Toroidal Coördinates:

1. $$u + iv = \log\frac{z+a+i\rho}{z-a+i\rho},$$

$$\rho = \frac{a\sinh u}{\cosh u - \cos v}.$$

2. $$z = \frac{a\sin v}{\cosh u - \cos v}.$$

3. $$h_1 = h_2 = \frac{\cosh u - \cos v}{a}, \quad h_3 = \frac{\cosh u - \cos v}{a\sinh u}.$$

The three orthogonal surfaces are:

(a) Anchor rings, whose axial circles have radii,

$$a\coth u,$$

and whose cross-sections are circles of radii,

$$a\operatorname{csch} u;$$

(b) Spheres, whose centers are on the axis of revolution at distances,

$$\pm a\cot v,$$

from the origin, whose radii are,

$$a\csc v,$$

and which accordingly have a common circle,

$$\rho = a,\ z = 0;$$

(c) Planes through the axis,

$$w = \theta = \text{const.}$$

VI. INFINITE SERIES

6.00 An infinite series:

$$\sum_{n=1}^{\infty} u_n = u_1 + u_2 + u_3 + \ldots .$$

is absolutely convergent if the series formed of the moduli of its terms:

$$|u_1| + |u_2| + |u_2| + \ldots .$$

is convergent.

A series which is convergent, but whose moduli do not form a convergent series, is conditionally convergent.

TESTS FOR CONVERGENCE

6.011 Comparison test. The series Σu_n is absolutely convergent if $|u_n|$ is less than $C|v_n|$ where C is a number independent of n, and v_n is the nth term of another series which is known to be absolutely convergent.

6.012 Cauchy's test. If

$$\operatorname*{Limit}_{n\to\infty} |u_n|^{\frac{1}{n}} < 1,$$

the series Σu_n is absolutely convergent.

6.013 D'Alembert's test. If for all values of n greater than some fixed value, r, the ratio $\left|\frac{u_{n+1}}{u_n}\right|$ is less than ρ, where ρ is a positive number less than unity and independent of n, the series Σu_n is absolutely convergent.

6.014 Cauchy's integral test. Let $f(x)$ be a steadily decreasing positive function such that,

$$f(n) \geqq a_n.$$

Then the positive term series Σa_n is convergent if,

$$\int_m^\infty f(x)dx,$$

is convergent.

6.015 Raabe's test. The positive term series Σa_n is convergent if,

$$n\left(\frac{a_n}{a_{n+1}} - 1\right) \geqq l \quad \text{where } l > 1.$$

It is divergent if,

$$n\left(\frac{a_n}{a_{n+1}} - 1\right) \leqq 1 .$$

6.020 Alternating series. A series of real terms, alternately positive and negative, is convergent if $a_{n+1} \leqslant a_n$ and

$$\lim_{n \to \infty} a_n = 0.$$

In such a series the sum of the first s terms differs from the sum of the series by a quantity less than the numerical value of the $(s + 1)st$ term.

6.025 If $\displaystyle\lim_{n \to \infty} \left| \frac{u_{n+1}}{u_n} \right| = 1$, the series Σu_n will be absolutely convergent if there is a positive number c, independent of n, such that,

$$\lim_{n \to \infty} n \left\{ \left| \frac{u_{n+1}}{u_n} \right| - 1 \right\} = -1 - c.$$

6.030 The sum of an absolutely convergent series is not affected by changing the order in which the terms occur.

6.031 Two absolutely convergent series,

$$S = u_1 + u_2 + u_3 + \dots\dots$$
$$T = v_1 + v_2 + v_3 + \dots\dots$$

may be multiplied together, and the sum of the products of their terms, written in any order, is ST,

$$ST = u_1v_1 + u_2v_1 + u_1v_2 + \dots\dots$$

6.032 An absolutely convergent power series may be differentiated or integrated term by term and the resulting series will be absolutely convergent and equal to the differential or integral of the sum of the given series.

6.040 Uniform Convergence. An infinite series of functions of x,

$$S(x) = u_1(x) + u_2(x) + u_3(x) + \dots\dots$$

is uniformly convergent within a certain region of the variable x if a finite number, N, can be found such that for all values of $n \geqslant N$ the absolute value of the remainder, $|R_n|$ after n terms is less than an assigned arbitrary small quantity e at all points within the given range.

Example. The series,

$$\sum_{n=0}^{\infty} \frac{x^2}{(1 + x^2)^n},$$

is absolutely convergent for all real values of x. Its sum is $1 + x^2$ if x is not zero. If x is zero the sum is zero. The series is non-uniformly convergent in the neighborhood of $x = 0$.

6.041 A uniformly convergent series is not necessarily absolutely convergent, nor is an absolutely convergent series necessarily uniformly convergent.

6.042 A sufficient, though not necessary, test for uniform convergence is as follows:

If for all values of x within a certain region the moduli of the terms of the series,

$$S = u_1(x) + u_2(x) + \dots\dots$$

are less than the corresponding terms of a convergent series of positive terms,

$$T = M_1 + M_2 + M_3 + \dots\dots$$

where M_n is independent of x, then the series S is uniformly convergent in the given region.

6.043 A power series is uniformly convergent at all points within its circle of convergence.

6.044 A uniformly convergent series,

$$S = u_1(x) + u_2(x) + \dots\dots$$

may be integrated term by term, and,

$$\int S\,dx = \sum_{n=1}^{\infty} \int u_n(x)\,dx.$$

6.045 A uniformly convergent series,

$$S = u_1(x) + u_2(x) + \dots\dots$$

may be differentiated term by term, and if the resulting series is uniformly convergent,

$$\frac{d}{dx} S = \sum_{n=1}^{\infty} \frac{d}{dx} u_n(x).$$

6.100 Taylor's theorem.

$$f(x+h) = f(x) + \frac{h}{1!} f'(x) + \frac{h^2}{2!} f''(x) + \dots\dots + \frac{h^n}{n!} f^{(n)}(x) + R_n.$$

6.101 Lagrange's form for the remainder:

$$R_n = f^{(n+1)}(x+\theta h) \cdot \frac{h^{n+1}}{(n+1)!};\quad 0<\theta<1.$$

6.102 Cauchy's form for the remainder:

$$R_n = f^{(n+1)}(x+\theta h)\, \frac{h^{n+1}(1-\theta)^n}{n!};\quad 0<\theta<1.$$

6.103

$$f(x) = f(h) + f'(h) \cdot \frac{x-h}{1!} + f''(h) \cdot \frac{(x-h)^2}{2!} + \ldots + f^{(n)}(h) \frac{(x-h)^n}{n!} + R_n$$

$$R_n = f^{(n+1)}\{h + \theta(x-h)\} \frac{(x-h)^{n+1}}{(n+1)!} \quad 0 < \theta < 1.$$

6.104 Maclaurin's theorem:

$$f(x) = f(0) + f'(0)\frac{x}{1!} + f''(0)\frac{x^2}{2!} + \ldots + f^{(n)}(0)\frac{x^n}{n!} + R_n$$

$$R_n = f^{(n+1)}(\theta x) \frac{x^{n+1}}{(n+1)!}(1-\theta)^n; \; 0 < \theta < 1.$$

6.105 Lagrange's theorem. Given:

$$y = z + x\phi(y).$$

The expansion of $f(y)$ in powers of x is:

$$f(y) = f(z) + x\phi(z)f'(z) + \frac{x^2}{2!}\frac{d}{dz}[\{\phi(z)\}^2 f'(z)]$$

$$+ \ldots\ldots + \frac{x^n}{n!}\frac{d^{n-1}}{dz^{n-1}}[\{\phi(z)\}^n f'(z)] + \ldots\ldots$$

SYMBOLIC REPRESENTATION OF INFINITE SERIES

6.150 The infinite series:

$$f(x) = 1 + a_1 x + \frac{1}{2!}a_2 x^2 + \frac{1}{3!}a_3 x^3 + \ldots + \frac{1}{k!}a_k x^k + \ldots$$

may be written:

$$f(x) = e^{ax},$$

where a^k is interpreted as equivalent to a_k.

6.151 The infinite series, written without factorials,

$$f(x) = 1 + a_1 x + a_2 x^2 + \ldots\ldots + a_k x^k + \ldots\ldots$$

may be written:

$$f(x) = \frac{1}{1 - ax},$$

where a^k is interpreted as equivalent to a_k.

6.152 Symbolic form of Taylor's theorem:

$$f(x+h) = e^{h\frac{\partial}{\partial x}} f(x).$$

6.153 Taylor's theorem for functions of many variables:

$$f(x_1 + h_1, x_2 + h_2, \ldots) = e^{h_1\frac{\partial}{\partial x_1} + h_2\frac{\partial}{\partial x_2} + \ldots} f(x_1, x_2, \ldots)$$

$$= f(x_1, x_2, \ldots) + h_1\frac{\partial f}{\partial x_1} + h_2\frac{\partial f}{\partial x_2} + \ldots$$

$$+ \frac{h_1^2}{2!}\frac{\partial^2 f}{\partial x_1^2} + \frac{2}{2!}h_1 h_2\frac{\partial^2 f}{\partial x_1 \partial x_2} + \frac{h_2^2}{2!}\frac{\partial^2 f}{\partial x_2^2} + \ldots$$

$$+ \ldots$$

TRANSFORMATION OF INFINITE SERIES

Series which converge slowly may often be transformed to more rapidly converging series by the following methods.

6.20 Euler's transformation formula:

$$S = a_0 + a_1x + a_2x^2 + \ldots\ldots\ldots$$
$$= \frac{1}{1-x}a_0 + \frac{1}{1-x}\sum_{k=1}^{\infty}\left(\frac{x}{1-x}\right)^k \Delta^k a_0,$$

where:

$$\Delta a_0 = a_1 - a_0,$$
$$\Delta^2 a_0 = \Delta a_1 - \Delta a_0 = a_2 - 2a_1 + a_0,$$
$$\Delta^3 a_0 = \Delta^2 a_1 - \Delta^2 a_0 = a_3 - 3a_2 + 3a_1 - a_0,$$
$$\ldots\ldots\ldots\ldots$$
$$\ldots\ldots\ldots\ldots$$
$$\Delta^k a_n = \sum_{m=0}^{k} (-1)^m \binom{k}{m} a_{k+n-m}.$$

The second series may converge more rapidly than the first.

Example 1.

$$S = \sum_{k=0}^{\infty} (-1)^k \frac{1}{2k+1},$$
$$x = -1, \quad a_k = \frac{1}{2k+1},$$
$$S = \frac{1}{2}\sum_{k=0}^{\infty} \frac{k!}{1\cdot3\cdot5\ldots(2k+1)}.$$

Example 2.

$$S = \sum_{k=0}^{\infty} (-1)^k \frac{1}{k+1} = \log 2,$$
$$x = -1, \quad a_k = \frac{1}{k+1}.$$
$$S = \sum_{k=1}^{\infty} \frac{1}{k2^k},$$

6.21 Markoff's transformation formula. (Differenzenrechnung, p. 180.)

$$\sum_{k=0}^{n} a_k x^k - \left(\frac{x}{1-x}\right)^m \sum_{k=0}^{n} x^k \Delta^m a_k = \sum_{k=0}^{m} \frac{x^k}{(1-x)^{k+1}}\Delta^k a_0 - \sum_{k=0}^{m} \frac{x^{k+n}}{(1-x)^{k+1}}\Delta^k a_n.$$

6.22 Kummer's transformation.

$A_0, A_1, A_2, \ldots .$ is a sequence of positive numbers such that

$$\lambda_m = A_m - A_{m+1}\frac{a_{m+1}}{a_m},$$

and

$$\operatorname*{Limit}_{m\to\infty} \lambda_m,$$

approaches a definite positive value. Usually this limit can be taken as unity. If not, it is only necessary to divide A_m by this limit:

$$\alpha = \operatorname*{Limit}_{m\to\infty} A_m\, a_m.$$

Then:

$$\sum_{m=n}^{\infty} a_m = (A_n a_n - \alpha) + \sum_{m=n}^{\infty} (1 - \lambda_m) a_m.$$

Example 1.

$$S = \sum_{m=1}^{\infty} \frac{1}{m^2},$$

$$A_m = m, \quad \lambda_m = \frac{m}{m+1}, \quad \operatorname*{Limit}_{m\to\infty} \lambda_m = 1,$$

$$\alpha = 0$$

$$\sum_{m=1}^{\infty} \frac{1}{m^2} = 1 + \sum_{m=1}^{\infty} \frac{1}{(m+1)m^2}.$$

Applying the transformation to the series on the right:

$$A_m = \frac{m}{2}, \quad \lambda_m = \frac{m}{m+2}, \quad \alpha = 0,$$

$$\sum_{m=1}^{\infty} \frac{1}{m^2} = 1 + \frac{1}{2^2} + 2\sum_{m=1}^{\infty} \frac{1}{m^2(m+1)(m+2)}.$$

Applying the transformation n times:

$$\sum_{m=n+1}^{\infty} \frac{1}{m^2} = n!\sum_{m=1}^{\infty} \frac{1}{m^2(m+1)(m+2)\ldots .(m+n)}.$$

Example 2.

$$S = \sum_{m=1}^{\infty} (-1)^{m-1} \frac{1}{2m-1},$$

$$A_m = \frac{1}{2}, \quad \lambda_m = \frac{2m}{2m+1}, \quad \alpha = 0,$$

$$S = \frac{1}{2} + \sum_{m=1}^{\infty} (-1)^{m-1} \frac{1}{4m^2-1}.$$

Applying the transformation again, with:

$$A_m = \frac{1}{2}\frac{2m+1}{2m-1}, \quad \lambda_m = \frac{4m^2+1}{4m^2-1}, \quad \alpha = 0,$$

$$S = 1 - 2\sum_{m=1}^{\infty}(-1)^{m-1}\frac{1}{(4m^2-1)^2}.$$

Applying the transformation again, with:

$$A_m = \frac{1}{2}\frac{2m+1}{2m-3}, \quad \lambda_m = \frac{4m^2+3}{4m^2-9}, \quad \alpha = 0,$$

$$S = \frac{4}{3} + 24\sum_{m=1}^{\infty}(-1)^{m-1}\frac{1}{(4m^2-1)^2(4m^2-9)}.$$

Example 3.

$$S = \sum_{m=1}^{\infty}(-1)^{m-1}\frac{1}{(2m-1)^2},$$

$$A_m = \frac{2m-1}{2(2m-3)}, \quad \lambda_m = \frac{4m^2-4m+1}{(2m-3)(2m+1)}, \quad \alpha = 0,$$

$$S = \frac{5}{6} + 4\sum_{m=1}^{\infty}(-1)^{m-1}\frac{1}{(2m-1)(2m+3)(2m+1)^2}.$$

6.23 Leclert's modification of Kummer's transformation. With the same notation as in **6.22** and,

$$\operatorname*{Limit}_{m\to\infty} \lambda_m = \omega,$$

$$\sum_{n=0}^{\infty} a_n = a_0 + \frac{A_1 a_1}{\lambda_1} - \frac{\alpha}{\omega} + \sum_{m=1}^{\infty}\left(\frac{1}{\lambda_{m+1}} - \frac{1}{\lambda_m}\right)A_{m+1}\,a_{m+1}.$$

Example 1.

$$S = \sum_{n=1}^{\infty}(-1)^{n-1}\frac{1}{2n-1},$$

$$a_0 = 0, \quad A_m = 1, \quad \omega = 2, \quad \alpha = 0, \quad \lambda_m = \frac{4m}{2m+1},$$

$$S = \frac{3}{4} + \frac{1}{4}\sum_{m=1}^{\infty}(-1)^{m-1}\frac{1}{m(2m+1)(m+1)}.$$

Applying the transformation to the series on the right, with:

$$a_0 = 0, \quad A_m = \frac{2m+1}{m-1}, \quad \lambda_m = \frac{(2m+1)^2}{(m-1)\,(m+2)}, \quad \omega = 4, \quad \alpha = 0,$$

$$S = \frac{19}{24} + \frac{9}{2}\sum_{m=1}^{\infty}(-1)^m \frac{1}{m(m+2)\,(2m+1)^2\,(2m+3)^2}.$$

6.26 Reversion of series. The power series:

$$z = x - b_1x^2 - b_2x^3 - b_3x^4 - \ldots\ldots$$

may be reversed, yielding:

$$x = z + c_1z^2 + c_2z^3 + c_3z^4 + \ldots\ldots$$

where:

$c_1 = b_1,$

$c_2 = b_2 + 2b_1^2,$

$c_3 = b_3 + 5b_1b_2 + 5b_1^3,$

$c_4 = b_4 + 6b_1b_3 + 3b_2^2 + 21b_1^2b_2 + 14b_1^4,$

$c_5 = b_5 + 7(b_1b_4 + b_2b_3) + 28(b_1^2b_3 + b_1b_2^2) + 84b_1^3b_2 + 42b_1^5,$

$c_6 = b_6 + 4(2b_1b_5 + 2b_2b_4 + b_3^2) + 12(3b_1^2b_4 + 6b_1b_2b_3 + b_2^3)$
$\qquad + 60(2b_1^3b_3 + 3b_1^2b_2^2) + 330b_1^4b_2 + 132b_1^6,$

$c_7 = b_7 + 9(b_1b_6 + b_2b_5 + b_3b_4) + 45(b_1^2b_5 + b_1b_3^2 + b_2^2b_3 + 2b_1b_2b_4)$
$\qquad + 165(b_1^3b_4 + b_1b_2^3 + 3b_1^2b_2b_3) + 495(b_1^4b_3 + 2b_1^3b_2^2)$
$\qquad + 1287b_1^5b_2 + 429b_1^7.$

Van Orstrand (Phil. Mag. 19, 366, 1910) gives the coefficients of the reversed series up to c_{12}.

6.30 Binomial series.

$$(1+x)^n = 1 + \frac{n}{1}x + \frac{n(n-1)}{2!}x^2 + \frac{n(n-1)\,(n-2)}{3!}x^3 + \ldots.$$

$$+ \frac{n!}{(n-k)!k!}x^k + \ldots. = 1 + \binom{n}{1}x + \binom{n}{2}x^2 + \binom{n}{3}x^3 + \ldots.\binom{n}{k}x^k + \ldots$$

6.31 Convergence of the binomial series.

The series converges absolutely for $|x| < 1$ and diverges for $|x| > 1$. When $x = 1$, the series converges for $n > -1$ and diverges for $n \leqslant -1$. It is absolutely convergent only for $n > 0$.

When $x = -1$ it is absolutely convergent for $n > 0$, and divergent for $n < 0$.

6.32 Special cases of the binomial series.

$$(a+b)^n = a^n\left(1+\frac{b}{a}\right)^n = b^n\left(1+\frac{a}{b}\right)^n.$$

If $\left|\frac{b}{a}\right| < 1$ put $x = \frac{b}{a}$ in **6.30**; if $\left|\frac{b}{a}\right| > 1$ put $x = \frac{a}{b}$ in **6.30.**

6.33

1. $(1+x)^{\frac{n}{m}} = 1 + \frac{n}{m}x - \frac{n(m-n)}{2!m^2}x^2 + \frac{n(m-n)(2m-n)}{3!m^3}x^3 - \ldots\ldots\ldots + (-1)^k\frac{n(m-n)(2m-n)\ldots\ldots[(k-1)m-n]}{k!m^k}x^k + \ldots\ldots$

2. $(1+x)^{-1} = 1 - x + x^2 - x^3 + x^4 - \ldots\ldots$

3. $(1+x)^{-2} = 1 - 2x + 3x^2 - 4x^3 + 5x^4 - \ldots\ldots$

4. $\sqrt{1+x} = 1 + \frac{1}{2}x - \frac{1\cdot 1}{2\cdot 4}x^2 + \frac{1\cdot 1\cdot 3}{2\cdot 4\cdot 6}x^3 - \frac{1\cdot 1\cdot 3\cdot 5}{2\cdot 4\cdot 6\cdot 8}x^4 + \ldots$

5. $\frac{1}{\sqrt{1+x}} = 1 - \frac{1}{2}x + \frac{1\cdot 3}{2\cdot 4}x^2 - \frac{1\cdot 3\cdot 5}{2\cdot 4\cdot 6}x^3 + \frac{1\cdot 3\cdot 5\cdot 7}{2\cdot 4\cdot 6\cdot 8}x^4 - \ldots$

6. $(1+x)^{\frac{1}{3}} = 1 + \frac{1}{3}x - \frac{1\cdot 2}{3\cdot 6}x^2 + \frac{1\cdot 2\cdot 5}{3\cdot 6\cdot 9}x^3 - \frac{1\cdot 2\cdot 5\cdot 8}{3\cdot 6\cdot 9\cdot 12}x^4 + \ldots\ldots$

7. $(1+x)^{-\frac{1}{3}} = 1 - \frac{1}{3}x + \frac{1\cdot 4}{3\cdot 6}x^2 - \frac{1\cdot 4\cdot 7}{3\cdot 6\cdot 9}x^3 + \frac{1\cdot 4\cdot 7\cdot 10}{3\cdot 6\cdot 9\cdot 12}x^4 - \ldots$

8. $(1+x)^{\frac{3}{2}} = 1 + \frac{3}{2}x + \frac{3\cdot 1}{2\cdot 4}x^2 - \frac{3\cdot 1\cdot 1}{2\cdot 4\cdot 6}x^3 + \frac{3\cdot 1\cdot 1\cdot 3}{2\cdot 4\cdot 6\cdot 8}x^4 - \frac{3\cdot 1\cdot 1\cdot 3\cdot 5}{2\cdot 4\cdot 6\cdot 8\cdot 10}x^5 + \ldots\ldots$

9. $(1+x)^{-\frac{3}{2}} = 1 - \frac{3}{2}x + \frac{3\cdot 5}{2\cdot 4}x^2 - \frac{3\cdot 5\cdot 7}{2\cdot 4\cdot 6}x^3 + \ldots\ldots$

10. $(1+x)^{\frac{1}{4}} = 1 + \frac{1}{4}x - \frac{3}{32}x^2 + \frac{7}{128}x^3 - \frac{77}{2048}x^4 + \ldots$

11. $(1+x)^{-\frac{1}{4}} = 1 - \frac{1}{4}x + \frac{5}{32}x^2 - \frac{15}{128}x^3 + \frac{195}{2048}x^4 - \ldots$

12. $(1+x)^{\frac{1}{5}} = 1 + \frac{1}{5}x - \frac{2}{25}x^2 + \frac{6}{125}x^3 - \frac{21}{625}x^4 + \ldots\ldots$

13. $(1+x)^{-\frac{1}{5}} = 1 - \frac{1}{5}x + \frac{3}{25}x^2 - \frac{11}{125}x^3 + \frac{44}{625}x^4 - \ldots$

14. $(1+x)^{\frac{1}{6}} = 1 + \frac{1}{6}x - \frac{5}{72}x^2 + \frac{55}{1296}x^3 - \frac{935}{31104}x^4 + \ldots$

15. $(1+x)^{-\frac{1}{6}} = 1 - \frac{1}{6}x + \frac{7}{72}x^2 - \frac{91}{1296}x^3 + \frac{1729}{31104}x^4 - \ldots.$

6.350

1. $\frac{x}{1-x} = \frac{x}{1+x} + \frac{2x^2}{1+x^2} + \frac{4x^4}{1+x^4} + \frac{8x^8}{1+x^8} + \ldots.$ $[x^2<1]$.

2. $\frac{x}{1-x} = \frac{x}{1-x^2} + \frac{x^2}{1-x^4} + \frac{x^4}{1-x^8} + \ldots.$ $[x^2<1]$.

3. $\frac{1}{x-1} = \frac{1}{x+1} + \frac{2}{x^2+1} + \frac{4}{x^4+1} + \ldots.$ $[x^2>1]$.

6.351

1. $$\left\{1+\sqrt{1+x}\right\}^n = 2^n\left\{1 + n\left(\frac{x}{4}\right) + \frac{n(n-3)}{2!}\left(\frac{x}{4}\right)^2 + \frac{n(n-4)(n-5)}{3!}\left(\frac{x}{4}\right)^3 + \ldots\right\}. \qquad [x^2<1].$$

n may be any real number.

2. $$\left(x+\sqrt{1+x^2}\right)^n = 1 + \frac{n^2}{2!}x^2 + \frac{n^2(n^2-2^2)}{4!}x^4 + \frac{n^2(n^2-2^2)(n^2-4^2)}{6!}x^6 + \ldots$$
$$+ \frac{n}{1!}x + \frac{n(n^2-1^2)}{3!}x^3 + \frac{n(n^2-1^2)(n^2-3^2)}{5!}x^5 + \ldots \qquad [x^2<1].$$

6.352 If a is a positive integer:

$$\frac{1}{a} + \frac{1}{a(a+1)}x + \frac{1}{a(a+1)(a+2)}x^2 + \ldots\ldots = \frac{(a-1)!}{x^a}\left\{e^x - \sum_{n=0}^{a-1}\frac{x^n}{n!}\right\}.$$

6.353 If a and b are positive integers, and $a<b$:

$$\frac{a}{b} + \frac{a(a+1)}{b(b+1)}x + \frac{a(a+1)(a+2)}{b(b+1)(b+2)}x^2 + \ldots.$$
$$= (b-a)\binom{b-1}{a-1}\left\{\frac{(-1)^{b-a}\log(1-x)}{x^b}(1-x)^{b-a-1} + \frac{1}{x^a}\sum_{k=1}^{b-a}(-1)^k\binom{b-a-1}{k-1}\sum_{n=1}^{a+k-1}\frac{x^{n-k}}{n}\right\}.$$

(Schwatt, Phil. Mag. 31, 75, 1916)

POLYNOMIAL SERIES

6.360
$$\frac{b_0 + b_1x + b_2x^2 + b_3x^3 + \ldots}{a_0 + a_1x + a_2x^2 + a_3x^3 + \ldots} = \frac{1}{a_0}(c_0 + c_1x + c_2x^2 + \ldots),$$

$$c_0 - b_0 = 0,$$

$$c_1 + \frac{c_0a_1}{a_0} - b_1 = 0,$$

$$c_2 + \frac{c_1a_1}{a_0} + \frac{c_0a_2}{a_0} - b_2 = 0,$$

$$c_3 + \frac{c_2a_1}{a_0} + \frac{c_1a_2}{a_0} + \frac{c_0a_3}{a_0} - b_3 = 0.$$

. . . . .

. . . . .

$$c_n = \frac{(-1)^n}{a_0{}^n}\begin{vmatrix} (a_1b_0 - a_0b_1) & a_0 & 0 & \cdots & 0 \\ (a_2b_0 - a_0b_2) & a_1 & a_0 & \cdots & 0 \\ (a_3b_0 - a_0b_3) & a_2 & a_1 & \cdots & 0 \\ \cdots\cdots & & & & \\ \cdots\cdots & & & & \\ (a_{n-1}b_0 - a_0b_{n-1}) & a_{n-2} & a_{n-3} & \cdots & a_0 \\ (a_nb_0 - a_0b_n) & a_{n-1} & a_{n-2} & \cdots & a_1 \end{vmatrix}$$

6.361
$$(a_0 + a_1x + a_2x^2 + \ldots)^n = c_0 + c_1x + c_2x^2 + \ldots.$$

$$c_0 = a_0{}^n,$$

$$a_0c_1 = na_1c_0,$$

$$2a_0c_2 = (n-1)a_1c_1 + 2na_2c_0,$$

$$3a_0c_3 = (n-2)a_1c_2 + (2n-1)a_2c_1 + 3na_3c_0.$$

. . . . . *cf.* **6.37.**

. . . . .

6.362
$$y = a_1x + a_2x^2 + a_3x^3 + \ldots.$$

$$b_1y + b_2y^2 + b_3y^3 + \ldots = c_1x + c_2x^2 + c_3x^3 + \ldots$$

$$c_1 = a_1b_1,$$

$$c_2 = a_2b_1 + a_1{}^2b_2,$$

$$c_3 = a_3b_1 + 2a_1a_2b_2 + a_1{}^3b_3,$$

$$c_4 = a_4b_1 + a_2{}^2b_2 + 2a_1a_3b_2 + 3a_1{}^2a_2b_3 + a_1{}^4b_4.$$

. . . .

. . . .

6.363
$$e^{a_1x + a_2x^2 + a_3x^3 + \ldots} = 1 + c_1x + c_2x^2 + \ldots$$

$$c_1 = a_1,$$

$$c_2 = a_2 + \frac{1}{2}a_1{}^2,$$

$$c_3 = a_3 + a_1a_2 + \frac{1}{6}a_1^3,$$

$$c_4 = a_4 + a_1a_3 + \frac{1}{2}a_2^2 + \frac{1}{2}a_2a_1^2 + \frac{1}{24}a_1^4.$$

$$\cdots\cdots$$

$$\cdots\cdots$$

6.364

$$\log(1 + a_1x + a_2x^2 + a_3x^3 + \ldots) = c_1x + c_2x^2 + c_3x^3 + \ldots$$

$$a_1 = c_1,$$

$$2a_2 = a_1c_1 + 2c_2,$$

$$3a_3 = a_2c_1 + 2a_1c_2 + 3c_3,$$

$$4a_4 = a_3c_1 + 2a_2c_2 + 3a_3c_3 + 4a_4.$$

$$\cdots$$

$$c_1 = a_1,$$

$$c_2 = a_2 - \frac{1}{2}c_1a_1,$$

$$c_3 = a_3 - \frac{1}{3}c_1a_2 - \frac{2}{3}c_2a_1,$$

$$c_4 = a_4 - \frac{1}{4}c_1a_3 - \frac{2}{4}c_2a_2 - \frac{3}{4}c_3a_1.$$

$$\cdots$$

6.365

$$y = a_1x + a_2x^2 + a_3x^3 + \ldots$$

$$z = b_1x + b_2x^2 + b_3x^3 + \ldots$$

$$yz = c_2x^2 + c_3x^3 + c_4x^4 + \ldots$$

$$c_2 = a_1b_1,$$

$$c_3 = a_1b_2 + a_2b_1,$$

$$c_4 = a_1b_3 + a_2b_2 + a_3b_1.$$

$$\cdots$$

$$c_k = a_1b_{k-1} + a_2b_{k-2} + a_3b_{k-3} + \ldots a_{k-1}b_1.$$

6.37. The Multinomial Theorem.

The general term in the expansion of

(1) $$(a_0 + a_1x + a_2x^2 + a_3x^3 + \ldots\ldots)^n$$

where n is positive or negative, integral or fractional, is,

(2) $$\frac{n(n-1)(n-2)\ldots(p+1)}{c_1!c_2!c_3!\ldots} a_0^p a_1^{c_1} a_2^{c_2} a_3^{c_3} \ldots x^{c_1+2c_2+3c_3+} \ldots$$

where

$$p + c_1 + c_2 + c_3 + \ldots\ldots = n.$$

$c_1, c_2, c_3, \ldots\ldots$ are positive integers.

If n is a positive integer, and hence p also, the general term in the expansion may be written,

(3) $$\frac{n!}{p!\,c_1!\,c_2!\ldots}\,a_0^{p}a_1^{c_1}a_2^{c_2}a_3^{c_3}\ldots\ldots x^{c_1+2c_2+3c_3+}\ldots$$

The coefficient of x^k (k an integer) in the expansion of (1) is found by taking the sum of all the terms (2) or (3) for the different combinations of p, c_1, c_2, $c_3, \ldots$ which satisfy

$$c_1 + 2c_2 + 3c_3 + \ldots\ldots = k,$$
$$p + c_1 + c_2 + c_3 + \ldots\ldots = n.$$

cf. **6.361.**

In the following series the coefficients B_n are Bernoulli's numbers (**6.902**) and the coefficients E_n, Euler's numbers (**6.903**).

6.400

1. $$\sin x = x - \frac{x^3}{3!} + \frac{x^5}{5!} - \frac{x^7}{7!} + \ldots\ldots = \sum_{n=0}^{\infty}(-1)^n\frac{x^{2n+1}}{(2n+1)!} \qquad [x^2 < \infty].$$

2. $$\cos x = 1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \frac{x^6}{6!} + \ldots\ldots = \sum_{n=0}^{\infty}(-1)^n\frac{x^{2n}}{(2n)!} \qquad [x^2 < \infty].$$

3. $$\tan x = x + \frac{1}{3}x^3 + \frac{2}{15}x^5 + \frac{17}{315}x^7 + \frac{62}{2835}x^9 + \ldots\ldots$$
$$= \sum_{n=1}^{\infty}\frac{2^{2n}(2^{2n}-1)}{(2n)!}B_n x^{2n-1} \qquad \left[x^2 < \frac{\pi^2}{4}\right].$$

4. $$\cot x = \frac{1}{x} - \frac{x}{3} - \frac{1}{45}x^3 - \frac{2}{945}x^5 - \frac{1}{4725}x^7 - \ldots\ldots$$
$$= \frac{1}{x} - \sum_{n=1}^{\infty}\frac{2^{2n}B_n}{(2n)!}x^{2n-1} \qquad [x^2 < \pi^2].$$

5. $$\sec x = 1 + \frac{1}{2!}x^2 + \frac{5}{4!}x^4 + \frac{61}{6!}x^6 + \ldots = \sum_{n=0}^{\infty}\frac{E_n}{(2n)!}x^{2n} \qquad \left[x^2 < \frac{\pi^2}{4}\right].$$

6. $$\csc x = \frac{1}{x} + \frac{1}{3!}x + \frac{7}{3\cdot 5!}x^3 + \frac{31}{3\cdot 7!}x^5 + \ldots$$
$$= \frac{1}{x} + \sum_{n=0}^{\infty}\frac{2(2^{2n+1}-1)}{(2n+2)!}B_{n+1}x^{2n+1} \qquad [x^2 < \pi^2].$$

6.41

1. $$\sin^{-1} x = x + \frac{1}{2\cdot 3}x^3 + \frac{1\cdot 3}{2\cdot 4\cdot 5}x^5 + \frac{1\cdot 3\cdot 5}{2\cdot 4\cdot 6\cdot 7}x^7 + \ldots\ldots \qquad \left[x^2 \leqq 1\right].$$
$$= \frac{\pi}{2} - \cos^{-1} x = \sum_{n=0}^{\infty}\frac{(2n)!}{2^{2n}(n!)^2\,(2n+1)}x^{2n+1}.$$

2. $\tan^{-1} x = x - \frac{1}{3}x^3 + \frac{1}{5}x^5 - \frac{1}{7}x^7 + \ldots$ (Gregory's Series) $\left[x^2 \leqslant 1\right]$

$$= \frac{\pi}{2} - \cot^{-1} x = \sum_{n=0}^{\infty} (-1)^n \frac{x^{2n+1}}{2n+1}.$$

3. $$\tan^{-1} x = \frac{x}{1+x^2}\left\{1 + \frac{2}{3}\frac{x^2}{1+x^2} + \frac{2\cdot 4}{3\cdot 5}\left(\frac{x^2}{1+x^2}\right)^2 + \ldots\right\}$$

$$= \frac{x}{1+x^2}\sum_{n=0}^{\infty}\frac{2^{2n}(n!)^2}{(2n+1)!}\left(\frac{x^2}{1+x^2}\right)^n \qquad x^2 < \infty.$$

4. $$\tan^{-1} x = \frac{\pi}{2} - \frac{1}{x} + \frac{1}{3x^3} - \frac{1}{5x^5} + \frac{1}{7x^7} - \ldots$$

$$= \frac{\pi}{2} - \sum_{n=0}^{\infty}(-1)^n\frac{1}{(2n+1)x^{2n+1}} \qquad \left[x^2 \geqslant 1\right].$$

5. $$\sec^{-1} x = \frac{\pi}{2} - \frac{1}{x} - \frac{1}{2\cdot 3}\frac{1}{x^3} - \frac{1\cdot 3}{2\cdot 4\cdot 5}\frac{1}{x^5} + \frac{1\cdot 3\cdot 5}{2\cdot 4\cdot 6\cdot 7}\frac{1}{x^7} - \ldots$$

$$= \frac{\pi}{2} - \csc^{-1} x = \frac{\pi}{2} - \sum_{n=0}^{\infty}\frac{(2n)!}{2^{2n}(n!)^2(2n+1)}x^{-2n-1} \qquad \left[x > 1\right].$$

6.42

1. $$(\sin^{-1} x)^2 = x^2 + \frac{2}{3}\frac{x^4}{2} + \frac{2\cdot 4}{3\cdot 5}\frac{x^6}{3} + \frac{2\cdot 4\cdot 6}{3\cdot 5\cdot 7}\frac{x^8}{4} + \ldots$$

$$= \sum_{n=0}^{\infty}\frac{2^{2n}(n!)^2}{(2n+1)!\,(n+1)}x^{2n+2} \qquad \left[x^2 \leqslant 1\right].$$

2. $$(\sin^{-1} x)^3 = x^3 + \frac{3!}{5!}3^2\left(1 + \frac{1}{3^2}\right)x^5 + \frac{3!}{7!}3^2 5^2\left(1 + \frac{1}{3^2} + \frac{1}{5^2}\right)x^7 + \ldots \qquad \left[x^2 \leqslant 1\right].$$

3. $$(\tan^{-1} x)^p = p!\sum_{k_0=1}^{\infty}(-1)^{k_0-1}\frac{x^{2k_0+p-2}}{2k_0+p-2}\prod_{a=1}^{p-1}\left(\sum_{k_a=1}^{k_{a-1}}\frac{1}{2k_a+p-a-2}\right).$$

(Schwatt, Phil. Mag. 31, p. 490, 1916).

4. $$\sqrt{1-x^2}\sin^{-1} x = x - \frac{x^3}{3} + \frac{2}{3\cdot 5}x^5 - \frac{2\cdot 4}{3\cdot 5\cdot 7}x^7 + \ldots$$

$$= x + \sum_{n=1}^{\infty}(-1)^n\frac{2^{2n-2}[(n-1)!]^2}{(2n-1)!\,(2n+1)}x^{2n+1} \qquad \left[x^2 < 1\right].$$

5. $$\frac{\sin^{-1} x}{\sqrt{1-x^2}} = x + \frac{2}{3}x^3 + \frac{2\cdot 4}{3\cdot 5}x^5 + \frac{2\cdot 4\cdot 6}{3\cdot 5\cdot 7}x^7 + \ldots$$

$$= \sum_{n=0}^{\infty}\frac{2^{2n}(n!)^2}{(2n+1)!}x^{2n+1} \qquad \left[x^2 < 1\right].$$

6.43

1. $\log \sin x = \log x - \left\{ \frac{1}{6} x^2 + \frac{1}{180} x^4 + \frac{1}{2835} x^6 + \dots \right\}$

$$= \log x - \sum_{n=1}^{\infty} \frac{2^{2n-1}}{n(2n)!} B_n x^{2n} \qquad \left[x^2 < \pi^2\right].$$

2. $\log \cos x = -\frac{1}{2} x^2 - \frac{1}{12} x^4 - \frac{1}{45} x^6 - \frac{17}{2520} x^8 - \dots$

$$= -\sum_{n=1}^{\infty} \frac{2^{2n-1}(2^{2n}-1) B_n}{n(2n)!} x^{2n} \qquad \left[x^2 < \frac{\pi^2}{4}\right].$$

3. $\log \tan x = \log x + \frac{1}{3} x^2 + \frac{7}{90} x^4 + \frac{62}{2835} x^6 + \frac{127}{18900} x^8 + \dots$

$$= \log x + \sum_{n=1}^{\infty} \frac{(2^{2n-1}-1) 2^{2n}}{n(2n)!} B_n x^{2n} \qquad \left[x^2 < \frac{\pi^2}{4}\right].$$

4. $\log \cos x = -\frac{1}{2} \left\{ \sin^2 x + \frac{1}{2} \sin^4 x + \frac{1}{3} \sin^6 x + \dots \right\}$

$$= -\frac{1}{2} \sum_{n=1}^{\infty} \frac{1}{n} \sin^{2n} x. \qquad \left[x^2 < \frac{\pi^2}{4}\right]$$

6.44

1. $\log(1+x) = x - \frac{1}{2} x^2 + \frac{1}{3} x^3 - \frac{1}{4} x^4 + \dots$

$$= \sum_{n=1}^{\infty} (-1)^{n+1} \frac{x^n}{n} \qquad \left[-1 < x \leqslant 1\right].$$

$\{\log(1+x)\}^p$ see **7.369.**

2. $\log(x + \sqrt{1+x^2}) = x - \frac{1 \cdot 1}{2 \cdot 3} x^3 + \frac{1 \cdot 1 \cdot 3}{2 \cdot 4 \cdot 5} x^5 - \frac{1 \cdot 1 \cdot 3 \cdot 5}{2 \cdot 4 \cdot 6 \cdot 7} x^7 + \dots$

$$= x + \sum_{n=1}^{\infty} (-1)^n \frac{(2n-1)!}{2^{2n-1} n!\,(n-1)!} \frac{x^{2n+1}}{(2n+1)} \qquad \left[-1 \leqslant x \leqslant 1\right].$$

3. $\log(1 + \sqrt{1+x^2}) = \log 2 + \frac{1 \cdot 1}{2 \cdot 2} x^2 - \frac{1 \cdot 1 \cdot 3}{2 \cdot 4 \cdot 4} x^4 + \frac{1 \cdot 1 \cdot 3 \cdot 5}{2 \cdot 4 \cdot 6 \cdot 6} x^6 - \dots$

$$= \log 2 - \sum_{n=1}^{\infty} (-1)^n \frac{(2n-1)!}{2^{2n-1} n!(n-1)!} \frac{x^{2n}}{2n} \qquad \left[x^2 \leqslant 1\right].$$

4. $$\log(1+\sqrt{1+x^2}) = \log x + \frac{1}{x} - \frac{1\cdot 1}{2\cdot 3}\frac{1}{x^3} + \frac{1\cdot 1\cdot 3}{2\cdot 4\cdot 5}\frac{1}{x^5} - \dots$$

$$= \log x + \frac{1}{x} + \sum_{n=1}^{\infty}(-1)^n \frac{(2n-1)!}{2^{2n-1}n!\,(n-1)!}\,\frac{x^{-2n-1}}{(2n+1)} \qquad \left[x^2 \geqslant 1\right].$$

5. $$\log x = (x-1) - \frac{1}{2}(x-1)^2 + \frac{1}{3}(x-1)^3 - \dots$$

$$= \sum_{n=1}^{\infty}(-1)^{n+1}\frac{(x-1)^n}{n} \qquad \left[0 < x \leqslant 2\right].$$

6. $$\log x = \frac{x-1}{x} + \frac{1}{2}\left(\frac{x-1}{x}\right)^2 + \frac{1}{3}\left(\frac{x-1}{x}\right)^3 + \dots .$$

$$= \sum_{n=1}^{\infty}\frac{1}{n}\left(\frac{x-1}{x}\right)^n \qquad \left[x \geqslant \tfrac{1}{2}\right].$$

7. $$\log x = 2\left\{\frac{x-1}{x+1} + \frac{1}{3}\left(\frac{x-1}{x+1}\right)^3 + \frac{1}{5}\left(\frac{x-1}{x+1}\right)^5 + \dots\right\}$$

$$= 2\sum_{n=0}^{\infty}\frac{1}{2n+1}\left(\frac{x-1}{x+1}\right)^{2n+1} \qquad \left[x > 0\right].$$

8. $$\log\frac{1+x}{1-x} = 2\left\{x + \frac{1}{3}x^3 + \frac{1}{5}x^5 + \dots .\right\}$$

$$= 2\sum_{n=0}^{\infty}\frac{1}{2n+1}x^{2n+1} \qquad \left[x^2 < 1\right].$$

9. $$\log\frac{x+1}{x-1} = 2\left\{\frac{1}{x} + \frac{1}{3}\frac{1}{x^3} + \frac{1}{5}\frac{1}{x^5} + \dots\right\}$$

$$= 2\sum_{n=0}^{\infty}\frac{1}{(2n+1)x^{2n+1}} \qquad \left[x^2 > 1\right].$$

10. $$\sqrt{1+x^2}\log(x+\sqrt{1+x^2}) = x + \frac{1}{3}x^3 - \frac{1\cdot 2}{3\cdot 5}x^5 + \frac{1\cdot 2\cdot 4}{3\cdot 5\cdot 7}x^7 - \dots$$

$$= x - \sum_{n=1}^{\infty}(-1)^n\frac{(n-1)!\,2^{2n-1}n!}{(2n+1)!}x^{2n+1} \qquad \left[x^2 < 1\right].$$

11. $$\frac{\log(x+\sqrt{1+x^2})}{\sqrt{1+x^2}} = x - \frac{2}{3}x^3 + \frac{2\cdot 4}{3\cdot 5}x^5 - \frac{2\cdot 4\cdot 6}{3\cdot 5\cdot 7}x^7 + \dots$$

$$= \sum_{n=0}^{\infty}(-1)^n\frac{2^{2n}(n!)^2}{(2n+1)!}x^{2n+1} \qquad \left[x^2 < 1\right].$$

12. $$\left\{\log(x+\sqrt{1+x^2})\right\}^2 = \frac{x^2}{1} - \frac{2}{3}\frac{x^4}{2} + \frac{2\cdot 4}{3\cdot 5}\frac{x^6}{3} - \dots .$$

$$= \sum_{n=1}^{\infty}(-1)^{n-1}\frac{2^{2n-2}(n-1)!\,(n-1)!}{(2n-1)!}\cdot\frac{x^{2n}}{n}. \qquad \left[x^2 < 1\right]$$

13. $\frac{1}{2}\left\{\log(1+x)\right\}^2 = \frac{1}{2}s_1x^2 - \frac{1}{3}s_2x^3 + \frac{1}{4}s_3x^4 - \ldots \qquad [x^2<1].$

where $s_n = \frac{1}{1}+\frac{1}{2}+\frac{1}{3}+\ldots\frac{1}{n}$ (See **1.876**).

14. $$\frac{1}{6}\left\{\log(1+x)\right\}^3 = \frac{1}{3}\cdot\frac{1}{2}s_1x^3 - \frac{1}{4}\left(\frac{1}{2}s_1+\frac{1}{3}s_2\right)x^4 + \frac{1}{5}\left(\frac{1}{2}s_1+\frac{1}{3}s_2+\frac{1}{4}s_3\right)x^5 - \ldots \qquad [x^2<1].$$

15. $$\frac{\log(1+x)}{(1+x)^n} = x - n(n+1)\left(\frac{1}{n}+\frac{1}{n+1}\right)\frac{x^2}{2!} + n(n+1)(n+2)\left(\frac{1}{n}+\frac{1}{n+1}+\frac{1}{n+2}\right)\frac{x^3}{3!} - \ldots \qquad [x^2<1].$$

6.445 (See **6.705**.)

1. $$\frac{3}{4x} - \frac{1}{2x^2} + \frac{(1-x)^2}{2x^3}\log\frac{1}{1-x} = \frac{1}{1\cdot2\cdot3} + \frac{x}{2\cdot3\cdot4} + \frac{x^2}{3\cdot4\cdot5} + \ldots \qquad [x^2<1].$$

2. $$\frac{1}{4x}\left\{\frac{1+x}{\sqrt{x}}\log\frac{1+\sqrt{x}}{1-\sqrt{x}} + 2\log(1-x) - 2\right\} = \frac{1}{1\cdot2\cdot3} + \frac{x}{3\cdot4\cdot5} + \frac{x^2}{5\cdot6\cdot7} + \ldots \qquad [0<x<1].$$

3. $$\frac{1}{2x}\left\{1 - \log(1+x) - \frac{1-x}{\sqrt{x}}\tan^{-1}x\right\} = \frac{1}{1\cdot2\cdot3} - \frac{x}{3\cdot4\cdot5} + \frac{x^2}{5\cdot6\cdot7} - \ldots \qquad [0<x\leqslant1].$$

6.455

1. $$-\log(1+x)\cdot\log(1-x) = x^2 + \left(1-\frac{1}{2}+\frac{1}{3}\right)\frac{x^4}{2} + \left(1-\frac{1}{2}+\frac{1}{3}-\frac{1}{4}+\frac{1}{5}\right)\frac{x^6}{3} + \ldots \qquad [x^2<1].$$

2. $$\frac{1}{2}\tan^{-1}x\cdot\log\frac{1+x}{1-x} = x^2 + \left(1-\frac{1}{3}+\frac{1}{5}\right)\frac{x^6}{3} + \left(1-\frac{1}{3}+\frac{1}{5}-\frac{1}{7}+\frac{1}{9}\right)\frac{x^{10}}{5} + \ldots \qquad [x^2<1].$$

3. $$\frac{1}{2}\tan^{-1}x\cdot\log(1+x^2) = \left(1+\frac{1}{2}\right)\frac{x^3}{3} - \left(1+\frac{1}{2}+\frac{1}{3}+\frac{1}{4}\right)\frac{x^5}{5} + \ldots \qquad [x^2<1].$$

6.456

1. $$\cos\left\{k\log(x+\sqrt{1+x^2})\right\} = 1 - \frac{k^2}{2!}x^2 + \frac{k^2(k^2+2^2)}{4!}x^4 - \frac{k^2(k^2+2^2)(k^2+4^2)}{6!}x^6 + \ldots \qquad x^2<1.$$

k may be any real number.

2. $$\sin\left\{k\log(x+\sqrt{1+x^2})\right\} = \frac{k}{1!}x - \frac{k^2(k^2+1^2)}{3!}x^3 + \frac{k^2(k^2+1^2)(k^2+3^2)}{5!}x^5 - \dots \qquad x^2<1.$$

6.457

$$\frac{1}{1-2x\cos\alpha+x^2} = 1+\sum_{n=1}^{\infty}A_nx^n \qquad \left[x^2<1\right],$$

where,

$$A_{2n} = (-1)^n\sum_{k=0}^{n}(-1)^k\binom{n+k}{2k}(2\cos\alpha)^{2k},$$

$$A_{2n+1} = (-1)^n\sum_{k=0}^{n}(-1)^k\binom{n+k+1}{2k+1}(2\cos\alpha)^{2k+1}.$$

6.460

1. $$e^x = 1+x+\frac{x^2}{2!}+\frac{x^3}{3!}+\dots\dots = \sum_{n=0}^{\infty}\frac{x^n}{n!} \qquad \left[x^2<\infty\right].$$

2. $$a^x = 1+x\log a+\frac{(x\log a)^2}{2!}+\frac{(x\log a)^3}{3!}+\dots \qquad \left[x^2<\infty\right].$$

3. $$e^{e^x} = e\left(1+x+\frac{2}{2!}x^2+\frac{5}{3!}x^3+\frac{15}{4!}x^4+\dots\right).$$

4. $$e^{\sin x} = 1+x+\frac{x^2}{2!}-\frac{3x^4}{4!}-\frac{8x^5}{5!}+\frac{3x^6}{6!}+\frac{56x^7}{7!}+\dots$$

5. $$e^{\cos x} = e\left(1-\frac{x^2}{2!}+\frac{4x^4}{4!}-\frac{31x^6}{6!}+\dots\right).$$

6. $$e^{\tan x} = 1+x+\frac{x^2}{2!}+\frac{3x^3}{3!}+\frac{9x^4}{4!}+\frac{37x^5}{5!}+\dots.$$

7. $$e^{\sin^{-1}x} = 1+x+\frac{x^2}{2!}+\frac{2x^3}{3!}+\frac{5x^4}{4!}+\dots\dots$$

8. $$e^{\tan^{-1}x} = 1+x+\frac{x^2}{2}-\frac{x^3}{6}+\frac{7x^4}{24}-\dots\dots$$

6.470

1. $$\sinh x = x+\frac{x^3}{3!}+\frac{x^5}{5!}+\frac{x^7}{7!}+\dots = \sum_{n=0}^{\infty}\frac{x^{2n+1}}{(2n+1)!} \qquad \left[x^2<\infty\right].$$

2. $\cosh x = 1 + \frac{x^2}{2!} + \frac{x^4}{4!} + \frac{x^6}{6!} + \ldots = \sum_{n=0}^{\infty} \frac{x^{2n}}{(2n)!}$ $\qquad [x^2 < \infty]$.

3. $\tanh x = x - \frac{1}{3} x^3 + \frac{2}{15} x^5 - \frac{17}{315} x^7 + \ldots$

$$= \sum_{n=1}^{\infty} (-1)^{n-1} \frac{2^{2n}(2^{2n} - 1)}{(2n)!} B_n x^{2n-1} \qquad \left[x^2 < \frac{\pi^2}{4}\right].$$

4. $x \coth x = 1 + \frac{1}{3} x^2 - \frac{1}{45} x^4 + \frac{2}{945} x^6 - \ldots$

$$= 1 + \sum_{n=1}^{\infty} (-1)^{n-1} \frac{2^{2n} B_n}{(2n)!} x^{2n} \qquad [x^2 < \pi^2].$$

5. $\operatorname{sech} x = 1 - \frac{1}{2} x^2 + \frac{5}{24} x^4 - \frac{61}{720} x^6 + \ldots = 1 + \sum_{n=1}^{\infty} (-1)^n \frac{E_n}{(2n)!} x^{2n}$ $\qquad \left[x^2 < \frac{\pi}{4}\right]$.

6. $x \operatorname{csch} x = 1 - \frac{1}{6} x^2 + \frac{7}{360} x^4 - \frac{31}{15120} x^6 + \ldots$

$$= 1 + \sum_{n=1}^{\infty} (-1)^n \frac{2(2^{2n-1} - 1)}{(2n)!} B_n x^{2n} \qquad [x^2 < \pi^2].$$

6.475

1. $\cosh x \cos x = 1 - \frac{2^2}{4!} x^4 + \frac{2^4}{8!} x^8 - \frac{2^6}{12!} x^{12} + \ldots$

2. $\sinh x \sin x = \frac{2^2}{2!} x^2 - \frac{2^4}{6!} x^6 + \frac{2^6}{10!} x^{10} - \ldots\ldots$

6.476

1. $e^{x \cos\theta} \cos(x \sin\theta) = \sum_{n=0}^{\infty} \frac{x^n \cos n\theta}{n!}$ $\qquad [x^2 < 1]$.

2. $e^{x \cos\theta} \sin(x \sin\theta) = \sum_{n=1}^{\infty} \frac{x^n \sin n\theta}{n!}$ $\qquad [x^2 < 1]$.

3. $\cosh(x \cos\theta) \cdot \cos(x \sin\theta) = \sum_{n=0}^{\infty} \frac{x^{2n} \cos 2n\theta}{(2n)!}$ $\qquad [x^2 < 1]$.

4. $\sinh(x \cos\theta) \cdot \cos(x \sin\theta) = \sum_{n=0}^{\infty} \frac{x^{2n+1} \cos(2n+1)\theta}{(2n+1)!}$ $\qquad [x^2 < 1]$.

5. $\cosh(x \cos\theta) \cdot \sin(x \sin\theta) = \sum_{n=0}^{\infty} \frac{x^{2n+1} \sin(2n+1)\theta}{(2n+1)!}$ $\qquad [x^2 < 1]$.

6. $\sinh(x \cos\theta) \cdot \sin(x \sin\theta) = \sum_{n=1}^{\infty} \frac{x^{2n} \sin 2n\theta}{(2n)!}$ $\qquad [x^2 < 1]$.

6.480

1. $$\sinh^{-1} x = x - \frac{1}{2\cdot 3}x^3 + \frac{1\cdot 3}{2\cdot 4\cdot 5}x^5 - \ldots$$
$$= \sum_{n=0}^{\infty} (-1)^n \frac{(2n)!}{2^{2n}(n!)^2\,(2n+1)}\, x^{2n+1} \qquad \left[x^2<1\right].$$

2. $$\sinh^{-1} x = \log 2x + \frac{1}{2}\,\frac{1}{2x^2} - \frac{1\cdot 3}{2\cdot 4}\,\frac{1}{4x^4} + \ldots$$
$$= \log 2x + \sum_{n=0}^{\infty} (-1)^n \frac{(2n)!}{2^{2n}(n!)^2 2n}\, x^{-2n} \qquad \left[x^2>1\right].$$

3. $$\cosh^{-1} x = \log 2x - \frac{1}{2}\,\frac{1}{2x^2} - \frac{1\cdot 3}{2\cdot 4}\,\frac{1}{4x^4} - \ldots$$
$$= \log 2x - \sum_{n=0}^{\infty} \frac{(2n)!}{2^{2n}(n!)^2 2n}\, x^{-2n} \qquad \left[x^2>1\right].$$

4. $$\tanh^{-1} x = x + \frac{1}{3}x^3 + \frac{1}{5}x^5 + \frac{1}{7}x^7 + \ldots = \sum_{n=0}^{\infty} \frac{x^{2n+1}}{2n+1} \qquad \left[x^2<1\right].$$

5. $$\sinh^{-1}\frac{1}{x} = \frac{1}{x} - \frac{1}{2}\,\frac{1}{3x^3} + \frac{1\cdot 3}{2\cdot 4}\,\frac{1}{5x^5} - \ldots.$$
$$= \operatorname{csch}^{-1} x = \sum_{n=0}^{\infty} (-1)^n \frac{(2n)!}{2^{2n}(n!)^2\,(2n+1)}\, x^{-2n-1} \qquad \left[x^2>1\right].$$

6. $$\cosh^{-1}\frac{1}{x} = \log\frac{2}{x} - \frac{1}{2}\,\frac{x^2}{2} - \frac{1\cdot 3}{2\cdot 4}\,\frac{x^4}{4} - \ldots$$
$$= \operatorname{sech}^{-1} x = \log\frac{2}{x} - \sum_{n=0}^{\infty} \frac{(2n)!}{2^{2n}(n!)^2 2n}\, x^{2n} \qquad \left[x^2<1\right].$$

7. $$\sinh^{-1}\frac{1}{x} = \log\frac{2}{x} + \frac{1}{2}\,\frac{x^2}{2} - \frac{1\cdot 3}{2\cdot 4}\,\frac{x^4}{4} + \ldots.$$
$$= \operatorname{csch}^{-1} x = \log\frac{2}{x} + \sum_{n=0}^{\infty} (-1)^n \frac{(2n)!}{2^{2n}(n!)^2 2n}\, x^{2n} \qquad \left[x^2<1\right].$$

8. $$\tanh^{-1}\frac{1}{x} = \frac{1}{x} + \frac{1}{3x^3} + \frac{1}{5x^5} + \ldots.$$
$$= \coth^{-1} x = \sum_{n=0}^{\infty} \frac{x^{-2n-1}}{2n+1} \qquad \left[x^2>1\right].$$

6.490

1. $$\frac{1}{2\sinh x} = \sum_{n=0}^{\infty} e^{-x(2n+1)}.$$

2. $$\frac{1}{2\cosh x} = \sum_{n=0}^{\infty} (-1)^n e^{-x(2n+1)}.$$

3. $$\frac{1}{2}(\tanh x - 1) = \sum_{n=1}^{\infty} (-1)^n e^{-2nx}.$$

4. $$-\frac{1}{2}\log\tanh\frac{x}{2} = \sum_{n=0}^{\infty} \frac{1}{2n+1} e^{-x(2n+1)}.$$

6.491

$$\frac{1}{2} + \sum_{n=1}^{\infty} e^{-(nx)^2} = \frac{\sqrt{\pi}}{x}\left\{\frac{1}{2} + \sum_{n=1}^{\infty} e^{-\left(\frac{n\pi}{x}\right)^2}\right\}.$$

By means of this formula a slowly converging series may be transformed into a rapidly converging series.

6.495

1. $$\tan x = 2x\left\{\frac{1}{\left(\frac{\pi}{2}\right)^2 - x^2} + \frac{1}{\left(\frac{3\pi}{2}\right)^2 - x^2} + \frac{1}{\left(\frac{5\pi}{2}\right)^2 - x^2} + \cdots\right\}$$
$$= \sum_{n=1}^{\infty} \frac{8x}{(2n-1)^2\pi^2 - 4x^2}.$$

2. $$\cot x = \frac{1}{x} - \frac{2x}{\pi^2 - x^2} - \frac{2x}{(2\pi)^2 - x^2} - \frac{2x}{(3\pi)^2 - x^2} - \cdots = \frac{1}{x} - \sum_{n=1}^{\infty} \frac{2x}{n^2\pi^2 - x^2}.$$

3. $$\sec x = \frac{\pi}{\left(\frac{\pi}{2}\right)^2 - x^2} - \frac{3\pi}{\left(\frac{3\pi}{2}\right)^2 - x^2} + \frac{5\pi}{\left(\frac{5\pi}{2}\right)^2 - x^2} - \cdots$$
$$= \sum_{n=1}^{\infty} (-1)^{n-1} \frac{4(2n-1)\pi}{(2n-1)^2\pi^2 - 4x^2}.$$

4. $$\csc x = \frac{1}{x} + \frac{2x}{\pi^2 - x^2} - \frac{2x}{(2\pi)^2 - x^2} + \frac{2x}{(3\pi)^2 - x^2} - \cdots$$
$$= \frac{1}{x} + \sum_{n=1}^{\infty} (-1)^{n-1} \frac{2x}{n^2\pi^2 - x^2}.$$

By replacing x by ix the corresponding series for the hyperbolic functions may be written.

INFINITE PRODUCTS

6.50

1. $$\sin x = x \prod_{n=1}^{\infty} \left(1 - \frac{x^2}{n^2\pi^2}\right).$$

2. $$\sinh x = x \prod_{n=1}^{\infty} \left(1 + \frac{x^2}{n^2\pi^2}\right).$$

3. $$\cos x = \prod_{n=0}^{\infty} \left(1 - \frac{4x^2}{(2n+1)^2\pi^2}\right).$$

4. $$\cosh x = \prod_{n=0}^{\infty} \left(1 + \frac{4x^2}{(2n+1)^2\pi^2}\right).$$

6.51

1. $$\frac{\sin x}{x} = \prod_{n=1}^{\infty} \cos \frac{x}{2^n}.$$

6.52

1. $$\frac{1}{1-x} = \prod_{n=0}^{\infty} (1 + x^{2^n}). \qquad [x^2 < 1].$$

6.53

1. $$\cosh x - \cos y = 2\left(1 + \frac{x^2}{y^2}\right) \sin^2 \frac{y}{2} \prod_{n=1}^{\infty} \left(1 + \frac{x^2}{(2n\pi + y)^2}\right)\left(1 + \frac{x^2}{(2n\pi - y)^2}\right).$$

2. $$\cos x - \cos y = 2\left(1 - \frac{x^2}{y^2}\right) \sin^2 \frac{y}{2} \prod_{n=1}^{\infty} \left(1 - \frac{x^2}{(2n\pi + y)^2}\right)\left(1 - \frac{x^2}{(2n\pi - y)^2}\right).$$

6.55 The convergent infinite series:

$$1 + u_1 + u_2 + \ldots . = 1 + \sum_{n=1}^{\infty} u_n.$$

may be transformed into the infinite product

$$(1 + v_1)(1 + v_2)(1 + v_3) \dots \dots$$

$$= \prod_{n=1}^{\infty} (1 + v_n),$$

where

$$v_n = \frac{u_n}{1 + u_1 + u_2 + \dots + u_{n-1}}.$$

6.600 The Gamma Function:

$$\Gamma(z) = \frac{1}{z} \prod_{n=1}^{\infty} \frac{\left(1 + \frac{1}{n}\right)^z}{1 + \frac{z}{n}},$$

z may have any real or complex value, except $0, -1, -2, -3, \dots\dots$

6.601

$$\frac{1}{\Gamma(z)} = z e^{\gamma z} \prod_{n=1}^{\infty} \left(1 + \frac{z}{n}\right) e^{-\frac{z}{n}}.$$

6.602

$$\gamma = \underset{m \to \infty}{\text{Limit}} \left\{ 1 + \frac{1}{2} + \frac{1}{3} + \dots + \frac{1}{m} - \log m \right\}$$

$$= \int_0^\infty \left\{ \frac{e^{-t}}{1 - e^{-t}} - \frac{e^{-t}}{t} \right\} dt = 0.5772157 \dots$$

6.603

$$\Gamma(z + 1) = z\Gamma(z),$$

$$\Gamma(z)\Gamma(1 - z) = \frac{\pi}{\sin \pi z}.$$

6.604 For z real and positive $= x$:

$$\Gamma(x) = \int_0^\infty e^{-t}\, t^{x-1}\, dt,$$

$$\log \Gamma(1 + x) = \left(x + \frac{1}{2}\right) \log x - x + \frac{1}{2} \log 2\pi + \int_0^\infty \left\{ \frac{1}{e^t - 1} - \frac{1}{t} + \frac{1}{2} \right\} e^{-xt} \frac{dt}{t}.$$

6.605 If $z = n$, a positive integer:

$$\Gamma(n) = (n - 1)!,$$

$$\Gamma\left(n + \frac{1}{2}\right) = \frac{1 \cdot 3 \cdot 5 \cdot \dots (2n - 1)}{2^n} \sqrt{\pi},$$

$$\Gamma(\tfrac{1}{2}) = \sqrt{\pi}.$$

6.606 The Beta Function. If x and y are real and positive:

$$B(x, y) = B(y, x) = \frac{\Gamma(x)\,\Gamma(y)}{\Gamma(x+y)},$$

$$B(x, y) = \int_0^1 t^{x-1}(1-t)^{y-1}\,dt,$$

$$B(x+1, y) = \frac{x}{x+y}\,B(x, y),$$

$$B(x, 1-x) = \frac{\pi}{\sin \pi x}.$$

6.610 For x real and positive:

$$\psi(x) = \frac{\Gamma'(x)}{\Gamma(x)} = -\gamma - \sum_{n=0}^{\infty}\left(\frac{1}{x+n} - \frac{1}{n+1}\right).$$

6.611

$$\psi(x+1) = \frac{1}{x} + \psi(x),$$

$$\psi(1-x) = \psi(x) + \pi \cot \pi x.$$

6.612

$$\psi(\tfrac{1}{2}) = -\gamma - 2 \log 2,$$
$$\psi(1) = -\gamma,$$
$$\psi(2) = 1 - \gamma,$$
$$\psi(3) = 1 + \frac{1}{2} - \gamma,$$
$$\psi(4) = 1 + \frac{1}{2} + \frac{1}{3} - \gamma.$$

. . . . .

. . . . .

6.613

$$\psi(x) = \int_0^\infty \left\{\frac{e^{-t}}{t} - \frac{e^{-tx}}{1-e^{-t}}\right\} dt$$

$$= -\gamma + \int_0^1 \frac{1-t^{x-1}}{1-t}\,dt.$$

6.620

$$\beta(x) = \sum_{n=0}^{\infty} \frac{(-1)^n}{x+n}$$
$$= \frac{1}{2}\left\{ \psi\left(\frac{x+1}{2}\right) - \psi\left(\frac{x}{2}\right) \right\}.$$

6.621

$$\beta(x+1) + \beta(x) = \frac{1}{x},$$
$$\beta(x) + \beta(1-x) = \frac{\pi}{\sin \pi x}.$$

6.622

$$\beta(1) = \log 2,$$
$$\beta\left(\frac{1}{2}\right) = \frac{\pi}{2}.$$

6.630 Gauss's Π Function:

1. $\Pi\ (k, z) = k^z \prod_{n=1}^{k} \frac{n}{z+n}.$
2. $\Pi\ (k, z+1) = \Pi\ (k, z) \cdot \dfrac{1+z}{1+\dfrac{1+z}{k}}.$
3. $\Pi\ (z) = \lim_{k\to\infty} \Pi\ (k, z).$
4. $\Pi\ (z) = \Gamma(z+1).$
5. $\Pi\ (-z)\, \Pi\ (z-1) = \pi \csc \pi z.$
6. $\Pi\left(\frac{1}{2}\right) = \frac{1}{2}\sqrt{\pi}.$

6.631 If z is an integer, n,

$$\Pi\ (n) = n!$$

DEFINITE INTEGRALS EXPRESSED AS INFINITE SERIES

6.700

$$\int_0^x e^{-x^2}\, dx = \sum_{k=0}^{\infty} \frac{(-1)k}{k!(2k+1)} x^{2k+1}.$$
$$= e^{-x^2} \sum_{k=0}^{\infty} \frac{2^k x^{2k+1}}{1\cdot 3\cdot 5 \cdot \ldots \cdot (2k+1)}.$$

Darling (Quarterly Journal, 49, p. 36, 1920) has obtained an approximation to this integral:

$$\frac{\sqrt{\pi}}{2} - \frac{2}{\sqrt{\pi}} \tan^{-1} \left\{ e^{\sqrt{\pi}}(1 + x^2 e^{-\sqrt{\pi}})^2 \right\}^{-x}$$

Fresnel's Integrals:

6.701 $$\int_0^x \cos(x^2)dx = \sum_{k=0}^{\infty} \frac{(-1)^k}{(2k)!\,(4k+1)} x^{4k+1}$$

$$= \cos(x^2) \sum_{k=0}^{\infty} (-1)^k \frac{2^{2k} x^{4k+1}}{1\cdot3\cdot5 \ldots . (4k+1)}$$

$$+ \sin(x^2) \sum_{k=0}^{\infty} (-1)^k \frac{2^{2k+1} x^{4k+3}}{1\cdot3\cdot5 \ldots . (4k+3)}.$$

6.702 $$\int_0^x \sin(x^2)dx = \sum_{k=0}^{\infty} \frac{(-1)^k}{(2k+1)!\,(4k+3)} x^{4k+3}$$

$$= \sin(x^2) \sum_{k=0}^{\infty} (-1)^k \frac{2^{2k}}{1\cdot3\cdot5 \ldots (4k+1)} x^{4k+1}$$

$$- \cos(x^2) \sum_{k=0}^{\infty} (-1)^k \frac{2^{2k+1} x^{4k+3}}{1\cdot3\cdot5 \ldots . (4k+3)}.$$

6.703 $$\int_0^1 \frac{t^{a-1}}{1+t^b} dt = \sum_{n=0}^{\infty} (-1)^n \frac{1}{a+nb}$$

6.704 $$\frac{1}{(k-1)!} \int_0^1 \frac{t^{a-1}(1-t)^{k-1}}{1-xt^b} dt$$

$$= \sum_{n=0}^{\infty} \frac{x^n}{(a+nb)\,(a+nb+1)\,(a+nb+2) \ldots (a+nb+k-1)}$$

$[b>0,\ x^2 \leqslant 1]$.

(Special cases, **6.445** and **6.922**).

6.705 $$\int_0^x e^{-t}\, t^{y-1}\, dt = \sum_{n=0}^{\infty} (-1)^n \frac{x^{n+y}}{n!(n+y)} = e^{-x} \sum_{n=0}^{\infty} \frac{x^{n+y}}{y(y+1) \ldots (y+n)}.$$

6.706 If the sum of the series,

$$f(x) = \sum_{n=0}^{\infty} c_n x^n \qquad [0 < x < 1]$$

is known, then

$$\sum_{n=0}^{\infty} \frac{c_n x^n}{(a+nb)\,(a+nb+1)\,(a+nb+2) \ldots . (a+nb+k-1)} \qquad [b>0]$$

$$= \frac{1}{(k-1)!} \int_0^1 t^{a-1}(1-t)^{k-1} f(xt^b)dt.$$

6.707 $$\int_0^\infty f(x)\sum_{n=1}^{\infty}\frac{1}{n}\sin nx\cdot dx = \frac{1}{2}\int_0^{2\pi}(\pi - t)\sum_{n=0}^{\infty}f(t+2n\pi)\cdot dt.$$

Example 1. $f(x) = e^{-kx}$ [$k>0$].

1. $$\frac{1}{k} + 2k\sum_{n=1}^{\infty}\frac{1}{k^2+n^2} = \pi\frac{e^{k\pi}+e^{-k\pi}}{e^{k\pi}-e^{-k\pi}}.$$

Replacing k by $\frac{k}{2}$, and subtracting,

2 $$\frac{1}{k} + 2k\sum_{n=1}^{\infty}(-1)^n\frac{1}{k^2+n^2} = \frac{2\pi}{e^{k\pi}-e^{-k\pi}}.$$

Example 2. With $f(x) = e^{-\lambda x}\cos\mu x$ and $e^{-\lambda x}\sin\mu x$.

3. $$\frac{\lambda}{\lambda^2+\mu^2} + \sum_{n=1}^{\infty}\left\{\frac{\lambda}{\lambda^2+(n-\mu)^2} + \frac{\lambda}{\lambda^2+(n+\mu)^2}\right\} = \frac{\pi\sinh 2\lambda\pi}{\cosh 2\lambda\pi - \cos 2\mu\pi}.$$

4. $$\frac{\mu}{\lambda^2+\mu^2} - \sum_{n=1}^{\infty}\left\{\frac{n-\mu}{\lambda^2+(n-\mu)^2} + \frac{n+\mu}{\lambda^2+(n+\mu)^2}\right\} = \frac{\pi\sin 2\mu\pi}{\cosh 2\lambda\pi - \cos 2\mu\pi}.$$

6.709 If the sum of the series,

$$f(x) = \sum_{n=0}^{\infty}a_nx^n,$$

is known, then

$$a_0 + a_1y + a_2y(y+1) + a_3y(y+1)(y+2) + \ldots\ldots = \frac{\int_0^\infty e^{-t}t^{y-1}f(t)\,dt}{\Gamma(y)}.$$

6.710 The complete elliptic integral of the first kind:

$$K = \int_0^1\frac{dx}{\sqrt{(1-x^2)(1-k^2x^2)}} = \int_0^{\frac{\pi}{2}}\frac{d\theta}{\sqrt{1-k^2\sin^2\theta}}$$

$$= \frac{\pi}{2}\left\{1 + \left(\frac{1}{2}\right)^2k^2 + \left(\frac{1\cdot 3}{2\cdot 4}\right)^2k^4 + \ldots\right\}$$

$$= \frac{\pi}{2}\left\{1 + \sum_{n=1}^{\infty}\left(\frac{1\cdot 3\cdot 5\ldots(2n-1)}{2\cdot 4\cdot 6\ldots 2n}\right)^2k^{2n}\right\} \qquad [k^2<1].$$

If $$k' = \frac{1-\sqrt{1-k^2}}{1+\sqrt{1-k^2}}$$

$$K = \frac{\pi(1+k')}{2}\left\{1 + \left(\frac{1}{2}\right)^2k'^2 + \left(\frac{1\cdot 3}{2\cdot 4}\right)^2k'^4 + \ldots\right\}$$

$$= \frac{\pi(1+k')}{2}\left\{1 + \sum_{n=1}^{\infty}\left(\frac{1\cdot 3\cdot 5\ldots(2n-1)}{2\cdot 4\cdot 6\ldots 2n}\right)^2k'^{2n}\right\}.$$

6.711 The complete elliptic integral of the second kind:

$$E = \int^{\frac{\pi}{2}} \sqrt{1 - k^2 \sin^2 \theta}\, d\theta.$$

$$E = \frac{\pi}{2}\left\{1 - \left(\frac{1}{2}\right)^2 \frac{k^2}{1} - \left(\frac{1\cdot 3}{2\cdot 4}\right)^2 \frac{k^4}{3} - \dots\right\}.$$

$$= \frac{\pi}{2}\left\{1 - \sum_{n=1}^{\infty}\left(\frac{1\cdot 3\cdot 5 \dots (2n-1)}{2\cdot 4\cdot 6 \dots 2n}\right)^2 \cdot \frac{k^{2n}}{2n-1}\right\}.$$

If $$k' = \frac{1 - \sqrt{1-k^2}}{1 + \sqrt{1-k^2}}.$$

$$E = \frac{\pi(1-k')}{2}\left\{1 + 5\left(\frac{1}{2}\right)^2 k'^2 + 9\left(\frac{1\cdot 3}{2\cdot 4}\right)^2 k'^4 + \dots\right\}$$

$$= \frac{\pi(1-k')}{2}\left\{1 + \sum_{n=1}^{\infty}(4n+1)\left(\frac{1\cdot 3\cdot 5 \dots (2n-1)}{2\cdot 4\cdot 6 \dots 2n}\right)^2 k'^{2n}\right\}$$

$$= \frac{\pi}{2(1+k')}\left\{1 + \left(\frac{1}{2}\right)^2 k'^2 + \left(\frac{1}{2\cdot 4}\right)^2 k'^4 + \left(\frac{1\cdot 3}{2\cdot 4\cdot 6}\right)^2 k'^6 + \dots\right\}$$

$$= \frac{\pi}{2(1+k')}\left\{1 + k'^2\left[\frac{1}{4} + \sum_{n=1}^{\infty}\left(\frac{1\cdot 3 \dots (2n-1)}{2\cdot 4\cdot 6 \dots (2n+2)}\right)^2 k'^{2n}\right]\right\}.$$

FOURIER'S SERIES

6.800 If $f(x)$ is uniformly convergent in the interval:

$$-c < x < +c$$

$$f(x) = \frac{1}{2}b_0 + b_1 \cos\frac{\pi x}{c} + b_2 \cos\frac{2\pi x}{c} + b_3 \cos\frac{3\pi x}{c} + \dots$$
$$+ a_1 \sin\frac{\pi x}{c} + a_2 \sin\frac{2\pi x}{c} + a_3 \sin\frac{3\pi x}{c} + \dots$$

$$b_m = \frac{1}{c}\int_{-c}^{+c} f(x)\cos\frac{m\pi x}{c}\,dx,$$

$$a_m = \frac{1}{c}\int_{-c}^{+c} f(x)\sin\frac{m\pi x}{c}\,dx.$$

6.801 If $f(x)$ is uniformly convergent in the interval:

$$0 < x < c$$

$$f(x) = \frac{1}{2}b_0 + b_1 \cos\frac{2\pi x}{c} + b_2 \cos\frac{4x\pi}{c} + b_3 \cos\frac{6\pi x}{c} + \dots$$
$$+ a_1 \sin\frac{2\pi x}{c} + a_2 \sin\frac{4\pi x}{c} + a_3 \sin\frac{6\pi x}{c} + \dots$$

$$b_m = \frac{2}{c}\int_0^c f(x)\cos\frac{2m\pi x}{c}\,dx,$$

$$a_m = \frac{2}{c}\int_0^c f(x)\sin\frac{2m\pi x}{c}\,dx.$$

6.802 Special Developments in Fourier's Series.

$$f(x) = a \text{ from } x = kc \text{ to } x = (k + \tfrac{1}{2})c,$$

$$f(x) = -a \text{ from } x = (k + \tfrac{1}{2})c \text{ to } x = (k + 1)c,$$

where k is any integer, including 0.

$$f(x) = \frac{4a}{\pi} \sum_{n=1}^{\infty} \frac{1}{2n-1} \sin \frac{2(2n-1)\pi}{c} x.$$

6.803

$$\begin{aligned} f(x) &= mx, && -\frac{c}{4} \leqslant x \leqslant +\frac{c}{4} \\ &= -m\left(x - \frac{c}{2}\right), && \frac{c}{4} \leqslant x \leqslant \frac{3c}{4} \\ &= m(x-c), && \frac{3c}{4} \leqslant x \leqslant \frac{5c}{4} \\ &= -m\left(x - \frac{3c}{2}\right), && \frac{5c}{4} \leqslant x \leqslant \frac{7c}{4} \\ &\cdots\cdots \\ &\cdots\cdots \end{aligned}$$

$$f(x) = \frac{2mc}{\pi^2} \sum_{n=1}^{\infty} (-1)^{n-1} \frac{1}{(2n-1)^2} \sin \frac{2(2n-1)\pi}{c} x.$$

6.804

$$\begin{aligned} f(x) &= mx, && -\frac{c}{2} < x < +\frac{c}{2} \\ &= m(x-c), && +\frac{c}{2} < x < \frac{3c}{2}, \end{aligned}$$

$$f(x) = \frac{cm}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^{n-1}}{n} \sin \frac{2n\pi x}{c}.$$

6.805

$$\begin{aligned} f(x) &= -a, && -5b \leqslant x \leqslant -3b, \\ &= \frac{a}{b}(x+2b), && -3b \leqslant x \leqslant -b, \\ &= a, && -b \leqslant x \leqslant +b, \\ &= -\frac{a}{b}(x-2b), && b \leqslant x \leqslant 3b, \\ &= -a, && 3b \leqslant x \leqslant 5b. \\ &\cdots\cdots \\ &\cdots\cdots \end{aligned}$$

$$f(x) = \frac{8\sqrt{2}a}{\pi^2} \left\{ \cos \frac{\pi x}{4b} - \frac{1}{3^2} \cos \frac{3\pi x}{4b} - \frac{1}{5^2} \cos \frac{7\pi x}{4b} + \frac{1}{7^2} \cos \frac{7\pi x}{4b} + \cdots \right\}$$

6.806
$$f(x) = \frac{b}{l}x + b, \qquad -l \leqslant x \leqslant 0,$$
$$= -\frac{b}{l}x + b, \qquad 0 \leqslant x \leqslant l.$$
$$f(x) = \frac{8b}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\cos(2n+1)\frac{\pi x}{2l}.$$

6.807
$$f(x) = \frac{a}{b}x, \qquad 0 \leqslant x \leqslant b,$$
$$= -\frac{a}{l-b}x + \frac{al}{l-b}, \qquad b \leqslant x \leqslant l,$$
$$f(x) = \frac{2al^2}{\pi^2 b(l-b)}\sum_{n=1}^{\infty}\frac{1}{n^2}\sin\frac{n\pi b}{l}\sin\frac{n\pi x}{l}.$$

6.810 $$x = 2\sum_{n=1}^{\infty}\frac{(-1)^{n-1}}{n}\sin nx \qquad \left[-\pi < x < \pi\right].$$

6.811 $$\cos ax = \frac{2}{\pi}\sin a\pi\left\{\frac{1}{2a} + a\sum_{n=1}^{\infty}\frac{(-1)^{n-1}}{n^2-a^2}\cos nx\right\} \qquad \left[-\pi < x < \pi\right].$$

6.812 $$\sin ax = \frac{2}{\pi}\sin a\pi\sum_{n=1}^{\infty}\frac{(-1)^{n-1}}{n^2-a^2}n\sin nx \qquad \left[-\pi < x < \pi\right].$$

6.813 $$\frac{\pi - x}{2} = \sum_{n=1}^{\infty}\frac{\sin nx}{n} \qquad \left[0 < x < 2\pi\right].$$

6.814 $$\frac{1}{2}\log\frac{1}{2(1-\cos x)} = \sum_{n=1}^{\infty}\frac{\cos nx}{n} \qquad \left[0 < x < 2\pi\right].$$

6.815 $$\frac{\pi^2}{6} - \frac{\pi x}{2} + \frac{x^2}{4} = \sum_{n=1}^{\infty}\frac{\cos nx}{n^2} \qquad \left[0 < x < 2\pi\right].$$

6.816 $$\frac{\pi^2 x}{6} - \frac{\pi x^2}{4} + \frac{x^3}{12} = \sum_{n=1}^{\infty}\frac{\sin nx}{n^3} \qquad \left[0 < x < 2\pi\right].$$

6.817 $$\frac{\pi^4}{90} - \frac{\pi^2 x^2}{12} + \frac{\pi x^3}{12} - \frac{x^4}{48} = \sum_{n=1}^{\infty}\frac{\cos nx}{n^4} \qquad \left[0 < x < 2\pi\right].$$

6.818 $$\frac{\pi^4 x}{90} - \frac{\pi^2 x^3}{36} + \frac{\pi x^4}{48} - \frac{x^5}{240} = \sum_{n=1}^{\infty}\frac{\sin nx}{n^5} \qquad \left[0 < x < 2\pi\right].$$

6.820 $$x^2 = \frac{c^2}{3} - \frac{4c^2}{\pi^2}\sum_{n=1}^{\infty} \frac{(-1)^{n-1}}{n^2} \cos \frac{n\pi x}{c} \qquad \left[-c \leqslant x \leqslant c\right].$$

6.821 $$\frac{e^x}{e^c - e^{-c}} = \frac{1}{2c} - c\sum_{n=1}^{\infty} (-1)^{n-1}\frac{1}{(n\pi)^2 + c^2} \cos \frac{n\pi x}{c}$$
$$+ \pi\sum_{n=1}^{\infty}(-1)^{n-1} \frac{1}{(n\pi)^2 + c^2} \sin \frac{n\pi x}{c} \qquad \left[-c < x < c\right].$$

6.822 $$e^{cx} = \frac{2c}{\pi}(e^{c\pi} - 1)\left\{\frac{1}{2c^2} - \sum_{n=1}^{\infty} (-1)^{n-1} \frac{1}{c^2 + n^2} \cos nx\right\} \qquad \left[0 < x < \pi\right].$$

6.823 $$\cos 2x - \left(\frac{\pi}{2} - x\right)\sin 2x + \sin^2 x \log (4\sin^2 x) = \sum_{n=1}^{\infty} \frac{\cos 2(n+1)x}{n(n+1)}$$
$$[0 \leqslant x \leqslant \pi].$$

6.824 $$\sin 2x - (\pi - 2x)\sin^2 x - \sin x \cos x \log (4\sin^2 x)$$
$$= \sum_{n=1}^{\infty} \frac{\sin 2(n+1)x}{n(n+1)} \qquad \left[0 \leqslant x \leqslant \pi\right].$$

6.825 $$\frac{1}{2} - \frac{\pi}{4}\sin x = \sum_{n=1}^{\infty} \frac{\cos 2nx}{(2n-1)(2n+1)} \qquad \left[0 \leqslant x \leqslant \frac{\pi}{2}\right].$$

6.830 $$\frac{r \sin x}{1 - 2r\cos x + r^2} = \sum_{n=1}^{\infty} r^n \sin nx \qquad \left[r^2 < 1\right].$$

6.831 $$\tan^{-1} \frac{r\sin x}{1 - r\cos x} = \sum_{n=1}^{\infty} \frac{1}{n} r^n \sin nx \qquad \left[r < 1\right].$$

6.832 $$\frac{1}{2}\tan^{-1} \frac{2r\sin x}{1 - r^2} = \sum_{n=1}^{\infty} \frac{r^{2n-1}}{2n-1} \sin(2n-1)x \qquad \left[r^2 < 1\right].$$

6.833 $$\frac{1 - r\cos x}{1 - 2r\cos x + r^2} = \sum_{n=0}^{\infty} r^n \cos nx \qquad \left[r^2 < 1\right].$$

6.834 $$\log \frac{1}{\sqrt{1 - 2r\cos x + r^2}} = \sum_{n=1}^{\infty} \frac{1}{n} r^n \cos nx \qquad \left[r^2 < 1\right].$$

6.835 $\frac{1}{2}\tan^{-1}\frac{2r\cos x}{1-r^2} = \sum_{n=1}^{\infty}(-1)^{n-1}\frac{r^{2n-1}}{2n-1}\cos(2n-1)x$ $\qquad [r^2<1]$.

NUMERICAL SERIES

6.900

$$S_n = \frac{1}{1^n}+\frac{1}{2^n}+\frac{1}{3^n}+\frac{1}{4^n}+\ldots\ldots = \sum_{k=1}^{\infty}\frac{1}{k^n},$$

$S_1 = \infty$

$S_2 = \frac{\pi^2}{6} = 1.6449340668$

$S_3 = \frac{\pi^3}{25.79436\ldots} = 1.2020569032$

$S_4 = \frac{\pi^4}{90} = 1.0823232337$

$S_5 = \frac{\pi^5}{295.1215} = 1.0369277551$

$S_6 = \frac{\pi^6}{945} = 1.0173430620,$

$S_7 = \frac{\pi^7}{2995.286\ldots} = 1.0083492774$

$S_8 = \frac{\pi^8}{9450} = 1.0040773562,$

$S_9 = \frac{\pi^9}{29749.35\ldots} = 1.0020083928,$

$S_{10} = 1.0009945751,$
$S_{11} = 1.0004941886.$

6.901

$$u_n = 1-\frac{1}{3^n}+\frac{1}{5^n}-\frac{1}{7^n}+\ldots\ldots = \sum_{k=0}^{\infty}(-1)^{k-1}\frac{1}{(2k+1)^n},$$

$u_1 = \frac{\pi}{4},$

$u_2 = 0.9159656\ldots$

$u_4 = 0.98894455\ldots.$

$u_6 = 0.99868522\ldots.$

A table of u_n from $n = 1$ to $n = 38$ to 18 decimal places is given by Glaisher, Messenger of Mathematics, 42, p. 49, 1913.

6.902 Bernoulli's Numbers.

1. $$\frac{2^{2n-1}\pi^{2n}}{(2n)!}B_n = \frac{1}{1^{2n}}+\frac{1}{2^{2n}}+\frac{1}{3^{2n}}+\frac{1}{4^{2n}}+\ldots\ldots = \sum_{k=1}^{\infty}\frac{1}{k^{2n}}.$$

2. $$\frac{(2^{2n}-1)\pi^{2n}}{2(2n)!}B_n = \frac{1}{1^{2n}}+\frac{1}{3^{2n}}+\frac{1}{5^{2n}}+\frac{1}{7^{2n}}+\ldots\ldots = \sum_{k=0}^{\infty}\frac{1}{(2k+1)^{2n}}.$$

3. $$\frac{(2^{2n-1}-1)\pi^{2n}}{(2n)!}B_n = \frac{1}{1^{2n}}-\frac{1}{2^{2n}}+\frac{1}{3^{2n}}-\frac{1}{4^{2n}}+\ldots\ldots = \sum_{k=1}^{\infty}(-1)^{n-1}\frac{1}{k^{2n}}.$$

$B_1 = \frac{1}{6},$ $\qquad B_3 = \frac{1}{42},$

$B_2 = \frac{1}{30},$ $\qquad B_4 = \frac{1}{30},$

$$B_5 = \frac{5}{66}, \qquad B_8 = \frac{3617}{510},$$

$$B_6 = \frac{691}{2730} \qquad B_9 = \frac{43867}{798},$$

$$B_7 = \frac{7}{6}, \qquad B_{10} = \frac{174611}{330}.$$

6.903 Euler's Numbers

$$\frac{\pi^{2n+1}}{2^{2n+2}(2n)!} E_n = 1 - \frac{1}{3^{2n+1}} + \frac{1}{5^{2n+1}} - \frac{1}{7^{2n+1}} + \quad \ldots = \sum_{k=1}^{\infty} (-1)^{k-1} \frac{1}{(2k-1)^{2n+1}}.$$

$$E_1 = 1, \qquad E_4 = 1385,$$
$$E_2 = 5, \qquad E_5 = 50521,$$
$$E_3 = 61, \qquad E_6 = 2702765.$$

6.904

$$E_n - \frac{2n(2n-1)}{2!} E_{n-1} + \frac{2n(2n-1)(2n-2)(2n-3)}{4!} E_{n-2} - \ldots .$$
$$- \ldots \ldots + (-1)^n = 0.$$

6.905

$$\frac{2^{2n}(2^{2n}-1)}{2n} B_n = (2n-1)E_{n-1} - \frac{(2n-1)(2n-2)(2n-3)}{3!} E_{n-2}$$
$$+ \frac{(2n-1)(2n-2)(2n-3)(2n-4)(2n-5)}{5!} E_{n-3} - \ldots \ldots + (-1)^{n-1}.$$

6.910

$$S_r = \sum_{n=1}^{\infty} \frac{n^r}{n!}$$

$$S_1 = e, \qquad S_5 = 52e,$$
$$S_2 = 2e, \qquad S_6 = 203e,$$
$$S_3 = 5e, \qquad S_7 = 877e,$$
$$S_4 = 15e, \qquad S_8 = 4140e.$$

6.911

$$S_r = \sum_{n=1}^{\infty} \frac{1}{(4n^2-1)^r}.$$

$$S_1 = \frac{1}{2}, \qquad S_3 = \frac{32 - 3\pi^2}{64},$$

$$S_2 = \frac{\pi^2 - 8}{16}, \qquad S_4 = \frac{\pi^4 + 30\pi^2 - 384}{768}.$$

6.912

1. $\log 2 = \sum_{n=1}^{\infty} \frac{1}{n \cdot 2^n}.$

2. $\frac{\pi^2}{12} - \frac{1}{2} (\log 2)^2 = \sum_{n=1}^{\infty} \frac{1}{n^2 2^n}.$

6.913

1. $2\log 2 - 1 = \sum_{n=1}^{\infty} \frac{1}{n(4n^2 - 1)}.$

2. $\frac{3}{2} (\log 3 - 1) = \sum_{n=1}^{\infty} \frac{1}{n(9n^2 - 1)}.$

3. $-3 + \frac{3}{2} \log 3 + 2 \log 2 = \sum_{n=1}^{\infty} \frac{1}{n(36n^2 - 1)}.$

6.914

$$S_r = \sum_{n=1}^{\infty} \left(\frac{1 \cdot 3 \cdot 5 \; . \; . \; . \; . \; . \; (2n-1)}{2 \cdot 4 \cdot 6 \; . \; . \; . \; . \; . \; 2n}\right)^2 \frac{1}{2n + r},$$

$u_2 = 0.9159656 \; . \; . \; . \; .$ (see **6.901**)

$S_0 = 2 \log 2 - \frac{4}{\pi} u_2,$

$S_1 = \frac{4}{\pi} u_2 - 1,$

$S_2 = \frac{2}{\pi} - \frac{1}{2},$

$S_3 = \frac{1}{2\pi} (2u_2 + 1) - \frac{1}{3},$

$S_4 = \frac{10}{9\pi} - \frac{1}{4},$

$S_5 = \frac{1}{32\pi} (18u_2 + 13) - \frac{1}{5},$

$S_6 = \frac{178}{225\pi} - \frac{1}{6},$

$S_7 = \frac{1}{128\pi} (50u_2 + 43) - \frac{1}{7},$

$S_{-1} = 1 - \frac{2}{\pi},$

$S_{-2} = \frac{1}{2} \log 2 + \frac{1}{4} - \frac{1}{2\pi} (2u_2 + 1),$

$S_{-3} = \frac{1}{3} - \frac{10}{9\pi},$

$S_{-4} = \frac{9}{32} \log 2 + \frac{11}{128} - \frac{1}{32\pi} (18u_2 + 13),$

$S_{-5} = \frac{1}{5} - \frac{178}{225\pi},$

$S_{-6} = \frac{25}{128} \log 2 + \frac{71}{1536} - \frac{1}{128\pi} (50u_2 + 43).$

When r is a negative even integer the value $n = \frac{r}{2}$ is to be excluded in the summation.

6.915

1. $A_n = \frac{1 \cdot 3 \cdot 5 \; . \; . \; . \; . \; (2n-1)}{2 \cdot 4 \cdot 6 \; . \; . \; . \; . \; 2n} = \frac{(2n-1)!}{2^{2n-1} n!(n-1)!}.$

2. $1 - \frac{\pi}{4} = \sum_{n=1}^{\infty} A_n \frac{1}{4n^2 - 1}.$

3. $\frac{\pi}{2} - 1 = \sum_{n=1}^{\infty} A_n \frac{1}{2n+1}.$

4. $\log(1+\sqrt{2}) - 1 = \sum_{n=1}^{\infty} (-1)^n A_n \frac{1}{2n+1}.$

5. $\frac{1}{2} = \sum_{n=1}^{\infty} A_n^2 \frac{4n+1}{(2n-1)(2n+2)}.$

6. $\frac{2}{\pi} - \frac{1}{2} = \sum_{n=1}^{\infty} (-1)^{n+1} A_n^3 \frac{4n+1}{(2n-1)(2n+2)}.$

7. $\frac{2}{\pi} - 1 = \sum_{n=1}^{\infty} (-1)^n A_n^3 (4n+1).$

8. $\frac{1}{2} - \frac{4}{\pi^2} = \sum_{n=1}^{\infty} A_n^4 \frac{4n+1}{(2n-1)(2n+2)}.$

6.916

If m is an integer, and $n = m$ is excluded from the summation:

1. $-\frac{3}{4m^2} = \sum_{n=1}^{\infty} \frac{1}{m^2 - n^2}.$

2. $\frac{3}{4m^2} = \sum_{n=1}^{\infty} \frac{(-1)^{n-1}}{m^2 - n^2}.$ (m even).

6.917

1. $1 = \sum_{n=2}^{\infty} \frac{n-1}{n!}.$

2. $\frac{1}{2} = \sum_{n=1}^{\infty} \frac{1}{4n^2 - 1}.$

3. $2 \log 2 = \sum_{n=1}^{\infty} \frac{12n^2 - 1}{n(4n^2-1)^2}.$

6.918 $\frac{2}{\sqrt{3}} \log \frac{1+\sqrt{3}}{\sqrt{2}} = 1 + \sum_{n=1}^{\infty} (-1)^n \frac{2 \cdot 4 \cdot 6 \cdot \ldots \cdot 2n}{3 \cdot 5 \cdot 7 \cdot \ldots \cdot (2n+1)} \frac{1}{2^n}.$

6.919 $\frac{1}{2}(1 - \log 2) = \sum_{n=1}^{\infty} \left\{ n \log\left(\frac{2n+1}{2n-1}\right) - 1 \right\}.$

6.920

1. $e = 1 + \frac{1}{1!} + \frac{1}{2!} + \frac{1}{3!} + \ldots \quad = 2.71828.$

2. $\frac{1}{e} = 1 - \frac{1}{1!} + \frac{1}{2!} - \frac{1}{3!} - \ldots = 0.36788.$

3. $\frac{1}{2}\left(e + \frac{1}{e}\right) = 1 + \frac{1}{2!} + \frac{1}{4!} + \ldots = 1.54308.$

4. $\frac{1}{2}\left(e - \frac{1}{e}\right) = 1 + \frac{1}{3!} + \frac{1}{5!} + \ldots = 1.175201.$

5. $\cos 1 = 1 - \frac{1}{2!} + \frac{1}{4!} - \ldots = 0.54030.$

6. $\sin 1 = 1 - \frac{1}{3!} + \frac{1}{5!} - \ldots = 0.84147.$

6.921

1. $\frac{4}{5} = 1 - \frac{1}{2^2} + \frac{1}{2^4} - \frac{1}{2^6} + \ldots$

2. $\frac{9}{10} = 1 - \frac{1}{3^2} + \frac{1}{3^4} - \frac{1}{3^6} + \ldots$

3. $\frac{16}{17} = 1 - \frac{1}{4^2} + \frac{1}{4^4} - \frac{1}{4^6} + \ldots$

4. $\frac{25}{26} = 1 - \frac{1}{5^2} + \frac{1}{5^4} - \frac{1}{5^6} + \ldots$

6.922 $\frac{(2^{\frac{1}{4}} - 1)\Gamma(\frac{1}{4})}{2^{\frac{11}{4}}\pi^{\frac{3}{4}}} = e^{-\pi} + e^{-9\pi} + e^{-25\pi} + \ldots ; \Gamma(\tfrac{1}{4}) = 3.6256 \ldots$

6.923 (Special cases of **6.705**):

1. $\frac{1}{1\cdot2\cdot3} + \frac{1}{3\cdot4\cdot5} + \frac{1}{5\cdot6\cdot7} + \ldots = \log 2 - \frac{1}{2}.$

2. $\frac{1}{1\cdot2\cdot3} - \frac{1}{3\cdot4\cdot5} + \frac{1}{5\cdot6\cdot7} - \ldots = \frac{1}{2}(1 - \log 2).$

3. $\frac{1}{2\cdot3\cdot4} + \frac{1}{4\cdot5\cdot6} + \frac{1}{6\cdot7\cdot8} + \ldots = \frac{3}{4} - \log 2.$

4. $\frac{1}{2\cdot3\cdot4} - \frac{1}{4\cdot5\cdot6} + \frac{1}{6\cdot7\cdot8} - \ldots = \frac{1}{4}(\pi - 3).$

5. $\frac{1}{1\cdot2\cdot3} + \frac{1}{4\cdot5\cdot6} + \frac{1}{7\cdot8\cdot9} + \ldots = \frac{1}{4}\left(\frac{\pi}{\sqrt{3}} - \log 3\right).$

6. $\frac{1}{2\cdot3\cdot4} + \frac{1}{6\cdot7\cdot8} + \frac{1}{10\cdot11\cdot12} + \ldots = \frac{\pi}{8} - \frac{1}{2}\log 2.$

7. $\frac{1}{1\cdot2\cdot3\cdot4} + \frac{1}{4\cdot5\cdot6\cdot7} + \frac{1}{7\cdot8\cdot9\cdot10} + \ldots = \frac{1}{6}\left(1 + \frac{\pi}{2\sqrt{3}}\right) - \frac{1}{4}\log 3.$

VII. SPECIAL APPLICATIONS OF ANALYSIS.

7.10 Indeterminate Forms.

7.101 $\frac{0}{0}$. If $\frac{f(x)}{F(x)}$ assumes the indeterminate value $\frac{0}{0}$ for $x = a$, the true value of the quotient may be found by replacing $f(x)$ and $F(x)$ by their developments in series, if valid for $x = a$.

Example:

$$\left[\frac{\sin^2 x}{1 - \cos x}\right]_{x=0};$$

$$\frac{\sin^2 x}{1 - \cos x} = \frac{\left(x - \frac{x^3}{3!} + \dots\right)^2}{\frac{x^2}{2!} - \frac{x^4}{4!} + \dots} = \frac{\left(1 - \frac{x^2}{3!} + \dots\right)^2}{\frac{1}{2!} - \frac{x^2}{4!} + \dots}$$

Therefore,

$$\left[\frac{\sin^2 x}{1 - \cos x}\right]_{x=0} = 2.$$

7.102 L'Hospital's Rule. If $f(a + h)$ and $F(a + h)$ can be developed by Taylor's Theorem (**6.100**) then the true value of $\frac{f(x)}{F(x)}$ for $x = a$ is,

$$\frac{f'(a)}{F'(a)}$$

provided that this has a definite value (0, finite, or infinite). If the ratio of the first derivatives is still indeterminate, the true value may be found by taking that of the ratio of the first one of the higher derivatives that is definite.

7.103 The true value of $\frac{f(x)}{F(x)}$ for $x = a$ is the limit, for $h = 0$, of

$$\frac{q!}{p!}\, h^{p-q} \cdot \frac{f^{(p)}(a)}{F^{(q)}(a)}$$

where $f^{(p)}(a)$ and $F^{(q)}(a)$ are the first of the higher derivatives of $f(x)$ and $F(x)$ that do not vanish for $x = a$. The true value of $\frac{f(x)}{F(x)}$ for $x = a$ is 0 if $p > q$, ∞ if $p < q$, and equal to $\frac{f^{(p)}(a)}{F^{(p)}(a)}$ if $p = q$.

Example:

$$\left[\frac{\sinh x - x\cosh x}{\sin x - x\cos x}\right]_{x=0} = \left[\frac{-x\sinh x}{x\sin x}\right]_{x=0}.$$

$$= \left[-\frac{\sinh x}{\sin x}\right]_{x=0} = \left[-\frac{\cosh x}{\cos x}\right]_{x=0} = -1.$$

7.104 Failure of L'Hospital's Rule. In certain cases this rule fails to determine the true value of an expression for the reason that all the higher derivatives vanish at the limit. In such cases the true value may often be found by factoring the given expression, or resolving into partial fractions (**1.61**).

Example:

$$\left[\frac{\sqrt{x^2 - a^2}}{\sqrt{x - a}}\right]_{x=a} = [\sqrt{x + a}]_{x=a} = \sqrt{2a}.$$

7.105 In applying L'Hospital's Rule, if any of the successive quotients contains a factor which can be evaluated at once its determinate value may be substituted.

Example:

$$\left[\frac{(1 - x)e^x - 1}{\tan^2 x}\right]_{x=0} = \left[\frac{-xe^x}{2\tan x\sec^2 x}\right]_{x=0}$$

$$\left[\frac{x}{\tan x}\right]_{x=0} = 1.$$

Hence the given function is,

$$\left[-\frac{e^x}{2\sec^2 x}\right]_{x=0} = -\frac{1}{2}.$$

7.106 If the given function can be separated into factors each of which is indeterminate, the factors may be evaluated separately.

Example:

$$\left[\frac{(e^x - 1)\tan^2 x}{x^3}\right]_{x=0} = \left[\left(\frac{\tan x}{x}\right)^2 \frac{e^x - 1}{x}\right]_{x=0} = 1.$$

7.110 $\frac{\infty}{\infty}$. If, for $x = a$, $\frac{f(x)}{F(x)}$ takes the form $\frac{\infty}{\infty}$, this quotient may be written:

$$\frac{\dfrac{1}{F(x)}}{\dfrac{1}{f(x)}}$$

which takes the form $\frac{0}{0}$ for $x = a$ and the preceding sections will apply to it.

7.111 L'Hospital's Rule (**7.102**) may be applied directly to indeterminate forms $\frac{\infty}{\infty}$, if the expansion by Taylor's Theorem is valid.

Example:

$$\left[\frac{x}{e^x}\right]_{x=\infty} = \left[\frac{1}{e^x}\right]_{x=\infty} = 0.$$

7.112 If $f(x)$ and x approach ∞ together, and if $f(x+1) - f(x)$ approaches a definite limit, then,

$$\underset{x\to\infty}{\text{Limit}}\left[\frac{f(x)}{x}\right] = \underset{x\to\infty}{\text{Limit}}\left[f(x+1) - f(x)\right].$$

7.120 $0 \times \infty$ . . If, for $x = a$, $f(x) \times F(x)$ takes the form $0 \times \infty$, this product may be written,

$$\frac{\dfrac{f(x)}{1}}{\dfrac{1}{F(x)}}$$

which takes the form $\frac{0}{0}$ (**7.101**).

7.130 $\infty - \infty$. If, $\underset{x\to a}{\text{Limit}}\ f(x) = \infty$ and $\underset{x\to\infty}{\text{Limit}}\ F(x) = \infty$,

$$f(x) - F(x) = f(x)\left\{1 - \frac{F(x)}{f(x)}\right\}.$$

If $\underset{x\to\infty}{\text{Limit}}\ \frac{F(x)}{f(x)}$ is different from unity the true value of $f(x) - F(x)$ for $x = a$ is ∞.

If $\underset{x\to\infty}{\text{Limit}}\ \frac{F(x)}{f(x)} = +1$, the expression has the indeterminate form $\infty \times 0$ which may be treated by **7.120.**

7.140 $1^\infty, 0^0, \infty^0$. If $\{F(x)\}^{(fx)}$ is indeterminate in any of these forms for $x = a$, its true value may be found by finding the true value of the logarithm of the given expression.

Example:

$$\left[\left(\frac{1}{x}\right)^{\tan x}\right]_{x\to 0}.$$

$$\left(\frac{1}{x}\right)^{\tan x} = y; \quad \log y = -\tan x \cdot \log x,$$

$$\left[\tan x \cdot \log x\right]_{x=0} = \left[\frac{\log x}{\cot x}\right]_{x=0} = \left[\frac{\frac{1}{x}}{\csc^2 x}\right]_{x=0} = \left[\frac{\sin x}{x} \cdot \sin x\right]_{x=0} = 0.$$

Hence,

$$\left[\left(\frac{1}{x}\right)^{\tan x}\right]_{x=0} = 1.$$

7.141 If $f(x)$ and x approach ∞ together, and $\dfrac{f(x+1)}{f(x)}$ approaches a definite limit, then,

$$\underset{x \to \infty}{\text{Limit}}\left[\{f(x)\}^{\frac{1}{x}}\right] = \underset{x \to \infty}{\text{Limit}} \frac{f(x+1)}{f(x)}.$$

7.150 Differential Coefficients of the form $\frac{0}{0}$. In determining the differential coefficient $\dfrac{dy}{dx}$ from an equation $f(x, y) = 0$, by means of the formula,

$$\frac{dy}{dx} = -\frac{\dfrac{\partial f}{\partial x}}{\dfrac{\partial f}{\partial y}} \tag{1}$$

it may happen that for a pair of values, $x = a$, $y = b$, satisfying $f(x, y) = 0$, $\dfrac{dy}{dx}$ takes the form $\frac{0}{0}$.

Writing $\dfrac{dy}{dx} = y'$, and applying **7.102** to the quotient (1), a quadratic equation is obtained for determining y', giving, in general, two different determinate values. If y' is still indeterminate, apply **7.102** again, giving a cubic equation for determining y'. This process may be continued until determinate values result.

Example:

$$f(x, y) = (x^2 + y^2)^2 - c^2xy = 0,$$

$$y' = -\frac{4x(x^2 + y^2) - c^2y}{4y(x^2 + y^2) - c^2x}.$$

For $x = 0$, $y = 0$, y' takes the value $\frac{0}{0}$.

Applying **7.102**,

$$-y' = \frac{12x^2 + 4y^2 + (8xy - c^2)y'}{4y'(x^2 + 3y^2) + 8xy - c^2}.$$

Solving this quadratic equation in y', the two determinate values, $y' = 0$, $y' = \infty$, result for $x = 0$, $y = 0$.

7.17 Special Indeterminate Forms and Limiting Values. In the following the notation $[f(x)]_a$ means the limit approached by $f(x)$ as x approaches a as a limit.

7.171

1. $\left[\left(1+\frac{c}{x}\right)^x\right]_\infty = e^c$ (c a constant).

2. $[\sqrt{x+c}-\sqrt{x}]_\infty = 0.$

3. $[\sqrt{x(x+c)}-x]_\infty = \frac{c}{2}.$

4. $[\sqrt{(x+c_1)(x+c_2)}-x]_\infty = \frac{1}{2}(c_1+c_2).$

5. $\left[\sqrt[n]{(x+c_1)(x+c_2)\ldots(x+c_n)}-x\right]_\infty = \frac{1}{n}(c_1+c_2+\ldots c_n).$

6. $\left[\frac{\log(c_1+c_2e^x)}{x}\right]_\infty = 1.$

7. $\left[\log\left(c_1+c_2e^x\right)\cdot\log\left(1+\frac{1}{x}\right)\right]_\infty = 1.$

8. $\left[\left(\frac{\log x}{x}\right)^{\frac{1}{x}}\right]_\infty = 1.$

9. $\left[\frac{x}{(\log x)^m}\right]_\infty = \infty.$

10. $\left[\frac{a^x}{x^m}\right]_\infty = \infty$ $(a>1).$

11. $\left[\frac{a^x}{x!}\right]_\infty = 0$ (x a positive integer).

12. $\left[x^{\frac{1}{x}}\right]_\infty = 1.$

13. $\left[\frac{\log x}{x}\right]_\infty = 0.$

14. $\left[(a+bc^x)^{\frac{1}{x}}\right]_\infty = c$ $(c>1).$

15. $\left[\left(\frac{1}{a+bc^x}\right)^{\frac{c}{x}}\right]_\infty = e^{-c}.$

16. $\left[\frac{x}{\alpha+\beta x^2}\cdot\log(a+be^x)\right]_\infty = \frac{1}{\beta}.$

17. $\left[\left(a+bx^m\right)^{\frac{1}{\alpha+\beta\log x}}\right]_\infty = e^{\frac{m}{\beta}}$ $(m>0).$

7.172

1. $\left[x \sin \frac{c}{x}\right]_\infty = c.$

2. $\left[x\left(1 - \cos \frac{c}{x}\right)\right]_\infty = 0.$

3. $\left[x^2\left(1 - \cos \frac{c}{x}\right)\right]_\infty = \frac{c^2}{2}.$

4. $\left[\left(\cos \frac{c}{x}\right)^x\right]_\infty = 1.$

5. $\left[\left(\cos \frac{c}{x}\right)^{x^2}\right]_\infty = e^{-\frac{c^2}{2}}.$

6. $\left[\left(\frac{\sin \frac{c}{x}}{\frac{c}{x}}\right)^x\right]_\infty = 1.$

7. $\left[\frac{\cot \frac{c}{x}}{x}\right]_\infty = \frac{1}{c}.$

8. $\left[\sin \frac{c}{x} \cdot \log (a + be^x)\right]_\infty = c.$

9. $\left[\left(\cos \sqrt{\frac{2c}{x}}\right)^x\right]_\infty = e^{-c}.$

10. $\left[\left(1 + a \tan \frac{c}{x}\right)^x\right]_\infty = e^{ac}.$

11. $\left[\left(\cos \frac{c}{x} + a \sin \frac{c}{x}\right)^x\right]_\infty = e^{ac}.$

7.173

1. $\left[\frac{\sin x}{x}\right]_0 = 1.$

2. $\left[\frac{\tan x}{x}\right]_0 = 1.$

3. $\left[\left(\frac{\sin nx}{x}\right)^m\right]_0 = n^m.$

4. $[\sin^{-1} x \cdot \cot x]_0 = 1.$

5. $\left[\left\{\tan\left(\frac{\pi}{4} + \frac{x}{2}\right)\right\}^{\cot x}\right]_0 = e.$

7.174

1. $[x^x]_0 = 1.$

2. $\left[x^{\frac{1}{a + b \log x}}\right]_0 = e^{\frac{1}{b}}.$

3. $\left[x^{\frac{1}{\log (e^x - 1)}}\right]_0 = e.$

4. $\left[x^m \log \frac{1}{x}\right]_0 = 0 \qquad (m \geqq 1).$

5. $[\log \cos x \cdot \cot x]_0 = 0.$

6. $\left[\log \tan \left(\frac{\pi}{4} + \frac{x}{2}\right) \cdot \cot x\right]_0 = 1.$

7. $\left[\frac{e^x - 1}{x}\right]_0 = 1.$

8. $[x^m \log x]_0 = 0 \qquad (m > 0).$

9. $\left[\frac{e^x - e^{-x} - 2x}{(e^x - 1)^3}\right]_0 = \frac{1}{3}.$

10. $[xe^{\frac{1}{x}}]_0 = \infty.$

11. $\left[\frac{e^x - e^{-x}}{\log (1 + x)}\right]_0 = 2.$

12. $\left[\frac{\log \tan 2x}{\log \tan x}\right]_0 = 1.$

7.175

1. $\left[x^{\frac{1}{1-x}}\right]_1 = \frac{1}{e}.$

2. $\left[(\pi - 2x)\tan x\right]_{\frac{\pi}{2}} = 2.$

3. $\left[\log\left(2 - \frac{x}{c}\right)\cdot \tan\frac{\pi x}{2c}\right]_c = \frac{2}{\pi}.$

4. $\left[(e^c - e^x)\tan\frac{\pi x}{2c}\right]_c = \frac{2c}{\pi}e^c.$

5. $\left[\cos^{-1}\frac{x}{c}\cdot \tan\frac{\pi x}{2c}\right]_c = \infty$

6. $\left[(a + be^{\tan x})^{\pi - 2x}\right]_{\frac{\pi}{2}} = e^2.$

7. $\left[\left(2 - \frac{2x}{\pi}\right)^{\tan x}\right]_{\frac{\pi}{2}} = e^{\frac{2}{\pi}}$

8. $\left[(\tan x)^{\tan 2x}\right]_{\frac{\pi}{4}} = \frac{1}{e}.$

7.18 Limiting Values of Sums.

1. $$\underset{n\to\infty}{\text{Limit}}\left(\frac{1^k + 2^k + 3^k + \ldots + n^k}{n^{k+1}}\right) = \frac{1}{k+1} \text{ if } k > -1.$$
$$\infty \text{ if } k < -1.$$

2. $$\underset{n\to\infty}{\text{Limit}}\left(\frac{1}{na} + \frac{1}{na+b} + \frac{1}{na+2b} + \ldots + \frac{1}{na+(n-1)b}\right)$$
$$= \frac{\log(a+b) - \log a}{b} \quad (a, b > 0).$$

3. $$\underset{n\to\infty}{\text{Limit}}\left(\frac{n-1^2}{1\cdot 2\cdot(n+1)} + \frac{n-2^2}{2\cdot 3\cdot(n+2)} + \frac{n-3^2}{3\cdot 4\cdot(n+3)} + \ldots\right.$$
$$\left. + \frac{(n-n^2}{n\cdot(n+1)\cdot(n+n)}\right) = 1 - \log 2.$$

4. $$\underset{n\to\infty}{\text{Limit}}\left[\left(a + b\frac{\sqrt{1}}{n}\right)^2 + \left(a^2 + b\frac{\sqrt{2}}{n}\right)^2 + \left(a^3 + b\frac{\sqrt{3}}{n}\right)^2 + \ldots\right.$$
$$\left. + \left(a^n + b\frac{\sqrt{n}}{n}\right)^2\right] = \frac{a^2}{1-a^2} + \frac{b^2}{2},$$
if a is a positive proper fraction.

5. $$\underset{n\to\infty}{\text{Limit}}\left[\sqrt{a + \frac{b}{n}} + \sqrt{a^2 + \frac{b}{n}} + \sqrt{a^3 + \frac{b}{n}} + \ldots + \sqrt{a^n + \frac{b}{n}}\right] = \infty,$$
if $b > 0$ and a is a positive proper fraction.

6. $$\underset{n\to\infty}{\text{Limit}}\left[\sqrt{a + \frac{b}{1\cdot n}} + \sqrt{a^2 + \frac{b}{2\cdot n}} + \sqrt{a^3 + \frac{b}{3\cdot n}} + \ldots + \sqrt{a^n + \frac{b}{n\cdot n}}\right]$$
$$= \frac{\sqrt{a}}{1 - \sqrt{a}} + 2\sqrt{b},$$
if $b > 0$ and a is a positive proper fraction.

7. $$\underset{n\to\infty}{\text{Limit}}\left[1 + \frac{1}{2} + \frac{1}{3} + \ldots + \frac{1}{n} - \log n\right] = \gamma = 0.5772157\ldots$$
(6.602).

7.19 Limiting Values of Products.

1. $$\underset{n\to\infty}{\text{Limit}}\left[\left(1+\frac{c}{n}\right)\left(1+\frac{c}{n+1}\right)\left(1+\frac{c}{n+2}\right)\cdots\cdots\left(1+\frac{c}{2n-1}\right)\right]=2^c,$$
if $c>0$.

2. $$\underset{n\to\infty}{\text{Limit}}\left[\left(1+\frac{c}{na}\right)\left(1+\frac{c}{na+b}\right)\left(1+\frac{c}{na+2b}\right)\cdots\cdots\left(1+\frac{c}{na+(n-1)b}\right)\right]$$
$$=\left(1+\frac{b}{a}\right)^{\frac{c}{b}},$$
if a, b, c are all positive.

3. $$\underset{n\to\infty}{\text{Limit}}\left[\frac{\{m(m+1)\,(m+2)\,\ldots\ldots(m+n-1)\}^{\frac{1}{n}}}{m+\frac{1}{2}(n-1)}\right]=\frac{2}{e},$$
if $m>0$.

4. $$\underset{n\to}{\text{Limit}}\left[\left(1+\frac{2c}{n^2}\right)\left(1+\frac{4c}{n^2}\right)\left(1+\frac{6c}{n^2}\right)\cdots\cdots\left(1+\frac{2nc}{n^2}\right)\right]=e^c.$$

7.20 Maxima and Minima.

7.201 Functions of One Variable. $y=f(x)$ is a maximum or minimum for the values of x satisfying the equation, $f'(x)=\dfrac{\partial f(x)}{\partial x}=0$, provided that $f'(x)$ is continuous for these values of x.

7.202 If, for $x=a$, $f'(a)=0$,

$y=f(a)$ is a maximum if $f''(a)<0$

$y=f(a)$ is a minimum if $f''(a)>0$.

Example:

$$y=\frac{x}{x^2+\alpha x+\beta},\qquad \beta>0,$$

$$f'(x)=\frac{-x^2+\beta}{(x^2+\alpha x+\beta)^2},$$

$$f'(x)=0 \text{ when } x=\pm\sqrt{\beta},$$

$$f''(x)=\frac{2x^3-6\beta x-2\alpha\beta}{(x^2+\alpha x+\beta)^3}$$

For $x=+\sqrt{\beta}$, $f''(x)=\dfrac{-2}{\sqrt{\beta}}\,\dfrac{1}{(2\sqrt{\beta}+\alpha)^2}$ Maximum,

$$\text{For } x = -\sqrt{\beta},\ f''(x) = \frac{+2}{\sqrt{\beta}} \frac{1}{(2\sqrt{\beta} - \alpha)^2} \quad \text{Minimum,}$$

$$y_{max} = \frac{1}{\alpha + 2\sqrt{\beta}},$$

$$y_{min} = \frac{1}{\alpha - 2\sqrt{\beta}}.$$

7.203 If for $x = a$, $f'(a) = 0$ and $f''(a) = 0$, in order to determine whether $y = f(a)$ is a maximum or minimum it is necessary to form the higher differential coefficients, until one of even order is found which does not vanish for $x = a$. $y = f(a)$ is a maximum or minimum according as the first of the differential coefficients, $f''(a)$, $f^{iv}(a)$, $f^{vi}(a)$, ... of even order which does not vanish is negative or positive.

7.210 Functions of Two Variables. $F(x, y)$ is a maximum or minimum for the pair of values of x and y that satisfy the equations,

$$\frac{\partial F}{\partial x} = 0,\ \frac{\partial F}{\partial y} = 0,$$

and for which

$$\left(\frac{\partial^2 F}{\partial x\, \partial y}\right)^2 - \frac{\partial^2 F}{\partial x^2} \frac{\partial^2 F}{\partial y^2} < 0.$$

If both $\frac{\partial^2 F}{\partial x^2}$ and $\frac{\partial^2 F}{\partial y^2}$ are negative for this pair of values of x and y, $F(x, y)$ is a maximum. If they are both positive $F(x, y)$ is a minimum.

7.220 Functions of n Variables. For the maximum or minimum of a function of n variables, $F(x_1, x_2 \ldots\ldots, x_n)$, it is necessary that the first derivatives, $\frac{\partial F}{\partial x_1}, \frac{\partial F}{\partial x_2}, \ldots\ldots, \frac{\partial F}{\partial x_n}$ all vanish; and that the lowest order of the higher derivatives which do not all vanish be an even number. If this number be 2 the necessary condition for a minimum is that all of the determinants,

$$D_k = \begin{vmatrix} f_{11}\ f_{12} & \ldots\ldots & f_{1k} \\ f_{21}\ f_{22} & \ldots\ldots & f_{2k} \\ \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots \\ f_{k1}\ f_{k2} & \ldots\ldots & f_{kk} \end{vmatrix},\quad k = 1, 2, \ldots\ldots n,$$

where

$$f_{ij} = \frac{\partial^2 F}{\partial x_i\, \partial x_j},$$

shall be positive. For a maximum the determinants must be alternately negative and positive, beginning with $D_1 = \frac{\partial^2 F}{\partial x_1^2}$ negative.

7.230 Maxima and Minima with Conditions. If $F(x_1, x_2, \ldots\ldots, x_n)$ is to be made a maximum or minimum subject to the conditions,

$$1. \quad \begin{cases} \phi_1(x_1, x_2, \ldots\ldots, x_n) = 0 \\ \phi_2(x_1, x_2, \ldots\ldots, x_n) = 0 \\ \ldots\ldots\ldots \\ \ldots\ldots\ldots \\ \phi_k(x_1, x_2, \ldots\ldots, x_n) = 0, \end{cases}$$

where $k<n$, the necessary conditions are,

$$2. \quad \frac{\partial F}{\partial x_i} + \sum_{j=1}^{k} \lambda_j \frac{\partial \phi_j}{\partial x_i} = 0 \qquad i = 1, 2, \ldots\ldots n,$$

where the λ's are k undetermined multipliers. The n equations (2) together with the k equations of condition (1) furnish $k + n$ equations to determine the $k + n$ quantities, $x_1, x_2, \ldots\ldots, x_n, \lambda_1, \lambda_2, \ldots\ldots, \lambda_k$.

Example:

To find the axes of the ellipsoid, referred to its center as origin,

$$a_{11}x^2 + a_{22}y^2 + a_{33}z^2 + 2a_{12}xy + 2a_{23}yz + 2a_{13}xz = 1.$$

Denoting the radius vector to the surface by r, and its direction-cosines by l, m, n, so that $x = lr$, $y = mr$, $z = nr$, it is necessary to find the maxima and minima of

$$r^2 = \frac{1}{a_{11}l^2 + a_{22}m^2 + a_{33}n^2 + 2a_{12}lm + 2a_{23}m + 2a_{13}lnn},$$

subject to the condition

$$\phi(l, m, n) = l^2 + m^2 + n^2 - 1 = 0.$$

This is the same as finding the minima and maxima of

$$F(l, m, n) = a_{11}l^2 + a_{22}m^2 + a_{33}n^2 + 2a_{12}lm + 2a_{23}mn + 2a_{13}ln.$$

Equation (2) gives:

$$\begin{aligned} (a_{11} + \lambda)l + a_{12}m + a_{13}n &= 0, \\ a_{12}l + (a_{22} + \lambda)m + a_{23}n &= 0, \\ a_{13}l + a_{23}m + (a_{33} + \lambda)n &= 0. \end{aligned}$$

Multiplying these 3 equations by l, m, n respectively and adding,

$$\lambda = -\frac{1}{r^2}.$$

Then by (1. **1.363**) the 3 values of r are given by the 3 roots of

$$\begin{vmatrix} a_{11} - \frac{1}{r^2} & a_{12} & a_{13} \\ a_{12} & a_{22} - \frac{1}{r^2} & a_{23} \\ a_{13} & a_{23} & a_{33} - \frac{1}{r^2} \end{vmatrix} = 0.$$

7.30 Derivatives.

7.31 First Derivatives.

1. $\dfrac{dx^n}{dx^n} = nx^{n-1}.$

2. $\dfrac{da^x}{dx} = a^x \log a.$

3. $\dfrac{de^x}{dx} = e^x.$

4. $\dfrac{dx^x}{dx} = x^x(1 + \log x).$

5. $\dfrac{d \log_a x}{dx} = \dfrac{1}{x \log a} = \dfrac{\log_a e}{x}.$

6. $\dfrac{d \log x}{dx} = \dfrac{1}{x}.$

7. $\dfrac{dx^{\log x}}{dx} = 2x^{\log x - 1} \log x.$

8. $\dfrac{d(\log x)^x}{dx} = (\log x)^{x-1} \{1 + \log x \cdot \log \log x\}.$

9. $\dfrac{d\left(\dfrac{x}{e}\right)^x}{dx} = \left(\dfrac{x}{e}\right)^x \log x.$

10. $\dfrac{d \sin x}{dx} = \cos x.$

11. $\dfrac{d \cos x}{dx} = -\sin x.$

12. $\dfrac{d \tan x}{dx} = \sec^2 x.$

13. $\dfrac{d \cot x}{dx} = -\csc^2 x.$

14. $\dfrac{d \sec x}{dx} = \sec^2 x \cdot \sin x.$

15. $\dfrac{d \csc x}{dx} = -\csc^2 x \cdot \cos x.$

16. $\dfrac{d \sin^{-1} x}{dx} = -\dfrac{d \cos^{-1} x}{dx} = \dfrac{1}{\sqrt{1 - x^2}}.$

17. $\dfrac{d \tan^{-1} x}{dx} = -\dfrac{d \cot^{-1} x}{dx} = \dfrac{1}{1 + x^2}.$

18. $\dfrac{d \sec^{-1} x}{dx} = -\dfrac{d \csc^{-1} x}{dx} = \dfrac{1}{x\sqrt{x^2 - 1}}.$

19. $\dfrac{d \sinh x}{dx} = \cosh x.$

20. $\dfrac{d \cosh x}{dx} = \sinh x.$

21. $\dfrac{d \tanh x}{dx} = \operatorname{sech}^2 x.$

22. $\dfrac{d \coth x}{dx} = -\operatorname{csch}^2 x.$

23. $\dfrac{d \operatorname{sech} x}{dx} = -\operatorname{sech} x \cdot \tanh x.$

24. $\dfrac{d \operatorname{csch} x}{dx} = -\operatorname{csch} x \cdot \coth x.$

25. $\dfrac{d \sinh^{-1} x}{dx} = \dfrac{1}{\sqrt{x^2+1}}.$

26. $\dfrac{d \cosh^{-1} x}{dx} = \dfrac{1}{\sqrt{x^2-1}}.$

27. $\dfrac{d \tanh^{-1} x}{dx} = \dfrac{d \coth^{-1} x}{dx} = \dfrac{1}{1-x^2}.$

28. $\dfrac{d \operatorname{sech}^{-1} x}{dx} = -\dfrac{1}{x\sqrt{1-x^2}}.$

29. $\dfrac{d \operatorname{csch}^{-1} x}{dx} = -\dfrac{1}{x\sqrt{1+x^2}}.$

30. $\dfrac{d \, gd \, x}{dx} = \operatorname{sech} x.$

31. $\dfrac{d \, gd^{-1} x}{dx} = \sec x.$

7.32

1. $\dfrac{d(y_1 y_2 y_3 \ldots y_n)}{dx} = y_1 y_2 \ldots y_n \left(\dfrac{1}{y_1}\dfrac{dy_1}{dx} + \dfrac{1}{y_2}\dfrac{dy_2}{dx} + \ldots + \dfrac{1}{y_n}\dfrac{dy_n}{dx} \right).$

2. $\dfrac{d\left(\dfrac{u}{v}\right)}{dx} = \dfrac{v\dfrac{du}{dx} - u\dfrac{dv}{dx}}{v^2}.$

3. $\dfrac{da^u}{dx} = a^u \dfrac{du}{dx} \log a.$

4. $\dfrac{de^u}{dx} = e^u \dfrac{du}{dx}.$

5. $\dfrac{df(u)}{dx} = \dfrac{df(u)}{du} \cdot \dfrac{du}{dx}.$

7.33 Derivative of a Definite Integral.

1. $\dfrac{d}{da}\displaystyle\int_{\psi(a)}^{\phi(a)} f(x, a)dx = f(\phi(a), a)\dfrac{d\phi(a)}{da} - f(\psi(a), a)\dfrac{d\psi(a)}{da} + \int_{\psi(a)}^{\phi(a)} \dfrac{d}{da} f(x, a)dx.$

2. $\dfrac{d}{da}\displaystyle\int_b^a f(x)dx = f(a).$

3. $\dfrac{d}{db}\displaystyle\int_b^a f(x)dx = -f(b).$

7.35 Higher Derivatives.

7.351 Leibnitz's Theorem. If u and v are functions of x,

$$\frac{d^n(uv)}{dx^n} = u\frac{d^n v}{dx^n} + \frac{n}{1!}\frac{du}{dx}\frac{d^{n-1}v}{dx^{n-1}} + \frac{n(n-1)}{2!}\frac{d^2u}{dx^2}\frac{d^{n-2}v}{dx^{n-2}} + \frac{n(n-1)(n-2)}{3!}\frac{d^3u}{dx^3}\frac{d^{n-3}v}{dx^{n-3}} + \ldots\ldots + v\frac{d^n u}{dx^n}.$$

7.352 Symbolically,

$$\frac{d^n(uv)}{dx^n} = (u+v)^{(n)},$$

where

$$u^0 = u, \quad v^0 = v.$$

7.353

$$\frac{d^n e^{ax}u}{dx^n} = e^{ax}\left(a + \frac{d}{dx}\right)^n u.$$

7.354 If $\phi\left(\frac{d}{dx}\right)$ is a polynomial in $\frac{d}{dx}$,

$$\phi\left(\frac{d}{dx}\right)e^{ax}u = e^{ax}\phi\left(a + \frac{d}{dx}\right)u.$$

7.355 Euler's Theorem. If u is a homogeneous function of the nth degree of r variables, $x_1, x_2, \ldots x_r$,

$$\left(x_1\frac{\partial}{\partial x_1} + x_2\frac{\partial}{\partial x_2} + \ldots + x_r\frac{\partial}{\partial x_r}\right)^m u = n^m u,$$

where m may be any integer, including 0.

7.36 Derivatives of Functions of Functions.

7.361 If $f(x) = F(y)$, and $y = \phi(x)$,

1. $$\frac{d^n}{dx^n}f(x) = \frac{U_1}{1!}F'(y) + \frac{U_2}{2!}F''(y) + \frac{U_3}{3!}F'''(y) + \ldots + \frac{U_n}{n!}F^{(n)}(y),$$

where

2. $$U_k = \frac{\partial^n}{\partial x^n}y^k - \frac{k}{1!}y\frac{\partial^n}{\partial x^n}y^{k-1} + \frac{k(k-1)}{2!}y^2\frac{\partial^n}{\partial x^n}y^{k-2} - \ldots\ldots$$

7.362

1. $$(-1)^n\frac{d^n}{dx^n}F\left(\frac{1}{x}\right) = \frac{1}{x^{2n}}F^{(n)}\left(\frac{1}{x}\right) + \frac{n-1}{x^{2n-1}}\frac{n}{1!}F^{(n-1)}\left(\frac{1}{x}\right) + \frac{(n-1)(n-2)}{x^{2n-2}}\cdot\frac{n(n-1)}{2!}F^{(n-2)}\left(\frac{1}{x}\right) + \ldots\ldots$$

2. $$(-1)^n\frac{d^n}{dx^n}e^{\frac{a}{x}} = \frac{1}{x^n}e^{\frac{a}{x}}\left\{\left(\frac{a}{x}\right)^n + (n-1)\frac{n}{1!}\left(\frac{a}{x}\right)^{n-1} + (n-1)(n-2)\frac{n(n-1)}{2!}\left(\frac{a}{x}\right)^{n-2} + (n-1)(n-2)(n-3)\frac{n(n-1)(n-2)}{3!}\left(\frac{a}{x}\right)^{n-3} + \ldots\right\}.$$

7.363

1. $$\frac{d^n}{dx^n} F(x^2) = (2x)^n F^{(n)}(x^2) + \frac{n(n-1)}{1!}(2x)^{n-2} F^{(n-1)}(x^2) + \frac{n(n-1)(n-2)(n-3)}{2!}(2x)^{n-4} F^{(n-2)}(x^2) + \frac{n(n-1)(n-2)(n-3)(n-4)(n-5)}{3!}(2x)^{n-6} F^{(n-3)}(x^2) + \ldots .$$

2. $$\frac{d^n}{dx^n} e^{ax^2} = (2ax)^n e^{ax^2}\left\{1 + \frac{n(n-1)}{1!(4ax^2)} + \frac{n(n-1)(n-2)(n-3)}{2!(4ax^2)^2} + \frac{n(n-1)(n-2)(n-3)(n-4)(n-5)}{3!(4ax^2)^3} + \ldots\right\}.$$

3. $$\frac{d^n}{dx^n}(1+ax^2)^\mu = \frac{\mu(\mu-1)(\mu-2)\ldots(\mu-n+1)(2ax)^n}{(1+ax^2)^{n-\mu}}\left\{1 + \frac{n(n-1)}{1\cdot(\mu-n+1)}\frac{(1+ax^2)}{4ax^2} + \frac{n(n-1)(n-2)(n-3)}{2!(\mu-n+1)(\mu-n+2)}\left(\frac{1+ax^2}{4ax^2}\right)^2 + \ldots\right\}.$$

4. $$\frac{d^{m-1}}{dx^{m-1}}(1-x^2)^{m-\frac{1}{2}} = (-1)^{m-1}\frac{1\cdot 3\cdot 5\ldots(2m-1)}{m}\sin(m\cos^{-1}x).$$

7.364

1. $$\frac{d^n}{dx^n} F(\sqrt{x}) = \frac{F^{(n)}(\sqrt{x})}{(2\sqrt{x})^n} - \frac{n(n-1)}{1!}\frac{F^{(n-1)}(\sqrt{x})}{(2\sqrt{x})^{n+1}} + \frac{(n+1)n(n-1)(n-2)}{2!}\frac{F^{(n-2)}(\sqrt{x})}{(2\sqrt{x})^{n+2}} - \ldots .$$

2. $$\frac{d^n}{dx^n}(1+a\sqrt{x})^{2n-1} = \frac{1\cdot 3\cdot 5\ldots(2n-1)}{2^n}\frac{a}{\sqrt{x}}\left(a^2 - \frac{1}{x}\right)^{n-1}.$$

7.365

1. $$\frac{d^n}{dx^n} F(e^x) = \frac{E_1}{1!}e^x F'(e^x) + \frac{E_2}{2!}e^{2x}F''(e^x) + \frac{E_3}{3!}e^{3x}F'''(e^x) + \ldots$$

where

2. $$E_k = k^n - \frac{k}{1!}(k-1)^n + \frac{k(k-1)}{2!}(k-2)^n - \ldots .$$

3. $$\frac{d^n}{dx^n}\frac{1}{1+e^{2x}} = -E_1 e^x \frac{\sin(2\tan^{-1}e^{-x})}{\sqrt{(1+e^{2x})^2}} + E_2 e^{2x}\frac{\sin(3\tan^{-1}e^{-x})}{\sqrt{(1+e^{2x})^3}} - E_3 e^{3x}\frac{\sin(4\tan^{-1}e^{-x})}{\sqrt{(1+e^{2x})^4}} + \ldots .$$

4. $$\frac{d^n}{dx^n}\frac{e^x}{1+e^{2x}} = -E_1 e^x \frac{\cos(2\tan^{-1}e^{-x})}{\sqrt{(1+e^{2x})^2}} + E_2 e^{2x}\frac{\cos(3\tan^{-1}e^{-x})}{\sqrt{(1+e^{2x})^3}} - E_3 e^{3x}\frac{\cos(4\tan^{-1}e^{-x})}{\sqrt{(1+e^{2x})^4}} + \ldots .$$

7.366

1. $$\frac{d^n}{dx^n} F(\log x) = \frac{1}{x^n}\left\{ \overset{n}{C}_0 F^{(n)}(\log x) - \overset{n}{C}_1 F^{(n-1)}(\log x) + \overset{n}{C}_2 F^{(n-2)}(\log x) - \ldots . \right\}.$$

$$\overset{n}{C}_0 = 1,$$

$$\overset{n}{C}_1 = 1 + 2 + 3 + \ldots\ldots + (n-1) \qquad = \frac{n(n-1)}{2},$$

$$\begin{aligned} \overset{n}{C}_2 = 1\cdot 2 + 1\cdot 3 + 1\cdot 4 + \ldots\ldots & + 1\cdot(n-1) \\ + 2\cdot 3 + 2\cdot 4 + \ldots\ldots & + 2\cdot(n-1) \\ + 3\cdot 4 + \ldots\ldots & + 3\cdot(n-1) \\ + \ldots\ldots & \ldots\ldots \\ & + (n-2)(n-1) = \frac{n(n-1)(n-2)(3n-1)}{24}. \end{aligned}$$

2. $\overset{n+1}{C}_k = \overset{n}{C}_k + n\overset{n}{C}_{k-1}.$

3. $\overset{-n}{C}_k = \overset{-(n-1)}{C}_k + n\overset{-n}{C}_{k-1}.$

$$\begin{array}{lll} \overset{n}{C}_0 = 1 & \overset{k}{C}_k = 0, & \\ \overset{2}{C}_1 = 1 & \overset{3}{C}_1 = 3 & \overset{4}{C}_1 = 6, \\ & \overset{3}{C}_2 = 2 & \overset{4}{C}_2 = 11, \\ & & \overset{4}{C}_3 = 6. \end{array} \qquad \begin{array}{lll} \overset{-n}{C}_0 = 1 & \overset{-1}{C}_k = 1, & \\ \overset{-2}{C}_1 = 3 & \overset{-3}{C}_1 = 6 & \overset{-4}{C}_1 = 10, \\ \overset{-2}{C}_2 = 7 & \overset{-3}{C}_2 = 25 & \overset{-4}{C}_2 = 65, \\ \overset{-2}{C}_3 = 15 & \overset{-3}{C}_3 = 90 & \overset{-4}{C}_3 = 350. \end{array}$$

7.367 Table of $\overset{n}{C}_k$.

$n =$	-4	-3	-2	-1	$+1$	$+2$	$+3$	$+4$	$+5$	$+6$	$+7$	$+8$	$+9$
$C_0 =$	1	1	1	1	1	1	1	1	1	1	1	1	1
$C_1 =$	10	6	3	1	...	1	3	6	10	15	21	28	36
$C_2 =$	65	25	7	1	...	....	2	11	35	85	175	322	546
$C_3 =$	350	90	15	1	...	....	....	6	50	225	735	1960	4536
$C_4 =$	1701	301	31	1	...	....	....	....	24	274	1624	6769	22449
$C_5 =$	7770	966	63	1	...	....	....	....	....	120	1764	13132	67284
$C_6 =$	34105	3025	127	1	...	....	....	....	....	....	720	13068	118124
$C_7 =$	145750	9330	225	1	...	....	....	....	....	....	....	5040	109584
$C_8 =$	611501	28501	511	1	...	....	....	....	....	....	....	.....	40320

7.368

1. $$\frac{d^n}{dx^n}(\log x)^p = \frac{(-1)^{n-1}}{x^n}\left\{ \overset{n}{C}_{n-1}p(\log x)^{p-1} - \overset{n}{C}_{n-2}p(p-1)(\log x)^{p-2} + \overset{n}{C}_{n-3}p(p-1)(p-2)(\log x)^{p-3} - \ldots \right\},$$

where p is a positive integer. If $n<p$ there are n terms in the series. If $n \geqslant p$,

2. $$\frac{d^n}{dx^n}(\log x)^p = \frac{(-1)^{n-1}}{x^n}\left\{ \overset{n}{C}_{n-1}p(\log x)^{p-1} - \overset{n}{C}_{n-2}p(p-1)(\log x)^{p-2} + \ldots\ldots + (-1)^{p+1}\overset{n}{C}_{n-p}p(p-1)(p-2)\ldots\ldots 2\cdot 1 \right\}.$$

7.369 $$\left\{\log(1+x)\right\}^p = \overset{p}{C}_0 x^p - \overset{p+1}{C}_1 \frac{x^{p+1}}{p+1} + \overset{p+2}{C}_2 \frac{x^{p+2}}{(p+1)(p+2)} - \ldots\ldots$$
$$-1 < x < +1.$$

7.37 Derivatives of Powers of Functions. If $y = \phi(x)$.

1. $$\frac{d^n}{dx^n}y^p = p\binom{n-p}{n}\left\{ -\binom{n}{1}\frac{1}{p-1}y^{p-1}\frac{d^n y}{dx^n} + \binom{n}{2}\frac{1}{p-2}y^{p-2}\frac{d^n y^2}{dx^n} - \ldots\ldots \right\}.$$

2. $$\frac{d^n}{dx^n}\log y = \binom{n}{1}\frac{1}{1\cdot y}\frac{d^n y}{dx^n} - \binom{n}{2}\frac{1}{2\cdot y^2}\frac{d^n y^2}{dx^n} + \binom{n}{3}\frac{1}{3\cdot y^3}\frac{d^n y^3}{dx^n} - \ldots\ldots$$

7.38

1. $$\frac{d^n(a+bx)^m}{dx^n} = m(m-1)(m-2)\ldots\ldots(m-[n-1])\,b^n(a+bx)^{m-n}.$$

2. $$\frac{d^n(a+bx)^{-1}}{dx^n} = (-1)^n\frac{n!b^n}{(a+bx)^{n+1}}.$$

3. $$\frac{d^n(a+bx)^{-\frac{1}{2}}}{dx^n} = (-1)^n\frac{1\cdot 3\cdot 5\ldots\ldots(2n-1)}{2^n(a+bx)^{n+\frac{1}{2}}}b^n.$$

4. $$\frac{d^n\log(a+bx)}{dx^n} = (-1)^{n-1}\frac{(n-1)!b^n}{(a+bx)^n}.$$

5. $$\frac{d^n e^{ax}}{dx^n} = a^n e^{ax}.$$

6. $$\frac{d^n\sin x}{dx^n} = \sin(\tfrac{1}{2}n\pi + x).$$

7. $$\frac{d^n\cos x}{dx^n} = \cos(\tfrac{1}{2}n\pi + x).$$

8. $$\frac{d^n}{dx^n}\left(\frac{\log x}{x}\right) = (-1)^n \frac{n!}{x^{n+1}} \left\{ \log x - \left(\frac{1}{1} + \frac{1}{2} + \frac{1}{3} + \cdots + \frac{1}{n}\right) \right\}.$$

9. $$\frac{d^{n+1}}{dx^{n+1}} \sin^{-1}x = \frac{1\cdot 3\cdot 5 \cdots (2n-1)}{2^n(1-x)^n \sqrt{1-x^2}} \left\{ 1 - \frac{1}{2n-1}\binom{n}{1}\frac{1-x}{1+x} + \frac{1\cdot 3}{(2n-1)(2n-3)}\binom{n}{2}\left(\frac{1-x}{1+x}\right)^2 - \frac{1\cdot 3\cdot 5}{(2n-1)(2n-3)(2n-5)}\binom{n}{3}\left(\frac{1-x}{1+x}\right)^3 + \cdots \right\}.$$

10. $$\frac{d^n}{dx^n}(\tan^{-1}x) = (-1)^{n-1} \frac{(n-1)!}{(1+x^2)^{\frac{n}{2}}} \sin\left(n \tan^{-1}\frac{1}{x}\right).$$

7.39 Derivatives of Implicit Functions.

7.391 If y is a function of x, and $f(x, y) = 0$.

1. $$\frac{dy}{dx} = -\frac{\dfrac{\partial}{\partial x}}{\dfrac{\partial f}{\partial y}}.$$

2. $$\frac{d^2y}{dx^2} = -\frac{\left(\dfrac{\partial f}{\partial y}\right)^2 \dfrac{\partial^2 f}{\partial x^2} - 2\dfrac{\partial f}{\partial x}\dfrac{\partial f}{\partial y}\dfrac{\partial^2 f}{\partial x \partial y} + \left(\dfrac{\partial f}{\partial x}\right)^2 \dfrac{\partial^2 f}{\partial y^2}}{\left(\dfrac{\partial f}{\partial y}\right)^3}$$

7.392 If z is a function of x and y, and $f(x, y, z) = 0$.

1. $$\frac{\partial z}{\partial x} = -\frac{\dfrac{\partial f}{\partial x}}{\dfrac{\partial f}{\partial z}}; \quad \frac{\partial z}{\partial y} = -\frac{\dfrac{\partial f}{\partial y}}{\dfrac{\partial f}{\partial z}}.$$

2. $$\frac{\partial^2 z}{\partial x^2} = -\frac{\left(\dfrac{\partial f}{\partial z}\right)^2 \dfrac{\partial^2 f}{\partial x^2} - 2\dfrac{\partial f}{\partial x}\dfrac{\partial f}{\partial x}\dfrac{d^2 f}{\partial x \partial z} + \left(\dfrac{\partial f}{\partial x}\right)^2 \dfrac{\partial^2 f}{\partial z^2}}{\left(\dfrac{\partial f}{\partial z}\right)^3}.$$

3. $$\frac{\partial^2 z}{\partial y^2} = -\frac{\left(\dfrac{\partial f}{\partial z}\right)^2 \dfrac{\partial^2 f}{\partial y^2} - 2\dfrac{\partial f}{\partial z}\dfrac{\partial f}{\partial y}\dfrac{\partial^2 f}{\partial y \partial z} + \left(\dfrac{\partial f}{\partial y}\right)^2 \dfrac{\partial^2 f}{\partial z^2}}{\left(\dfrac{\partial f}{\partial z}\right)^3}.$$

4. $$\frac{\partial^2 z}{\partial x \partial y} = -\frac{\left(\dfrac{\partial f}{\partial z}\right)^2 \dfrac{\partial^2 f}{\partial x \partial y} - \dfrac{\partial f}{\partial z}\left(\dfrac{\partial f}{\partial x}\dfrac{\partial^2 f}{\partial y \partial z} + \dfrac{\partial f}{\partial y}\dfrac{\partial^2 f}{\partial x \partial z}\right) + \dfrac{\partial f}{\partial x}\dfrac{\partial f}{\partial y}\dfrac{\partial^2 f}{\partial z^2}}{\left(\dfrac{\partial f}{\partial z}\right)^3}.$$

VIII. DIFFERENTIAL EQUATIONS.

8.000 Ordinary differential equations of the first order. General form:

$$\frac{dy}{dx} = f(x, y).$$

8.001 Variables are separable. $f(x, y)$ is of, or can be reduced to, the form:

$$f(x, y) = -\frac{X}{Y},$$

where X is a function of x alone and Y is a function of y alone.
The solution is:

$$\int X\, dx + \int Y\, dy = C.$$

8.002 Linear equations of the form:

$$\frac{dy}{dx} + P(x)y = Q(x).$$

Solution:

$$y = e^{-\int P(x)dx}\left\{\int Q(x)e^{-\int P(x)dx}\,dx + C\right\}.$$

8.003 Equations of the form:

$$\frac{dy}{dx} + P(x)y = y^n Q(x).$$

Solution:

$$\frac{1}{y^{n-1}}e^{-(n-1)\int P(x)dx} + (n-1)\int Q(x)e^{-(n-1)\int P(x)dx}dx = C.$$

8.010 Homogeneous equations of the form:

$$\frac{dy}{dx} = -\frac{P(x, y)}{Q(x, y)},$$

where $P(x, y)$ and $Q(x, y)$ are homogeneous functions of x and y of the same degree. The change of variable:

$$y = vx,$$

gives the solution:

$$\int \frac{dv}{\dfrac{P(1, v)}{Q(1, v)} + v} + \log x = C.$$

8.011 Equations of the form:

$$\frac{dy}{dx} = \frac{a'x + b'y + c'}{ax + by + c}.$$

If $ab' - a'b \neq 0$, the substitution

$$x = x' + p, \quad y = y' + q,$$

where

$$ap + bq + c = 0,$$
$$a'p + b'q + c' = 0,$$

renders the equation homogeneous, and it may be solved by **8.010.**

If $ab' - a'b = 0$ and $b' \neq 0$, the change of variables to either x and z or y and z by means of

$$z = ax + by,$$

will make the variables separable (**8.001**).

8.020 Exact differential equations. The equation,

$$P(x, y)dx + Q(x, y)dy = 0,$$

is exact if,

$$\frac{\partial Q}{\partial x} = \frac{\partial P}{\partial y}.$$

The solution is:

$$\int P(x, y)dx + \int \left\{ Q(x, y) - \frac{\partial}{\partial y} \int P(x, y)dx \right\} dy = C,$$

or

$$\int Q(x, y)dy + \int \left\{ P(x, y) - \frac{\partial}{\partial x} \int Q(x, y)dy \right\} dx = C.$$

8.030 Integrating factors. $v(x, y)$ is an integrating factor of

$$P(x, y)\ dx + Q(x, y)\ dy = 0,$$

if

$$\frac{\partial}{\partial x}(vQ) = \frac{\partial}{\partial y}(vP).$$

8.031 If one only of the functions $Px + Qy$ and $Px - Qy$ is equal to 0, the reciprocal of the other is an integrating factor of the differential equation.

8.032 Homogeneous equations. If neither $Px + Qy$ nor $Px - Qy$ is equal to 0, $\dfrac{1}{Px + Qy}$ is an integrating factor of the equation if it is homogeneous.

8.033 An equation of the form,

$$P(x, y)y\,dx + Q(x, y)x\,dy = 0,$$

has an integrating factor:

$$\frac{1}{xP - yQ}.$$

8.034 If

$$\frac{\frac{\partial P}{\partial y} - \frac{\partial Q}{\partial x}}{Q} = F(x)$$

is a function of x only, an integrating factor is

$$e^{\int F(x)dx}.$$

8.035 If

$$\frac{\frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y}}{P} = F(y)$$

is a function of y only, an integrating factor is

$$e^{\int F(y)dy}.$$

8.036 If

$$\frac{\frac{\partial P}{\partial y} - \frac{\partial Q}{\partial x}}{Qy - Px} = F(xy)$$

is a function of the product xy only, an integrating factor is

$$e^{\int F(xy)d(xy)}.$$

8.037 If

$$\frac{x^2\left(\frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y}\right)}{Px + Qy} = F\left(\frac{y}{x}\right)$$

is a function of the quotient $\frac{y}{x}$ only, an integrating factor is

$$e^{\int F\left(\frac{y}{x}\right)d\left(\frac{y}{x}\right)}.$$

8.040 Ordinary differential equations of the first order and of degree higher than the first.

Write:

$$\frac{dy}{dx} = p.$$

General form of equation:

$$f(x, y, p) = 0.$$

8.041 The equation can be solved as an algebraic equation in p. It can be written

$$(p - R_1)(p - R_2) \ldots\ldots\ldots (p - R_n) = 0.$$

The differential equations:

$$p = R_1(x, y),$$
$$p = R_2(x, y),$$
$$\ldots\ldots$$

may be solved by the previous methods. Write the solutions:

$$f_1(x, y, c) = 0; \quad f_2(x, y, c) = 0; \quad \ldots\ldots\ldots$$

where c is the same arbitrary constant in each. The solution of the given differential equation is:

$$f_1(x, y, c) f_2(x, y, c) \ldots\ldots\ldots\ldots f_n(x, y, c) = 0.$$

8.042 The equation can be solved for y:

1. $$y = f(x, p).$$

Differentiate with respect to x:

2. $$p = \psi\left(x, p, \frac{dp}{dx}\right).$$

It may be possible to integrate (2) regarded as an equation in the two variables x, p, giving a solution

3. $$\phi(x, p, c) = 0.$$

If p is eliminated between (1) and (3) the result will be the solution of the given equation.

8.043 The equation can be solved for x:

1. $$x = f(y, p).$$

Differentiate with respect to y:

2. $$\frac{1}{p} = \psi\left(y, p, \frac{dp}{dy}\right).$$

If a solution of (2) can be found:

3. $$\phi(y, p, c) = 0.$$

Eliminate p between (1) and (3) and the result will be the solution of the given equation.

8.044 The equation does not contain x:

$$f(y, p) = 0.$$

It may be solved for p, giving,

$$\frac{dy}{dx} = F(y),$$

which can be integrated.

8.045 The equation does not contain y:

$$f(x, p) = 0.$$

It may be solved for p, giving,

$$\frac{dy}{dx} = F(x),$$

which can be integrated.
It may be solved for x, giving,

$$x = F(p),$$

which may be solved by **8.043.**

8.050 Equations homogeneous in x and y.

General form:

$$F\left(p, \frac{y}{x}\right) = 0.$$

(a) Solve for p and proceed as in **8.001**

(b) Solve for $\frac{y}{x}$:

$$y = xf(p).$$

Differentiate with respect to x:

$$\frac{dx}{x} = \frac{f'(p)dp}{p - f(p)},$$

which may be integrated.

8.060 Clairaut's differential equation:

1. $$y = px + f(p),$$

the solution is:

$$y = cx + f(c).$$

The singular solution is obtained by eliminating p between (1) and

2. $$x + f'(p) = 0.$$

8.061 The equation

1. $$y = xf(p) + \phi(p).$$

The solution is that of the linear equation of the first order:

2. $$\frac{dx}{dp} - \frac{f'(p)}{p - f(p)}x = \frac{\phi'(p)}{p - f(p)},$$

which may be solved by **8.002.** Eliminating p between (1) and the solution of (2) gives the solution of the given equation.

8.062 The equation:

$$x\phi(p) + y\psi(p) = \chi(p),$$

may be reduced to **8.061** by dividing by $\psi(p)$.

DIFFERENTIAL EQUATIONS OF AN ORDER HIGHER THAN THE FIRST

8.100 Linear equations with constant coefficients. General form:

$$\frac{d^n y}{dx^n} + a_1 \frac{d^{n-1}y}{dx^{n-1}} + a_2 \frac{d^{n-2}y}{dx^{n-2}} + \ldots . + a_n y = V(x).$$

The complete solution consists of the sum of

(a) The complementary function, obtained by solving the equation with $V(x) = 0$, and containing n arbitrary constants, and

(b) The particular integral, with no arbitrary constants.

8.101 The complementary function. Assume $y = e^{\lambda x}$. The equation for determining λ is:

$$\lambda^n + a_1\lambda^{n-1} + a_2\lambda^{n-2} + \ldots . . + a_n = 0.$$

8.102 If the roots of **8.101** are all real and distinct the complementary function is:

$$y = c_1 e^{\lambda_1 x} + c_2 e^{\lambda_2 x} + \ldots . + c_n e^{\lambda_n x}.$$

8.103 For a pair of complex roots:

$$\mu \pm i\nu,$$

the corresponding terms in the complementary function are:

$$e^{\mu x}(A \cos \nu x + B \cos \nu x) = Ce^{\mu x} \cos (\nu x - \theta) = Ce^{\mu x} \sin (\nu x + \theta),$$

where

$$C = \sqrt{A^2 + B^2}, \quad \tan \theta = \frac{B}{A}.$$

8.104 If there are r equal real roots the terms in the complementary function corresponding to them are:

$$e^{\lambda x}(A_1 + A_2 x + A_3 x^2 + \ldots . + A_r x^{r-1}),$$

where λ is the repeated root, and $A_1, A_2, \ldots .., A_r$ are the r arbitrary constants.

8.105 If there are m equal pairs of complex roots the terms in the complementary function corresponding to them are:

$$\begin{aligned} & e^{\mu x}\{(A_1 + A_2 x + A_3 x^2 + \ldots . + A_m x^{m-1}) \cos \nu x \\ & \qquad + (B_1 + B_2 x + B_3 x^2 + \ldots . + B_m x^{m-1}) \sin \nu x\} \\ & = e^{\mu x}\{C_1 \cos (\nu x - \theta_1) + C_2 x \cos (\nu x - \theta_2) + \ldots .. + C_m x^{m-1} \cos (\nu x - \theta_m)\} \\ & = e^{\mu x}\{C_1 \sin (\nu x + \theta_1) + C_2 x \sin (\nu x + \theta_2) + \ldots .. + C_m x^{m-1} \sin (\nu x + \theta_m)\} \end{aligned}$$

where $\lambda \pm i\mu$ is the repeated root and

$$C_k = \sqrt{A_k^2 + B_k^2},$$

$$\tan \theta_k = \frac{B_k}{A_k}.$$

The particular integral.

8.110 The operator D stands for $\frac{\partial}{\partial x}$, D^2 for $\frac{\partial^2}{\partial x^2}$, ...

The differential equation **8.100** may be written:

$$(D^n + a_1 D^{n-1} + a_2 D^{n-2} + \ldots\ldots + a_n)y = f(D)y = V(x)$$

$$y = \frac{V(x)}{f(D)},$$

$$f(D) = (D - \lambda_1)(D - \lambda_2) \ldots\ldots (D - \lambda_n),$$

where $\lambda_1, \lambda_2, \ldots\ldots, \lambda_n$ are determined as in **8.101.** The particular integral is:

$$y = e^{\lambda_1 x}\int e^{(\lambda_2-\lambda_1)x}\,dx\int e^{(\lambda_3-\lambda_2)x}\,dx \ldots\ldots \int e^{-\lambda_n(x)}\,V(x)dx.$$

8.111 $\frac{1}{f(D)}$ may be resolved into partial fractions:

$$\frac{1}{f(D)} = \frac{N_1}{D-\lambda_1} + \frac{N_2}{D-\lambda_2} + \ldots + \frac{N_n}{D-\lambda_n}.$$

The particular integral is:

$$y = N_1 e^{\lambda_1 x}\int e^{-\lambda_1 x}V(x)dx + N_2 e^{\lambda_2 x}\int e^{-\lambda_2 x}V(x)dx + \ldots\ldots$$
$$+ N_n e^{\lambda_n x}\int e^{-\lambda_n x}V(x)dx.$$

THE PARTICULAR INTEGRAL IN SPECIAL CASES

8.120 $V(x) = \text{const.} = c$,

$$y = \frac{c}{a_n}.$$

8.121 $V(x)$ is a rational integral function of x of the mth degree. Expand $\frac{1}{f(D)}$ in ascending powers of D, ending with D^m. Apply the operators D, D^2, ..., D^m to each term of $V(x)$ separately and the particular integral will be the sum of the results of these operations.

8.122 $$V(x) = ce^{kx},$$

$$y = \frac{c}{f(k)} e^{kx},$$

unless k is a root of $f(D) = 0$. If k is a multiple root of order r of $f(D) = 0$

$$y = \frac{cx^r e^{kx}}{r!\psi(k)},$$

where

$$f(D) = (D - k)^r \psi(D).$$

8.123 $$V(x) = c \cos (kx + \alpha).$$

If ik is not a root of $f(D) = 0$ the particular integral is the real part of

$$\frac{c}{f(ik)} e^{i(kx+\alpha)}.$$

If ik is a multiple root of order r of $f(D) = 0$ the particular integral is the real part of

$$\frac{cx^r e^{i(kx+\alpha)}}{f^{(r)}(ik)},$$

where $f^{(r)}(ik)$ is obtained by taking the rth derivative of $f(D)$ with respect to D, and substituting ik for D.

8.124 $$V(x) = c \sin (kx + \alpha).$$

If ik is not a root of $f(D) = 0$ the particular integral is the real part of

$$\frac{-ic\, e^{i(kx+\alpha)}}{f(ik)}.$$

If ik is a multiple root of order r of $f(D) = 0$ the particular integral is the real part of

$$\frac{-icx^r e^{i(kx+\alpha)}}{f^{(r)}(ik)}.$$

8.125 $$V(x) = ce^{kx}\cdot X,$$

where X is any function of x.

$$y = ce^{kx}\frac{1}{f(D+k)}X.$$

If X is a rational integral function of x this may be evaluated by the method of **8.121.**

8.126 $$V(x) = c \cos (kx + \alpha)\cdot X,$$

where X is any function of x. The particular integral is the real part of

$$ce^{i(kx+\alpha)} \frac{1}{f(D+ik)} X.$$

8.127 $$V(x) = c \sin (kx + \alpha)\cdot X.$$

The particular integral is the real part of

$$-ice^{i(kx+\alpha)} \frac{1}{f(D+ik)} X.$$

8.128 $$V(x) = ce^{\beta x} \cos (kx + \alpha).$$

If $(\beta + ik)$ is not a root of $f(D) = 0$ the particular integral is the real part of

$$ce^{i(kx+\alpha)} \frac{1}{f(\beta + ik)} e^{\beta x}.$$

If $(\beta + ik)$ is a multiple root of order r of $f(D) = 0$ the particular integral is the real part of

$$\frac{ce^{i(kx+\alpha)}x^r e^{\beta x}}{f^{(r)}(\beta + ik)},$$

where $f^{(r)}$ $(\beta + ik)$ is formed as in **8.123.**

8.129 $$V = ce^{\beta x} \sin (kx + \alpha).$$

If $(\beta + ik)$ is not a root of $f(D) = 0$ the particular integral is the real part of

$$\frac{-ice^{i(kx+\alpha)}e^{\beta x}}{f(\beta + ik)}.$$

If $(\beta + ik)$ is a multiple root of order r of $f(D) = 0$ the particular integral is the real part of

$$\frac{-ice^{i(kx+\alpha)}x^r e^{\beta x}}{f^{(r)}(\beta + ik)}.$$

8.130 $$V(x) = x^m X,$$

where X is any function of x.

$$y = x^m \frac{1}{f(D)} X + mx^{m-1} \left\{ \frac{d}{dD} \frac{1}{f(D)} \right\} X + \frac{m(m-1)}{2!} x^{m-2} \left\{ \frac{d^2}{dD^2} \frac{1}{f(D)} \right\} X + \ldots\ldots$$

The series must be extended to the $(m + 1)$th term.

8.200 Homogeneous linear equations. General form:

$$x^n \frac{d^n y}{dx^n} + a_1 x^{n-1} \frac{d^{n-1}y}{dx^{n-1}} + \ldots + a_{n-1} x \frac{dy}{dx} + a_n y = V(x).$$

Denote the operator:

$$x \frac{d}{dx} = \theta,$$

$$x^m \frac{d^m}{dx^m} = \theta(\theta - 1)(\theta - 2) \ldots\ldots (\theta - m + 1).$$

The differential equation may be written:

$$F(\theta) \cdot y = V(x).$$

The complete solution is the sum of the complementary function, obtained by solving the equation with $V(x) = 0$, and the particular integral.

8.201 The complementary function.

$$y = c_1x^{\lambda_1} + c_2x^{\lambda_2} + \ldots\ldots + c_nx^{\lambda_n},$$

where $\lambda_1, \lambda_2, \ldots\ldots, \lambda_n$ are the n roots of

$$F(\lambda) = 0$$

if the roots are all distinct.

If λ_k is a multiple root of order r, the corresponding terms in the complementary function are:

$$x^{\lambda_k}\{b_1 + b_2 \log x + b_3 (\log x)^2 + \ldots\ldots + b_r (\log x)^{r-1}\}.$$

If $\lambda = \mu \pm i\nu$ is a pair of complex roots, of order r, the corresponding terms in the complementary function are:

$$x^{\mu}\{[A_1 + A_2 \log x + A_3 (\log x)^2 + \ldots\ldots + A_r (\log x)^{r-1}] \cos (\nu \log x)$$
$$+ [B_1 + B_2 \log x + B_3 (\log x)^2 + \ldots\ldots + B_r(\log x)^{r-1}] \sin (\nu \log x)\}.$$

8.202 The particular integral.

If

$$F(\theta) = (\theta - \lambda_1)(\theta - \lambda_2) \ldots\ldots (\theta - \lambda_n),$$

$$y = x^{\lambda_1}\int x^{\lambda_2-\lambda_1-1}dx\int x^{\lambda_3-\lambda_2-1}dx \ldots\ldots \int x^{\lambda_n-\lambda_{n-1}-1}V(x)dx.$$

8.203 The operator $\dfrac{1}{F(\theta)}$ may be resolved into partial fractions:

$$\frac{1}{F(\theta)} = \frac{N_1}{\theta - \lambda_1} + \frac{N_2}{\theta - \lambda_2} + \ldots\ldots + \frac{N_n}{\theta - \lambda_n},$$

$$y = N_1x^{\lambda_1}\int x^{-\lambda_1-1}V(x)dx + N_2x^{\lambda_2}\int x^{-\lambda_2-1}V(x)dx$$
$$+ \ldots\ldots + N_nx^{\lambda_n}\int x^{-\lambda_n-1}V(x)dx.$$

The particular integral in special cases.

8.210

$$V(x) = cx^k,$$

$$y = \frac{c}{F(k)}\,x^k,$$

unless k is a root of $F(\theta) = 0$.

If k is a multiple root of order r of $F(\theta) = 0$.

$$y = \frac{c\,(\log x)^r}{F^{(r)}(k)},$$

where $F^{(r)}(k)$ is obtained by taking the rth derivative of $F(\theta)$ with respect to θ and after differentiation substituting k for θ.

8.211

$$V(x) = cx^k X,$$

where X is any function of x.

$$y = cx^k \frac{1}{F(\theta + k)} X.$$

8.220 The differential equation:

$$(a + bx)^n \frac{d^n y}{dx^n} + (a + bx)^{n-1} a_1 \frac{d^{n-1} y}{dx^{n-1}} + \ldots\ldots + (a + bx) a_{n-1} \frac{dy}{dx} + a_n y = V(x),$$

may be reduced to the homogeneous linear equation (**8.200**) by the change of variable

$$z = a + bx.$$

It may be reduced to a linear equation with constant coefficients by the change of variable:

$$e^z = a + bx.$$

8.230 The general linear equation. General form:

$$P_0 \frac{d^n y}{dx^n} + P_1 \frac{d^{n-1} y}{dx^{n-1}} + \ldots\ldots + P_{n-1} \frac{dy}{dx} + P_n = V,$$

where $P_0, P_1, \ldots\ldots, P_n, V$ are functions of x only.

The complete solution is the sum of:

(a) The complementary function, which is the general solution of the equation with $V = 0$, and containing n arbitrary constants, and

(b) The particular integral.

8.231 Complementary Function. If $y_1, y_2, \ldots\ldots, y_n$ are n independent solutions of **8.230** with $V = 0$, the complementary function is

$$y = c_1 y_1 + c_2 y_2 + \ldots\ldots + c_n y_n.$$

The conditions that $y_1, y_2, \ldots\ldots, y_n$ be n independent solutions is that the determinant $\Delta \neq 0$.

$$\Delta = \begin{vmatrix} \frac{d^{n-1} y_1}{dx^{n-1}} & \frac{d^{n-1} y_2}{dx^{n-1}} & \cdots & \frac{d^{n-1} y_n}{dx^{n-1}} \\ \frac{d^{n-2} y_1}{dx^{n-2}} & \frac{d^{n-2} y_2}{dx^{n-2}} & \cdots & \frac{d^{n-2} y_n}{dx^{n-2}} \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ \frac{dy_1}{dx} & \frac{dy_2}{dx} & \cdots & \frac{dy_n}{dx} \\ y_1 & y_2 & \cdots & y_n \end{vmatrix}$$

When $\Delta \neq 0$:

$$\Delta = Ce^{-\int \frac{P_1}{P_0} dx}.$$

8.232 The particular integral. If Δ_k is the minor of $\frac{d^{n-1}y_k}{dx^{n-1}}$ in Δ, the particular integral is:

$$y = y_1 \int \frac{V\Delta_1}{P_0\Delta}\,dx + y_2 \int \frac{V\Delta_2}{P_0\Delta}\,dx + \ldots + y_n \int \frac{V\Delta_n}{P_0\Delta}\,dx.$$

8.233 If y_1 is one integral of the equation **8.230** with $v = 0$, the substitution

$$y = uy_1, \quad v = \frac{du}{dx},$$

will result in a linear equation of order $n - 1$.

8.234 If $y_1, y_2, \ldots\ldots, y_{n-1}$ are $n - 1$ independent integrals of **8.230** with $V = 0$ the complete solution is:

$$y = \sum_{k=1}^{n-1} y\, c_{kk} + c_n \sum_{k=1}^{n-1} y_k \int \frac{\Delta_k}{\Delta^2}\, e^{-\int \frac{P_1}{P_0} dx}\, dx$$

where Δ is the determinant:

$$\Delta = \begin{vmatrix} \frac{d^{n-2}y_1}{dx^{n-2}} & \frac{d^{n-2}y_2}{dx^{n-2}} & \ldots\ldots & \frac{d^{n-2}y_{n-1}}{dx^{n-2}} \\ \frac{d^{n-3}y_1}{dx^{n-3}} & \frac{d^{n-3}y_2}{dx^{n-3}} & \ldots\ldots & \frac{d^{n-3}y_{n-1}}{dx^{n-3}} \\ \ldots & \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots \\ \frac{dy_1}{dx} & \frac{dy_2}{dx} & \ldots\ldots & \frac{dy_{n-1}}{dx} \\ y_1 & y_2 & \ldots\ldots & y_{n-1} \end{vmatrix}$$

and Δ_k is the minor of $\frac{d^{n-2}y_k}{dx^{n-2}}$ in Δ.

SYMBOLIC METHODS

8.240 Denote the operators:

$$\frac{d}{dx} = D$$

$$x\frac{d}{dx} = \theta.$$

8.241 If X is a function of x:

1. $$(D - m)^{-1} X = e^{mx} \int e^{-mx} X dx.$$

2. $$(D - m)^{-1}\, 0 = ce^{mx}.$$

3. $$(\theta - m)^{-1} X = x^m \int x^{-m-1} X dx.$$

4. $$(\theta - m)^{-1}\, 0 = cx^m.$$

8.242 If $F(D)$ is a polynomial in D,

1. $$F(D)e^{mx} = e^{mx}F(m).$$

2. $$F(D)e^{mx}X = e^{mx}F(D+m)X.$$

3. $$e^{mx}F(D)X = F(D-m)e^{mx}X.$$

8.243 If $F(\theta)$ is a polynomial in θ,

1. $$F(\theta)x^m = x^m F(m).$$

2. $$F(\theta)x^m X = x^m F(\theta+m)X.$$

3. $$x^m F(\theta)X = F(\theta-m)x^m X.$$

8.244 $$x^m \frac{d^m}{dx^m} = \theta(\theta-1)(\theta-2)\ldots\ldots(\theta-m+1).$$

INTEGRATION IN SERIES

8.250 If a linear differential equation can be expressed in the symbolic form:

$$[x^m F(\theta) + f(\theta)]\, y = 0,$$

where $F(\theta)$ and $f(\theta)$ are polynomials in θ, the substitution,

$$y = \sum_{n=0}^{\infty} a_n x^{\rho+nm},$$

leads to the equations,

$$\begin{aligned} a_0 f(\rho) &= 0, \\ a_0 F(\rho) + a_1 f(\rho+m) &= 0, \\ a_1 F(\rho+m) + a_2 f(\rho+2m) &= 0, \\ a_2 F(\rho+2m) + a_3 f(\rho+3m) &= 0. \\ \ldots\ldots & \\ \ldots\ldots & \end{aligned}$$

8.251 The equation

$$f(\rho) = 0,$$

is the "indicial equation." If it is satisfied a_0 may be chosen arbitrarily, and the other coefficients are then determined.

8.252 An equation:

$$\left[F(\theta) + \phi(\theta)\frac{d^m}{dx^m}\right] y = 0,$$

may be reduced to the form **8.250**, where,

$$f(\theta) = \phi(\theta-m)\,\theta(\theta-1)(\theta-2)\ldots\ldots(\theta-m+1).$$

If the degree of the polynomial f is greater than that of F the series always converges; if the degree of f is less than that of F the series always diverges.

ORDINARY DIFFERENTIAL EQUATIONS OF SPECIAL TYPES

8.300

$$\frac{d^n y}{dx^n} = X,$$

where X is a function of x only.

$$y = \frac{1}{(n-1)!}\int_0^x (x-t)^{n-1}\,T dt + c_1 x^{n-1} + c_2 x^{n-2} + \ldots + c_{n-1}\,x + c_n,$$

where T is the same function of t that X is of x.

8.301

$$\frac{d^2 y}{dx^2} = Y,$$

where Y is a function of y only.
If

$$\psi(y) = 2\int Y dy,$$

the solution is:

$$\int \frac{dy}{\{\psi(y) + c_1\}^{\frac{1}{2}}} = x + c_2.$$

8.302

$$\frac{d^n y}{dx^n} = F\left(\frac{d^{n-1} y}{dx^{n-1}}\right).$$

Put

$$\frac{d^{n-1} y}{dx^{n-1}} = Y; \quad \frac{dY}{dx} = F(Y),$$

$$x + c_1 = \int \frac{dY}{F(Y)} = \psi(Y),$$

$$Y = \phi(x + c_1),$$

$$\frac{d^{n-1} y}{dx^{n-1}} = \phi(x + c_1),$$

and this equation may be solved by **8.300.**

Or the equation can be solved:

$$y = \int \frac{dY}{F(Y)} \int \frac{dY}{F(Y)} \cdot \cdot \cdot \cdot \cdot \cdot \int \frac{Y dY}{F(Y)},$$

where the integration is to be carried out from right to left and an arbitrary constant added after each integration. Eliminating Y between this result and

$$Y = \phi(x + c_1)$$

gives the solution.

8.303

$$\frac{d^n y}{dx^n} = F\left(\frac{d^{n-2} y}{dx^{n-2}}\right).$$

Put

$$\frac{d^{n-2}y}{dx^{n-2}} = Y,$$

$$\frac{d^2Y}{dx^2} = F(Y),$$

which may be solved by **8.301.** If the solution can be expressed:

$$Y = \phi(x),$$

$n - 2$ integrations will solve the given differential equation.

Or putting

$$\psi(y) = 2\int Y\,dy,$$

$$y = \int \frac{dY}{\{c_1 + \psi(Y)\}^{\frac{1}{2}}} \int \frac{dY}{\{c_1 + \psi(Y)\}^{\frac{1}{2}}} \cdots\cdots \int \frac{Y\,dY}{\{c_1 + \psi(Y)\}^{\frac{1}{2}}},$$

where the integration is to be carried out from right to left and an arbitrary constant added after each integration. The solution of the given differential equation is obtained by elimination between this result and

$$Y = \phi(x).$$

8.304 Differential equations of the second order in which the independent variable does not appear. General type:

$$F\left(y, \frac{dy}{dx}, \frac{d^2y}{dx^2}\right) = 0.$$

Put

$$p = \frac{dy}{dx}, \quad p\frac{dp}{dy} = \frac{d^2y}{dx^2}.$$

A differential equation of the first order results:

$$F\left(y, p, p\frac{dp}{dy}\right) = 0.$$

If the solution of this equation is:

$$p = f(y),$$

the solution of the given equation is,

$$x + c_2 = \int \frac{dy}{f(y)}.$$

8.305 Differential equations of the second order in which the dependent variable does not appear. General type:

$$F\left(x, \frac{dy}{dx}, \frac{d^2y}{dx^2}\right) = 0.$$

Put

$$p = \frac{dy}{dx}, \quad \frac{dp}{dx} = \frac{d^2y}{dx^2}.$$

A differential equation of the first order results:

$$F\left(x, p, \frac{dp}{dx}\right) = 0.$$

If the solution of this equation is:

$$p = f(x),$$

the solution of the given equation is:

$$y = c_2 + \int f(x)dx.$$

8.306 Equations of an order higher than the second in which either the independent or the dependent variable does not appear. The substitution:

$$\frac{dy}{dx} = p,$$

as in **8.304** and **8.305** will result in an equation of an order less by unity than the given equation.

8.307 Homogeneous differential equations. If y is assumed to be of dimensions n, x of dimensions 1, $\frac{dy}{dx}$ of dimensions $(n - 1)$, $\frac{d^2y}{dx^2}$ of dimensions $(n - 2)$, ... then if every term has the same dimensions the equation is homogeneous. If the independent variable is changed to θ and the dependent variable changed to z by the relations,

$$x = e^{\theta}, \quad y = ze^{n\theta},$$

the resulting equation will be one in which the independent variable does not appear and its order can be lowered by unity by **8.306.**

If $y, \frac{dy}{dx}, \frac{d^2y}{dx^2}$, ... are assumed all to be of the same dimensions, and the equation is homogeneous, the substitution:

$$y = e^{\int u dx},$$

will result in an equation in u and x of an order less by unity than the given equation.

8.310 Exact differential equations. A linear differential equation:

$$P_n \frac{d^ny}{dx^n} + P_{n-1} \frac{d^{n-1}y}{dx^{n-1}} + \ldots\ldots + P_1 \frac{dy}{dx} + P_0 = P,$$

where $P, P_0, P_1, \ldots\ldots P_n$ are functions of x is exact if:

$$P_0 - \frac{dP_1}{dx} + \frac{d^2P_2}{dx^2} - \ldots\ldots + (-1)^n \frac{d^nP_n}{dx^n} = 0.$$

The first integral is:

$$Q_n \frac{d^{n-1}}{dx^{n-1}} + Q_{n-1} \frac{d^{n-2}y}{dx^{n-2}} + \ldots + Q_1 y = \int P\,dx + c_1,$$

where,

$$Q_n = P_n,$$

$$Q_{n-1} = P_{n-1} - \frac{dP_n}{dx},$$

$$Q_{n-2} = P_{n-2} - \frac{dP_{n-1}}{dx} + \frac{d^2P_n}{dx^2},$$

$$\ldots\ldots$$

$$\ldots\ldots$$

$$Q_1 = P_1 - \frac{dP_2}{dx} + \frac{d^2P_3}{dx^2} - \ldots + (-1)^{n-1} \frac{d^{n-1}P_n}{dx^{n-1}}.$$

If the first integral is an exact differential equation the process may be continued as long as the coefficients of each successive integral satisfy the condition of integrability.

8.311 Non-linear differential equations. A non-linear differential equation of the nth order:

$$V\left(\frac{d^ny}{dx^n}, \frac{d^{n-1}y}{dx^{n-1}}, \ldots, \frac{dy}{dx}, y, x\right) = 0,$$

to be exact must contain $\dfrac{d^ny}{dx^n}$ in the first degree only. Put

$$\frac{d^{n-1}y}{dx^{n-1}} = p, \quad \frac{d^ny}{dx^n} = \frac{dp}{dx}.$$

Integrate the equation on the assumption that p is the only variable and $\dfrac{dp}{dx}$ its differential coefficient. Let the result be V_1. In $V\,dx - dV_1$, $\dfrac{d^{n-1}y}{dx^{n-1}}$ is the highest differential coefficient and it occurs in the first degree only. Repeat this process as often as may be necessary and the first integral of the exact differential equation will be

$$V_1 + V_2 + \ldots\ldots = c.$$

If this process breaks down owing to the appearance of the highest differential coefficient in a higher degree than the first the given differential equation was not exact.

8.312 General condition for an exact differential equation. Write:

$$\frac{dy}{dx} = y' \quad \frac{d^2y}{dx^2} = y'' \quad \ldots\ldots \quad \frac{d^ny}{dx^n} = y^{(n)}.$$

In order that the differential equation:

$$V(x, y, y', y'', \ldots\ldots, y^{(n)}) = 0,$$

be exact it is necessary and sufficient that

$$\frac{\partial V}{\partial y} - \frac{\partial}{\partial x}\left(\frac{\partial V}{\partial y'}\right) + \frac{\partial^2}{\partial x^2}\left(\frac{\partial V}{\partial y''}\right) - \ldots\ldots + (-1)^n \frac{\partial^n}{\partial x^n}\left(\frac{\partial V}{\partial y^{(n)}}\right) = 0.$$

8.400 Linear differential equations of the second order.

General form:

$$\frac{d^2y}{dx^2} + P\frac{dy}{dx} + Qy = R,$$

where P, Q, R are, in general, functions of x.

8.401 If a solution of the equation with $R = 0$:

$$y = w$$

can be found, the complete solution of the given differential equation is:

$$y = c_2 w + c_1 w \int e^{-\int P dx} \frac{dx}{w^2} + w \int e^{-\int P dx} \frac{dx}{w^2} \int w R e^{\int P dx} dx.$$

8.402 The general linear differential equation of the second order may be reduced to the form:

$$\frac{d^2v}{dx^2} + Iv = Re^{\frac{1}{2}\int P dx},$$

where:

$$y = ve^{-\frac{1}{2}\int P dx},$$

$$I = Q - \frac{1}{2}\frac{dP}{dx} - \frac{1}{4}P^2.$$

8.403 The differential equation:

$$\frac{d^2y}{dx^2} + P\frac{dy}{dx} + Qy = 0,$$

by the change of independent variable to

$$z = \int e^{-\int P dx} dx,$$

becomes:

$$\frac{d^2y}{dz^2} + Qe^{2\int P dx} y = 0.$$

By the change of independent variable.

$$dz = Qe^{\int P dx} dx,$$

$$Qe^{2\int P dx} = \frac{1}{U(z)},$$

it becomes:

$$\frac{d}{dz}\left\{\frac{1}{U}\frac{dy}{dz}\right\} + y = 0.$$

8.404 Resolution of the operator. The differential equation:

$$u\frac{d^2y}{dx^2} + v\frac{dy}{dx} + wy = 0,$$

may sometimes be solved by resolving the operator,

$$u\frac{d^2}{dx^2} + v\frac{d}{dx} + w,$$

into the product,

$$\left(p\frac{d}{dx} + q\right)\left(r\frac{d}{dx} + s\right).$$

The solution of the differential equation reduces to the solution of

$$r\frac{dy}{dx} + sy = c_1 e^{-\int \frac{q}{p}dx}.$$

The equations for determining p, r, q, s are:

$$pr = u,$$

$$qr + ps + p\frac{dr}{dx} = v,$$

$$qs + p\frac{ds}{dx} = w.$$

8.410 Variation of parameters. The complete solution of the differential equation:

$$\frac{d^2y}{dx^2} + P\frac{dy}{dx} + Qy = R,$$

is

$$y = c_1 f_2(x) + c_2 f_1(x) + \frac{1}{C}\int^x R(\xi) e^{\int^\xi Pdx}\left\{ f_2(x)f_1(\xi) - f_1(x)f_2(\xi) \right\} d\xi,$$

where $f_1(x)$ and $f_2(x)$ are two particular solutions of the differential equation with $R = 0$, and are therefore connected by the relation

$$f_1\frac{df_2}{dx} - f_2\frac{df_1}{dx} = Ce^{-\quad Pdx}.$$

C is an absolute constant depending upon the forms of f_1 and f_2 and may be taken as unity.

8.500 The differential equation:

$$(a_2 + b_2x)\frac{d^2y}{dx^2} + (a_1 + b_1x)\frac{dy}{dx} + (a_0 + b_0x)y = 0.$$

8.501 Let

$$D = (a_0b_1 - a_1b_0)(a_1b_2 - a_2b_1) - (a_0b_2 - a_2b_0)^2.$$

Special cases.

8.502 $b_2 = b_1 = b_0 = 0$.

The solution is:

$$y_1 = c_1 e^{\lambda_1 x} + c_2 e^{\lambda_2 x},$$

where:

$$\begin{matrix}\lambda_1 \\ \lambda_2\end{matrix} = \frac{-a_1 \pm \sqrt{a_1^2 - 4a_0 a_2}}{2a_2}.$$

8.503 $D = 0,\ b_2 = 0,$

$$y = e^{\lambda x}\left\{c_1 + c_2 \int e^{-(k+2\lambda)x - mx^2} dx\right\},$$

where:

$$k = \frac{a_1}{a_2} \quad m = \frac{b_1}{2a_2} \quad \lambda = -\frac{b_0}{b_1}.$$

8.504 $D = 0,\ b_2 \neq 0$:

$$y = e^{\lambda x}\left\{c_1 + c_2 \int e^{-(k+2\lambda)x}(a_2 + b_2 x)^m dx\right\},$$

where

$$k = \frac{b_1}{b_2} \quad m = \frac{a_2 b_1 - a_1 b_2}{b_2^3},$$

and λ is the common root of:

$$a_2\lambda^2 + a_1\lambda + a_0 = 0,$$
$$b_2\lambda^2 + b_1\lambda + b_0 = 0.$$

8.505 $D \neq 0,\ b_2 = b_1 = 0$. If $\eta = f(\xi)$ is the complete solution of:

$$\frac{d^2\eta}{d\xi^2} + \xi\eta = 0,$$

$$y = e^{\lambda x} f\left(\frac{\alpha + \beta x}{\beta^{\frac{2}{3}}}\right),$$

where

$$\alpha = \frac{4a_0 a_2 - a_1^2}{4a_2^2} \quad \beta = \frac{b_0}{a_2} \quad \lambda = -\frac{a_1}{2a_2}.$$

8.510 The differential equation **8.500** under the condition $D \neq 0$ can always be reduced to the form:

$$\xi \frac{d^2\phi}{d\xi^2} + (p + q + \xi)\frac{d\phi}{d\xi} + p\phi = 0.$$

8.511 Denote the complete solution of **8.510**:

$$\phi = F\{\xi\}.$$

8.512 $b_2 = b_1 = 0$:

$$y = e^{\lambda x + (\mu + \nu x)^{\frac{3}{2}}} F\{2(\mu + \nu x)^{\frac{3}{2}}\},$$

where:

$$\lambda = -\frac{a_1}{2a_2} \quad \mu = \frac{a_1^2 - 4a_0 a_2}{4a_2^2}\left(\frac{4a_2^2}{9b_0^2}\right)^{\frac{1}{3}},$$

$$\nu = -\left(\frac{4b_0}{9a_2}\right)^{\frac{1}{3}},$$

$$p = q = \frac{1}{6}.$$

8.513 $b_2 = 0,\ b_1 \neq 0$:

$$y = e^{\lambda x} F\left\{\frac{(\alpha_1 + \beta_1 x)^2}{2\beta_1}\right\},$$

where:

$$\lambda = -\frac{b_0}{b_1}\quad \alpha_1 = \frac{a_1 b_1 - 2a_2 b_0}{a_2 b_1},\quad \beta_1 = \frac{b_1}{a_2},$$

$$p = \frac{a_2 b_0^2 - a_1 b_0 b_1 + a_0 b_1^2}{2b_1^3},$$

$$q = \frac{1}{2} - p.$$

8.514 $b_2 \neq 0,\ b_0 = \dfrac{b_1^2}{4b_2}$:

$$y = e^{\lambda x + \sqrt{\mu + \nu x}} F\left\{2\sqrt{\mu + \nu x}\right\},$$

where:

$$\lambda = -\frac{b_1}{2b_2},\quad \mu = -a_2\frac{4a_0 b_2^2 - 2a_1 b_1 b_2 + a_2 b_1^2}{b_2^4},$$

$$\nu = -\frac{4a_0 b_2^2 - 2a_1 b_1 b_2 + a_2 b_1^2}{b_2^3},$$

$$p = q = \frac{a_1 b_2 - a_2 b_1}{b_2^2} - \frac{1}{2}.$$

8.515 $b_2 \neq 0,\ b_0 \neq \dfrac{b_1^2}{4b_2}$:

$$y = e^{\lambda x} F\left\{\frac{\beta_1(\alpha_2 + \beta_2 x)}{\beta_2^2}\right\},$$

where $\alpha_2 = a_2$, $\beta_2 = b_2$, $\beta_1 = 2b_2\lambda + b_1$ and λ is one of the roots of

$$b_2\lambda^2 + b_1\lambda + b_0 = 0.$$

$$p = \frac{a_2\lambda^2 + a_1\lambda + a_0}{2b_2\lambda + b_1},\qquad q = \frac{a_1 b_2 - a_2 b_1}{b_2^2} - p.$$

8.520 The solution of **8.510** will be denoted:

$$\phi = F(p, q, \xi).$$

1. $F(p, q, \xi) = e^{-\xi} F(q, p, -\xi).$

2. $F(p, q, -\xi) = e^{\xi} F(q, p, \xi)$

3. $F(q, p, \xi) = e^{-\xi} F(p, q, -\xi).$

4. $F(p, q, \xi) = \xi^{1-p-q} F(1 - q, 1 - p, \xi).$

5. $F(-p, -q, \xi) = \xi^{1+p+q} F(1 + q, 1 + p, \xi).$

6. $F(p + m, q, \xi) = \dfrac{d^m}{d\xi^m} F(p, q, \xi).$

7. $F(p, q + n, \xi) = (-1)^n e^{-\xi}\dfrac{d^n}{d\xi^n}\left\{e^{\xi} F(p, q, \xi)\right\}.$

8.521 The function $F(p, q, \xi)$ can always be found if it is known for positive proper fractional values of p and q.

8.522 p and q positive improper fractions:

$$p = m + r, \quad q = n + s$$

where m and n are positive integers and r and s positive proper fractions.

$$F(m + r, n + s, \xi) = (-1)^n \frac{d^m}{d\xi^m}\left[e^{-\xi} \frac{d^n}{d\xi^n}\left\{ e^{\xi} F(r, s, \xi) \right\}\right].$$

8.523 p and q both negative:

$$p = -(m - 1 + r) \quad q = -(n - 1 + s),$$

$$F(-m + 1 - r, -n + 1 - s, \xi) = (-1)^m \xi^{m+n+r+s-1} \frac{d^n}{d\xi^n}\left[e^{-\xi} \frac{d^m}{d\xi^m}\left\{ e^{\xi} F(s, r, \xi) \right\}\right].$$

8.524 p positive, q negative:

$$p = m + r, \quad q = -n + s,$$

$$F(m + r, -n + s, \xi) = \frac{d^m}{d\xi^m}\left[\xi^{n+1-r-s} \frac{d^n}{d\xi^n} F(1 - s, 1 - r, \xi)\right].$$

8.525 p negative, q positive:

$$p = -m + r, \quad q = n + s,$$

$$F(-m + r, n + s, \xi) = (-1)^{m+n} e^{-\xi} \frac{d^n}{d\xi^n}\left[\xi^{m+1-r-s} \frac{d^m}{d\xi^m}\left\{ e^{\xi} F(1 - s, 1 - r, \xi) \right\}\right].$$

8.530 If either p or q is zero the relation $D = 0$ is satisfied and the complete solution of the differential equation is given in **8.502, 3.**

8.531 If $p = m$, a positive integer:

$$\phi = F(m, q, \xi) = c_1 \frac{d^{m-1}}{d\xi^{m-1}}\left[\xi^{-q} e^{-\xi} \int \xi^{q-1} e^{\xi} d\xi\right] + c_2 \frac{d^{m-1}}{d\xi^{m-1}}\left[\xi^{-q} e^{-\xi}\right].$$

8.532 If $p = m$, a positive integer and both q and ξ are positive:

$$\phi = F(m, q, \xi) = c_1 \int_0^1 u^{m-1}(1 - u)^{q-1} e^{-\xi u}\, du + c_2 e^{-\xi} \int^{\infty} (1 + u)^{m-1} u^{q-1} e^{-\xi u}\, du.$$

8.533 If $q = n$, a positive integer:

$$\phi = F(p, n, \xi) = c_1 e^{-\xi} \frac{d^{n-1}}{d\xi^{n-1}}\left[\xi^{-p} e^{\xi} \int \xi^{p-1} e^{-\xi}\, d\xi\right] + c_2 e^{-\xi} \frac{d^{n-1}}{d\xi^{n-1}}\left[\xi^{-p} e^{\xi}\right].$$

8.534 If $q = n$, a positive integer and both p and ξ are positive:

$$\phi = F(p, n, \xi) = c_1 \int_0^1 u^{p-1}(1 - u)^{n-1} e^{-\xi u}\, du + c_2 e^{-\xi} \int_0^{\infty} (1 + u)^{p-1} u^{n-1} e^{-\xi u}\, du.$$

8.540 The general solution of equation **8.510** may be written:

$$\phi = F(p, q, \xi) = c_1 M + c_2 N,$$

$$M = \int_0^1 u^{p-1}(1 - u)^{q-1} e^{-\xi u} du \qquad \begin{matrix} p > 0 \\ q > 0 \end{matrix}$$

$$N = \int_0^\infty (1 + u)^{p-1} u^{q-1} e^{-\xi(1+u)} du \qquad \begin{matrix} q > 0 \\ \xi > 0 \end{matrix}$$

$$M = \frac{\Gamma(p)\Gamma(q)}{\Gamma(s)} \left\{ 1 - \frac{p}{s}\frac{\xi}{1!} + \frac{p(p+1)}{s(s+1)}\frac{\xi^2}{2!} - \frac{p(p+1)(p+2)}{s(s+1)(s+2)}\frac{\xi^3}{3!} + \dots \right\}$$

$$s = p + q,$$

$$N = \frac{\Gamma(q)e^{-\xi}}{\xi^q} \left\{ 1 + \frac{(p-1)q}{1!\xi} + \frac{(p-1)(p-2)q(q+1)}{2!\xi} + \dots \right.$$

$$+ \frac{(p-1)(p-2)\dots\dots(p-\overline{n-1})(q)(q+1)\dots\dots(q+n-2)}{(n-1)!\xi^{n-1}}$$

$$\left. + \frac{\rho(p-1)(p-2)\dots(p-n)q(q+1)(q+2)\dots(q+n-1)}{n!\xi^n} \right\},$$

where $0 < \rho < 1$ and the real part of ξ is positive.

THE COMPLETE SOLUTION OF EQUATION 8.510 IN SPECIAL CASES

8.550 $p>0$, $q>0$, real part of $\xi>0$:

$$F(p, q, \xi) = c_1 \int_0^1 u^{p-1}(1-u)^{q-1} e^{-\xi u} du + c_2 e^{-\xi} \int_0^\infty (1+u)^{p-1} u^{q-1} e^{-\xi u} du.$$

8.551 $p>0$, $q>0$, $\xi<0$:

$$F(p, q, \xi) = c_1 \int_0^1 u^{p-1}(1-u)^{q-1} e^{-\xi u} du + c_2 \int^\infty u^{p-1}(1+u)^{q-1} e^{\xi u} du.$$

8.552 $p<0$, $q<0$, $\xi>0$:

$$F(p,q,\xi) = \xi^{1-p-q} \left\{ c_1 \int_0^1 (1-u)^{-p} u^{-q} e^{-\xi u} du + c_2 e^{-\xi} \int_0^\infty u^{-p}(1+u)^{-q} e^{-\xi u} du \right\}.$$

8.553 $p<0$, $q<0$, $\xi<0$:

$$F(p, q, \xi) = \xi^{1-p-q} \left\{ c_1 \int_0^1 (1-u)^{-p} u^{-q} e^{-\xi u} du + c_2 \int_0^\infty (1+u)^{-p} u^{-q} e^{+\xi u} du \right\}.$$

8.554 $p>0$, $q<0$

$p = m + r$, where m is a positive integer and r a proper fraction.

$$F(m + r, q, \xi) = \frac{d^m}{d\xi^m} \left\{ \xi^{1-r-q} F(1 - r, 1 - q, \xi) \right\},$$

$$\xi>0:\quad F(1-r, 1-q, \xi) = c_1 \int_0^1 u^{-r}(1-u)^{-q} e^{-\xi u}\, du + c_2 e^{-\xi} \int_0^\infty (1+u)^{-r} u^{-q} e^{-\xi u}\, du,$$

$$\xi<0:\quad F(1-r, 1-q, \xi) = c_1 \int_0^1 u^{-r}(1-u)^{-q} e^{-\xi u}\, du + c_2 \int_0^\infty u^{-r}(1+u)^{-q} e^{\xi u}\, du.$$

8.555 $p<0$, $q>0$,

$q = n + s$, where n is a positive integer and s a proper fraction.

$$F(p, n+s, \xi) = e^{-\xi} \frac{d^n}{d\xi^n} \left\{ e^{\xi} \xi^{1-p-s} F(1-s, 1-p, \xi) \right\},$$

$$\xi>0:\quad F(1-s, 1-p, \xi) = c_1 \int_0^1 u^{-s}(1-u)^{-p} e^{-\xi u}\, du + c_2 e^{-\xi} \int_0^\infty (1+u)^{-s} u^{-p} e^{-\xi u}\, du,$$

$$\xi<0:\quad F(1-s, 1-p, \xi) = c_1 \int_0^1 u^{-s}(1-u)^{-p} e^{-\xi}\, du + c_2 \int_0^\infty u^{-s}(1+u)^{-p} e^{\xi u} du.$$

8.556 ξ pure imaginary:

$p = r$, $q = s$, where r and s are positive proper fractions.

$r + s \neq 1$:

$$F(r, s, \xi) = c_1 \int_0^1 u^{r-1}(1-u)^{s-1} e^{-\xi u}\, du + c_2 \xi^{1-r-s} \int_0^1 u^{-s}(1-u)^{-r} e^{-\xi u}\, du.$$

$r + s = 1$:

$$F(r, s, \xi) = c_1 \int_0^1 u^{r-1}(1-u)^{s-1} e^{-\xi u}\, du + c_2 \int_0^1 u^{r-1}(1-u)^{s-1} e^{-\xi u} \log \left\{ \xi u(1-u) \right\} du.$$

8.600 The differential equation:

$$x \frac{d^2y}{dx^2} + (\gamma - x) \frac{dy}{dx} - \alpha y = 0$$

is satisfied by the confluent hypergeometric function. The complete solution is:

$$y = c_1 M(\alpha, \gamma, x) + c_2 x^{1-\gamma} M(\alpha - \gamma + 1, 2 - \gamma, x) = \overline{M}(\alpha, \gamma, x),$$

where

$$M(\alpha, \gamma, x) = 1 + \frac{\alpha}{\gamma}\frac{x}{1} + \frac{\alpha(\alpha+1)}{\gamma(\gamma+1)}\frac{x^2}{2!} + \frac{\alpha(\alpha+1)(\alpha+2)}{\gamma(\gamma+1)(\gamma+2)}\frac{x^3}{3!} + \cdots\cdots$$

The series is absolutely and uniformly convergent for all real and complex values of α, γ, x, except when γ is a negative integer or zero.

When γ is a positive integer the complete solution of the differential equation is:

$$y = \left\{c_1 + c_2 \log x\right\} M(\alpha, \gamma, x) + c_2 \left\{ \frac{ax}{\gamma}\left(\frac{1}{\alpha} - \frac{1}{\gamma} - 1\right) \right.$$

$$+ \frac{\alpha(\alpha+1)}{\gamma(\gamma+1)}\frac{x^2}{2!}\left(\frac{1}{\alpha} + \frac{1}{\alpha+1} - \frac{1}{\gamma} - \frac{1}{\gamma+1} - 1 - \frac{1}{2}\right)$$

$$+ \frac{\alpha(\alpha+1)(\alpha+2)}{\gamma(\gamma+1)(\gamma+2)}\frac{x^3}{3!}\left(\frac{1}{\alpha} + \frac{1}{\alpha+1} + \frac{1}{\alpha+2} - \frac{1}{\gamma} - \frac{1}{\gamma+1} - \frac{1}{\gamma+2} - 1 - \frac{1}{2} - \frac{1}{3}\right)$$

$$\left. + \cdots\cdots \right\}.$$

8.601 For large values of x the following asymptotic expansion may be used:

$$M(\alpha, \gamma, x)$$

$$= \frac{\Gamma(\gamma)}{\Gamma(\gamma-\alpha)}(-x)^{-\alpha}\left\{1 - \frac{\alpha(\alpha-\gamma+1)}{1}\frac{1}{x} + \frac{\alpha(\alpha+1)(\alpha-\gamma+1)(\alpha-\gamma+2)}{2!}\frac{1}{x^2}\cdots\right\}$$

$$+ \frac{\Gamma(\gamma)}{\Gamma(\alpha)}e^x x^{\alpha-\gamma}\left\{1 + \frac{(1-\alpha)(\gamma-\alpha)}{1}\frac{1}{x} + \frac{(1-\alpha)(2-\alpha)(\gamma-\alpha)(\gamma-\alpha+1)}{2!}\frac{1}{x^2} + \cdots\right\}.$$

8.61

1. $M(\alpha, \gamma, x) = e^x M(\gamma - \alpha, \gamma, -x)$.
2. $x^{1-\gamma} M(\alpha - \gamma + 1, 2 - \gamma, x) = e^x x^{1-\gamma} M(1 - \alpha, 2 - \gamma, -x)$.
3. $\dfrac{x}{\gamma} M(\alpha + 1, \gamma + 1, x) = M(\alpha + 1, \gamma, x) - M(\alpha, \gamma, x)$.
4. $\alpha M(\alpha + 1, \gamma + 1, x) = (\alpha - \gamma) M(\alpha, \gamma + 1, x) + \gamma M(\alpha, \gamma, x)$.
5. $(\alpha + x) M(\alpha + 1, \gamma + 1, x) = (\alpha - \gamma) M(\alpha, \gamma + 1, x) + \gamma M(\alpha + 1, \gamma, x)$.
6. $\alpha\gamma M(\alpha + 1, \gamma, x) = \gamma(\alpha + x) M(\alpha, \gamma, x) - x(\gamma - \alpha) M(\alpha, \gamma + 1, x)$.
7. $\alpha M(\alpha + 1, \gamma, x) = (x + 2\alpha - \gamma) M(\alpha, \gamma, x) + (\gamma - \alpha) M(\alpha - 1, \gamma, x)$.
8. $\dfrac{\gamma - \alpha}{\gamma} x M(\alpha, \gamma + 1, x) = (x + \gamma - 1) M(\alpha, \gamma, x) + (1 - \gamma) M(\alpha, \gamma - 1, x)$.

8.62

1. $\dfrac{d}{dx} M(\alpha, \gamma, x) = \dfrac{\alpha}{\gamma} M(\alpha + 1, \gamma + 1, x)$.
2. $(1 - \alpha)\displaystyle\int_0^x M(\alpha, \gamma, x)\, dx = (1 - \gamma) M(\alpha - 1, \gamma - 1, x) + (\gamma - 1)$.

SPECIAL DIFFERENTIAL EQUATIONS AND THEIR SOLUTIONS IN TERMS OF $\overline{M}(\alpha, \gamma, x)$

8.630

$$\frac{d^2y}{dx^2} + 2(p + qx)\frac{dy}{dx} + \left\{ 4\alpha q + p^2 - q^2m^2 + 2qx(p + qm) \right\} y = 0,$$

$$y = e^{-(p+qm)x}\,\overline{M}\left(\alpha, \frac{1}{2}, -q(x - m)^2\right).$$

8.631

$$\frac{d^2y}{dx^2} + \left(2p + \frac{\gamma}{x}\right)\frac{dy}{dx} + \left\{ p^2 - t^2 + \frac{1}{x}\left(\gamma p + \gamma t - 2\alpha t\right) \right\} y = 0,$$

$$y = e^{-(p+t)x}\,\overline{M}(\alpha, \gamma, 2tx).$$

8.632

$$\frac{d^2y}{dx^2} + 2(p + qx)\frac{dy}{dx} + \left\{ q + c(1 - 4\alpha) + (p + qx)^2 - c^2(x - m)^2 \right\} y = 0,$$

$$y = e^{-px-\frac{1}{2}qx^2-\frac{1}{2}c(x-m)^2}\,\overline{M}\left(\alpha, \frac{1}{2}, c(x - m)^2\right).$$

8.633

$$\frac{d^2y}{dx^2} + \left(2p + \frac{q}{x}\right)\frac{dy}{dx} + \left\{ p^2 - t^2 + \frac{1}{x}\left(pq + \gamma t - 2\alpha t\right) + \frac{1}{4x^2}\left(\gamma - q\right)\left(2 - q - \gamma\right) \right\} y = 0,$$

$$y = e^{-(p+t)x}\,x^{\frac{\gamma-q}{2}}\,\overline{M}(\alpha, \gamma, 2tx).$$

8.634

$$\frac{d^2y}{dx^2} + \left\{ \frac{2\gamma - 1}{x} + 2a + 2(b - c)x \right\}\frac{dy}{dx}$$

$$+ \left\{ \frac{a(2\gamma - 1)}{x} + (a^2 + 2b\gamma - 4\alpha c) + 2a(b - c)x + b(b - 2c)x^2 \right\} y = 0,$$

$$y = e^{-ax-\frac{1}{2}bx^2}\,\overline{M}(\alpha, \gamma, cx^2).$$

8.635

$$\frac{d^2y}{dx^2} + \frac{1}{x}\left(2px^r + qr - r + 1\right)\frac{dy}{dx}$$

$$+ \frac{1}{x^2}\left\{ (p^2 - t^2)x^{2r} + r(pq + \gamma t - 2\alpha t)x^r + \frac{1}{4}r^2(\gamma - q)(2 - q - \gamma) \right\} y = 0,$$

$$y = e^{-\frac{(p+t)}{r}x^r}\,x^{\frac{r}{2}(\gamma-q)}\,\overline{M}\left(\alpha, \gamma, \frac{2tx^r}{r}\right).$$

8.640 Tables and graphs of the function $M(\alpha, \gamma, x)$ are given by Webb and Airey (Phil. Mag. 36, p. 129, 1918) for getting approximate numerical solutions of any of these differential equations. The range in x is 1 to 10; in α, +0.5 to +4.0 and −0.5 to −3.0; in γ, 1 to 7. For negative values of x the equations of **8.61** may be used.

SPECIAL DIFFERENTIAL EQUATIONS

8.700

$$\frac{d^2y}{dx^2} + n^2y = X(x)$$

where $X(x)$ is any function of x. The complete solution is:

$$y = c_1e^{nx} + c_2e^{-nx} + \frac{1}{n}\int^x X(\xi)\sinh n(x-\xi)\,d\xi.$$

8.701

$$\frac{d^2y}{dx^2} + \kappa\frac{dy}{dx} + n^2y = X(x).$$

The complete solution, satisfying the conditions:

$$x = 0 \qquad y = y_0,$$

$$x = 0 \qquad \frac{dy}{dx} = y_0',$$

$$y = e^{-\frac{1}{2}\kappa x}\left\{y_0'\frac{\sin n'x}{n'} + y_0\left(\cos n'x + \frac{\kappa}{2n'}\sin n'x\right)\right\}$$
$$+ \frac{1}{n'}\int_0^x e^{-\frac{1}{2}\kappa(x-\xi)}\sin n'(x-\xi)X(\xi)\,d\xi,$$

where $$n' = \sqrt{n^2 - \frac{\kappa^2}{4}}.$$

8.702

$$\frac{d^2y}{dx^2} + f(x)\frac{dy}{dx} + g(x)\left(\frac{dy}{dx}\right)^2 = 0,$$

$$y = \int\frac{e^{-\int f(x)dx}\,dx}{\int e^{-\int f(x)dx}g(x)\,dx + c_1} + c_2.$$

8.703

$$\frac{d^2y}{dx^2} + f(y)\left(\frac{dy}{dx}\right)^2 + g(y) = 0,$$

$$x = \pm\int\frac{e^{\int f(y)dy}\,dy}{\{c_1 - 2\int e^{2\int f(y)dy}g(y)\,dy\}^{\frac{1}{2}}} + c_2.$$

8.704

$$\frac{d^2y}{dx^2} + f(y)\frac{dy}{dx} + g(y)\left(\frac{dy}{dx}\right)^2 = 0,$$

$$x = \int\frac{e^{\int g(y)dy}\,dy}{c_1 - \int e^{\int g(y)dy}f(y)\,dy} + c_2.$$

8.705

$$\frac{d^2y}{dx^2} + f(x)\frac{dy}{dx} + g(y)\left(\frac{dy}{dx}\right)^2 = 0,$$

$$\int e^{\int g(y)dy}\, dy = c_1 \int e^{-\int f(x)dx}\, dx + c_2.$$

8.706

$$\frac{d^2y}{dx^2} + (a + bx)\frac{dy}{dx} + abxy = 0.$$

$$y = e^{-ax}\{c_1 + c_2 \int e^{ax - \frac{1}{2}bx^2}\, dx\}.$$

8.707

$$x\frac{d^2y}{dx^2} + (a + bx)\frac{dy}{dx} + aby = 0,$$

$$y = e^{-bx}\{c_1 + c \int x^{-a} e^{bx}\, dx\}$$

8.708

$$\frac{d^2y}{dx^2} + \frac{a}{x}\frac{dy}{dx} + \frac{b}{x^2}\, y = 0.$$

1. $(a - 1)^2 > 4b$; $\lambda = \frac{1}{2}\sqrt{(a - 1)^2 - 4b}$

$$y = x^{-\frac{a-1}{2}}\{c_1 x + c_2 x^{-\lambda}\}.$$

2. $(a - 1)^2 < 4b$; $\lambda = \frac{1}{2}\sqrt{4b - (a - 1)^2}$

$$y = x^{-\frac{a-1}{2}}\{c_1 \cos(\lambda \log x) + c_2 \sin(\lambda \log x)\}.$$

3. $(a - 1)^2 = 4b$

$$y = x^{-\frac{a-1}{2}}(c_1 + c_2 \log x).$$

8.709

$$\frac{d^2y}{dx^2} + 2bx\frac{dy}{dx} + (a + b^2x^2\, y = 0.$$

1. $a < b$, $\lambda = \sqrt{b - a}$,

$$y = e^{-\frac{bx^2}{2}}(c_1 e^{\lambda x} + c_2 e^{-\lambda x}).$$

2. $a > b$, $\lambda = \sqrt{a - b}$,

$$y = e^{-\frac{bx^2}{2}}(c_1 \cos \lambda x + c_2 \sin \lambda x).$$

8.710

$$f(x)\frac{d^2y}{dx^2} - (a + bx)\frac{dy}{dx} + by = 0,$$

$$\int \frac{a + bx}{f(x)}\, dx = X,$$

$$y = c_1(a + bx) + c_2\left\{e^X - (a + bx)\int \frac{1}{f(x)} e^X\, dx\right\}.$$

8.711

$$(a^2 - x^2)\frac{d^2y}{dx^2} + 2(\mu - 1)x\frac{dy}{dx} - \mu(\mu - 1)y = 0,$$

$$y = (a + x)_{\mu}\left\{c_1 + c_2\int\frac{(a - x)^{\mu-1}}{(a + x)^{\mu+1}}\,dx\right\}.$$

8.712

$$\frac{d^2y}{dx^2} + \frac{2}{x}\frac{dy}{dx} + \mu^2 y = \frac{a}{x},$$

$$y = \frac{1}{x}\left\{c_1 \cos \mu x + c_2 \sin \mu x + \frac{a}{\mu^2}\right\}.$$

8.713

$$\frac{d^4y}{dx^4} + 2\,d\frac{d^3y}{dx^3} + c\frac{d^2y}{dx^2} + 2b\frac{dy}{dx} + ay = 0,$$

$$\begin{aligned} y = c_1 e^{-\rho_1 x}\{\rho_1 \sin(\omega_1 x + \alpha_1) + \omega_1 \cos(\omega_1 x + \alpha_1)\} \\ + c_2 e^{-\rho_2 x}\{\rho_2 \sin(\omega_2 x + \alpha_2) + \omega_2 \cos(\omega_2 x + \alpha_2)\}, \end{aligned}$$

where:

$$\begin{aligned} 4\omega_1^2 &= z + c - 2\,d^2 + 2\sqrt{z^2 - 4a} - 2\,d\sqrt{z - c + d^2}, \\ 4\omega_2^2 &= z + c - 2\,d^2 - 2\sqrt{z^2 - 4a} + 2\,d\sqrt{z - c + d^2}, \\ 2\rho_1 &= d + \sqrt{z - c + d^2}, \\ 2\rho_2 &= d - \sqrt{z - c + d^2}, \end{aligned}$$

and z is a root of

$$z^3 - cz^2 - 4(a - bd)z + 4(ac - ad^2 - b^2) = 0.$$

(Kiebitz, Ann. d. Physik, 40, p. 138, 1913)

IX. DIFFERENTIAL EQUATIONS
(*continued*)

9.00 Legendre's Equation:

$$(1 - x^2)\frac{d^2y}{dx^2} - 2x\frac{dy}{dx} + n(n+1)y = 0.$$

9.001 If n is a positive integer one solution is the Legendre polynomial, or Zonal Harmonic, $P_n(x)$:

$$P_n(x) = \frac{(2n)!}{2^n(n!)^2}\left\{x^n - \frac{n(n-1)}{2(2n-1)}x^{n-2} + \frac{n(n-1)(n-2)(n-3)}{2\cdot 4\cdot(2n-1)(2n-3)}x^{n-4} - \dots\right\}.$$

9.002 If n is even the last term in the finite series in the brackets is:

$$(-1)^{\frac{n}{2}}\frac{(n!)^3}{\left(\frac{n}{2}!\right)^2(2n)!}.$$

9.003 If n is odd the last term in the brackets is:

$$(-1)^{\frac{n-1}{2}}\frac{(n!)^2(n-1)!}{([\frac{1}{2}(n-1)]!)^2\,(2n-1)!}x.$$

9.010 If n is a positive integer a second solution of Legendre's Equation is the infinite series:

$$Q_n(x) = \frac{2^n(n!)^2}{(2n+1)!}\left\{x^{-(n+1)} + \frac{(n+1)(n+2)}{2(2n+3)}x^{-(n+3)} + \frac{(n+1)(n+2)(n+3)(n+4)}{2\cdot 4\cdot(2n+3)(2n+5)}x^{-(n+5)} + \dots\right\}.$$

9.011

$$P_{2n}(\cos\theta) = (-1)^n\frac{(2n)!}{2^{2n}(n!)^2}\left\{\sin^{2n}\theta - \frac{(2n)^2}{2!}\sin^{2n-2}\theta\cos^2\theta + \dots + (-1)^n\frac{(2n)^2(2n-2)^2\dots 4^2 2^2}{(2n)!}\cos^{2n}\theta\right\}.$$

9.012

$$P_{2n+1}(\cos\theta) = (-1)^n\frac{(2n+1)!}{2^{2n}(n!)^2}\left\{\sin^{2n}\theta\cos\theta - \frac{(2n)^2}{3!}\sin^{2n-2}\theta\cos^3\theta + \dots + (-1)^n\frac{(2n)^2(2n-2)^2\dots 4^2 2^2}{(2n+1)!}\cos^{2n+1}\theta\right\}.$$

(Brodetsky: Mess. of Math. 42, p. 65, 1912)

9.02 Recurrence formulae for $P_n(x)$:

1. $$(n+1)P_{n+1} + nP_{n-1} = (2n+1)xP_n.$$

2. $$(2n+1)P_n = \frac{dP_{n+1}}{dx} - \frac{dP_{n-1}}{dx}.$$

3. $$(n+1)P_n = \frac{dP_{n+1}}{dx} - x\frac{dP_n}{dx}.$$

4. $$nP_n = x\frac{dP_n}{dx} - \frac{dP_{n-1}}{dx}.$$

5. $$(1-x^2)\frac{dP_n}{dx} = (n+1)(xP_n - P_{n+1}).$$

6. $$(1-x^2)\frac{dP_n}{dx} = n(P_{n-1} - xP_n).$$

7. $$(2n+1)(1-x^2)\frac{dP_n}{dx} = n(n+1)(P_{n-1} - P_{n+1}).$$

9.028 Recurrence formulae for $Q_n(x)$. These are the same as those for $P_n(x)$.

9.030 Special Values.

$$P_0(x) = 1,$$
$$P_1(x) = x,$$
$$P_2(x) = \tfrac{1}{2}(3x^2 - 1),$$
$$P_3(x) = \tfrac{1}{2}(5x^3 - 3x),$$
$$P_4(x) = \tfrac{1}{8}(35x^4 - 30x^2 + 3),$$
$$P_5(x) = \tfrac{1}{8}(63x^5 - 70x^3 + 15x),$$
$$P_6(x) = \tfrac{1}{16}(231x^6 - 315x^4 + 105x^2 - 5),$$
$$P_7(x) = \tfrac{1}{16}(429x^7 - 693x^5 + 315x^3 - 35x),$$
$$P_8(x) = \tfrac{1}{128}(6435x^8 - 12012x^6 + 6930x^4 - 1260x^2 + 35).$$

9.031

$$Q_0(x) = \frac{1}{2}\log\frac{x+1}{x-1},$$

$$Q_1(x) = \frac{1}{2}x\log\frac{x+1}{x-1} - 1,$$

$$Q_2(x) = \frac{1}{2}P_2(x)\log\frac{x+1}{x-1} - \frac{3}{2}x,$$

$$Q_3(x) = \frac{1}{2}P_3(x)\log\frac{x+1}{x-1} - \frac{5}{2}x^2 + \frac{2}{3}.$$

9.032

$$P_{2n}(0) = (-1)^n \frac{1\cdot 3\cdot 5 \ldots (2n-1)}{2\cdot 4\cdot 6 \ldots 2n},$$

$$P_{2n+1}(0) = 0,$$

$$P_n(1) = 1,$$

$$P_n(-x) = (-1)^n P_n(x).$$

9.033 If $z = r\cos\theta$:

$$\frac{\partial P_n(\cos\theta)}{\partial z} = \frac{n+1}{r}\left\{ P_1(\cos\theta)P_n(\cos\theta) - P_{n+1}(\cos\theta) \right\}$$

$$= \frac{n(n+1)}{(2n+1)r}\left\{ P_{n-1}(\cos\theta) - P_{n+1}(\cos\theta) \right\}.$$

9.034 Rodrigues' Formula:

$$P_n(x) = \frac{1}{2^n n!}\frac{d^n}{dx^n}(x^2-1)^n.$$

9.035 If $z = r\cos\theta$:

$$P_n(\cos\theta) = \frac{(-1)^n}{n!} r^{n+1} \frac{\partial^n}{\partial z^n}\left(\frac{1}{r}\right).$$

9.036 If $m \leqslant n$:

$$P_m(x)P_n(x) = \sum_{k=0}^{m} \frac{A_{m-k}A_k A_{n-k}}{A_{n+m-k}}\left(\frac{2n+2m-4k+1}{2n+2m-2k+1}\right)P_{n+m-2k}(x),$$

where:

$$A_r = \frac{1\cdot 3\cdot 5 \ldots (2r-1)}{r!}.$$

MEHLER'S INTEGRALS

9.040 For all values of n:

$$P_n(\cos\theta) = \frac{2}{\pi}\int_0^\theta \frac{\cos(n+\frac{1}{2})\phi\, d\phi}{\sqrt{2(\cos\phi - \cos\theta)}}.$$

9.041 If n is a positive integer:

$$P_n(\cos\theta) = \frac{2}{\pi}\int^\pi \frac{\sin(n+\frac{1}{2})\phi\, d\phi}{\sqrt{2(\cos\theta - \cos\phi)}}.$$

LAPLACE'S INTEGRALS, FOR ALL VALUES OF n

9.042

$$P_n(x) = \frac{1}{\pi}\int_0^\pi \{x + \sqrt{x^2-1}\cos\phi\}^n\, d\phi.$$

9.043

$$Q_n(x) = \int^\infty \frac{d\phi}{\{x + \sqrt{x^2-1}\cosh\phi\}^{n+1}}.$$

INTEGRAL PROPERTIES

9.044

$$\int_{-1}^{+1} P_m(x)P_n(x)\,dx = 0 \text{ if } m \neq n$$
$$= \frac{2}{2n+1} \text{ if } m = n.$$

9.045

$$(m-n)(m+n+1)\int_x^1 P_m(x)P_n(x)\,dx$$
$$= \tfrac{1}{2}\{P_m[(n+1)P_{n+1} - nP_{n-1}] - P_n[(m+1)P_{m+1} - mP_{m-1}]\}.$$

9.046

$$(2n+1)\int^1 P_n^2(x)\,dx = 1 - xP_n^2 - 2x(P_1^2 + P_2^2 + \ldots + P_{n-1}^2)$$
$$+ 2(P_1P_2 + P_2P_3 + \ldots + P_{n-1}P_n)$$

EXPANSIONS IN LEGENDRE FUNCTIONS

9.050 Neumann's expansion:

$$f(x) = \sum_{n=0}^{\infty} a_nP_n(x),$$

$$a_n = (n + \tfrac{1}{2})\int_{-1}^{+1} f(x)P_n(x)\,dx,$$

$$= \frac{n+\frac{1}{2}}{2^n n!}\int_{-1}^{+1} f^{(n)}(x)\cdot(1-x^2)^n\,dx.$$

9.051 Any polynomial in x may be expressed as a series of Legendre's polynomials. If $f_n(x)$ is a polynomial of degree n:

$$f_n(x) = \sum_{k=0}^{n} a_kP_k(x),$$

$$a_k = \frac{2k+1}{2}\int_{-1}^{+1} f_n(x)P_k(x)\,dx.$$

SPECIAL EXPANSIONS IN LEGENDRE FUNCTIONS

9.060 For all positive real values of n:

1. $$\cos n\theta = -\frac{1+\cos n\pi}{2(n^2-1)}\left\{P_0(\cos\theta) + \frac{5n^2}{(n^2-3^2)}P_2(\cos\theta)\right.$$
$$\left. + \frac{9n^2(n^2-2^2)}{(n^2-3^2)(n^2-5^2)}P_4(\cos\theta) + \ldots\right\} - \frac{1-\cos n\pi}{2(n^2-2^2)}\left\{3P_1(\cos\theta)\right.$$
$$\left. + \frac{7(n^2-1^2)}{(n^2-4^2)}P_3(\cos\theta) + \frac{11(n^2-1^2)(n^2-3^2)}{(n^2-4^2)(n^2-6^2)}P_5(\cos\theta) + \ldots\right\}.$$

2. $$\sin n\theta = -\frac{1}{2}\frac{\sin n\pi}{(n^2-1)}\left\{P_0(\cos\theta)+\frac{5n^2}{(n^2-3^2)}P_2(\cos\theta)+\frac{9n^2(n^2-2^2)}{(n^2-3^2)(n^2-5^2)}P_4(\cos\theta)+\ldots\right\}+\frac{1}{2}\frac{\sin n\pi}{(n^2-2^2)}\left\{3P_1(\cos\theta)+\frac{7(n^2-1^2)}{(n^2-4^2)}P_3(\cos\theta)+\frac{11(n^2-1^2)(n^2-3^2)}{(n^2-4^2)(n^2-6^2)}P_5(\cos\theta)+\ldots\right\}.$$

9.061 If n is a positive integer:

1. $$\cos n\theta = \frac{1}{2}\frac{2\cdot4\cdot6\ldots2n}{3\cdot5\cdot7\ldots(2n+1)}\left\{(2n+1)P_n(\cos\theta)+(2n-3)\frac{[n^2-(n+1)^2]}{[n^2-(n-2)^2]}P_{n-2}(\cos\theta)+(2n-7)\frac{[n^2-(n+1)^2][n^2-(n-1)^2]}{[n^2-(n-2)^2][n^2-(n-4)^2]}P_{n-4}(\cos\theta)+\ldots\right\}.$$

2. $$\sin n\theta = \frac{\pi}{4}\frac{1\cdot3\cdot5\ldots(2n-3)}{2\cdot4\cdot6\ldots(2n-2)}\left\{(2n-1)P_{n-1}(\cos\theta)+(2n+3)\frac{[n^2-(n-1)^2]}{[n^2-(n+2)^2]}P_{n+1}(\cos\theta)+(2n+7)\frac{[n^2-(n-1)^2][n^2-(n+1)^2]}{[n^2-(n+2)^2][n^2-(n+4)^2]}P_{n+3}(\cos\theta)+\ldots\right\}.$$

9.062

1. $$\theta = \frac{\pi}{2}-\frac{\pi}{2}\sum_{n=1}^{\infty}\frac{(4n-1)}{(2n-1)^2}\left(\frac{1\cdot3\cdot5\ldots(2n-1)}{2\cdot4\cdot6\ldots2n}\right)^2P_{2n-1}(\cos\theta).$$

2. $$\sin\theta = \frac{\pi}{4}-\frac{\pi}{2}\sum_{n=1}^{\infty}\frac{(4n+1)}{(2n-1)(2n+2)}\left(\frac{1\cdot3\cdot5\ldots(2n-1)}{2\cdot4\cdot6\ldots2n}\right)^2P_{2n}(\cos\theta).$$

3. $$\cot\theta = \frac{\pi}{2}\sum_{n=1}^{\infty}\frac{2n(4n-1)}{(2n-1)}\left(\frac{1\cdot3\cdot5\ldots(2n-1)}{2\cdot4\cdot6\ldots2n}\right)^2P_{2n-1}(\cos\theta).$$

4. $$\csc\theta = \frac{\pi}{2}+\frac{\pi}{2}\sum_{n=1}^{\infty}(4n+1)\left(\frac{1\cdot3\cdot5\ldots(2n-1)}{2\cdot4\cdot6\ldots2n}\right)^2P_{2n}(\cos\theta).$$

9.063

1. $$\log\frac{1+\sin\frac{\theta}{2}}{\sin\frac{\theta}{2}} = 1+\sum_{n=1}^{\infty}\frac{1}{n+1}P_n(\cos\theta).$$

2. $$\log\frac{\tan\frac{1}{4}(\pi-\theta)}{\frac{1}{2}\sin\theta} = -\log\sin\frac{\theta}{2}-\log\left(1+\sin\frac{\theta}{2}\right) = \sum_{n=1}^{\infty}\frac{1}{n}P_n(\cos\theta).$$

9.064 $K(k)$ and $E(k)$ denote the complete elliptic integrals of the first and second kinds, and $k = \sin\theta$:

1. $$K(k) = \frac{\pi^2}{4}+\frac{\pi^2}{4}\sum_{n=1}^{\infty}(-1)^n(4n+1)\left(\frac{1\cdot3\cdot5\ldots(2n-1)}{2\cdot4\cdot6\ldots2n}\right)^3P_{2n}(\cos\theta).$$

2. $$E(k) = \frac{\pi^2}{8} + \frac{\pi^2}{4}\sum_{n=1}^{\infty}(-1)^{n+1}\frac{(4n+1)}{(2n-1)(2n+2)}\left(\frac{1\cdot 3\cdot 5\ldots\ldots(2n-1)}{2\cdot 4\cdot 6\ldots\ldots 2n}\right)^3 P_{2n}(\cos\theta).$$

(Hargreaves, Mess. of Math. 26, p. 89, 1897)

9.070 The differential equation:

$$(1-x^2)\frac{d^2y}{dx^2} - 2x\frac{dy}{dx} + \left\{n(n+1) - \frac{m^2}{1-x^2}\right\}y = 0.$$

If m is a positive integer, and $-1 > x > +1$, two solutions of this differential equation are the associated Legendre functions

$$P_n^m(x) = (1-x^2)^{\frac{m}{2}}\frac{d^m P_n(x)}{dx^m},$$

$$Q_n^m(x) = (1-x^2)^{\frac{m}{2}}\frac{d^m Q_n(x)}{dx^m}.$$

9.071 If n, m, r are positive integers, and $n > m$, $r > m$:

$$\int_{-1}^{+1} P_n^m(x)\,P_r^m(x)\,dx = 0 \text{ if } r \neq n,$$

$$= \frac{2}{2n+1}\frac{(n+m)!}{(n-m)!} \text{ if } r = n.$$

9.100 Bessel's Differential Equation:

$$\frac{d^2y}{dx^2} + \frac{1}{x}\frac{dy}{dx} + \left(1 - \frac{\nu^2}{x^2}\right)y = 0.$$

9.101 One solution is:

$$y = J_\nu(x) = \sum_{k=0}^{\infty}(-1)^k\frac{x^{\nu+2k}}{2^{\nu+2k}k!\,\Gamma(\nu+k+1)}.$$

9.102 A second independent solution when ν is not an integer is:

$$y = J_{-\nu}(x).$$

9.103 If $\nu = n$, an integer:

$$J_{-n}(x) = (-1)^n J_n(x).$$

9.104 A second independent solution when $\nu = n$, an integer, is:

$$\pi Y_n(x) = 2J_n(x)\cdot\log\frac{x}{2} - \sum_{k=0}^{n-1}\frac{(n-k-1)!}{k!}\left(\frac{x}{2}\right)^{2k-n}$$

$$-\sum_{k=0}^{\infty}(-1)^k\frac{1}{k!(k+n)!}\left(\frac{x}{2}\right)^{n+2k}\left\{\psi(k+1) + \psi(k+n+1)\right\}$$

(see **6.61**).

9.105 For all values of ν, whether integral or not:

$$Y_\nu(x) = \frac{1}{\sin \nu\pi}\left(\cos \nu\pi J_\nu(x) - J_{-\nu}(x)\right),$$

$$J_{-\nu}(x) = \cos \nu\pi J_\nu(x) - \sin \nu\pi Y_\nu(x),$$

$$Y_{-\nu}(x) = \sin \nu\pi J_\nu(x) + \cos \nu\pi Y_\nu(x).$$

9.106 For $\nu = n$, an integer:

$$Y_{-n}(x) = (-1)^n Y_n(x).$$

9.107 Cylinder Functions of the third kind, solutions of Bessel's differential equation:

1. $$\overset{\mathrm{I}}{H_\nu}(x) = J_\nu(x) + iY_\nu(x).$$

2. $$\overset{\mathrm{II}}{H_\nu}(x) = J_\nu(x) - iY_\nu(x).$$

3. $$\overset{\mathrm{I}}{H_{-\nu}}(x) = e^{\nu\pi i}\,\overset{\mathrm{I}}{H_\nu}(x).$$

4. $$\overset{\mathrm{II}}{H_{-\nu}}(x) = e^{-\nu\pi i}\overset{\mathrm{II}}{H_\nu}(x).$$

9.110 Recurrence formulae satisfied by the functions J_ν, Y_ν, $\overset{\mathrm{I}}{H_\nu}$, $\overset{\mathrm{II}}{H_\nu}$, C_ν represents any one of these functions.

1. $$C_{\nu-1}(x) - C_{\nu+1}(x) = 2\frac{d}{dx}C_\nu(x).$$

2. $$C_{\ -1}(x) + C_{\nu+1}(x) = \frac{2\nu}{x}C_\nu(x).$$

3. $$\frac{d}{dx}C_\nu(x) = C_{\nu-1}(x) - \frac{\nu}{x}C_\nu(x).$$

4. $$\frac{d}{dx}C\ (x) = \frac{\nu}{x}C_\nu(x) - C_{\nu+1}(x).$$

5. $$\frac{d}{dx}\left\{x^\nu C_{\nu(x)}\right\} = x^\nu C_{\nu-1}(x).$$

6. $$\frac{d^2C_\nu(x)}{dx^2} = \frac{1}{4}\left\{C_{\nu+2}(x) + C_{\nu-2}(x) - 2C_\nu(x)\right\}.$$

9.111

1. $$J_\nu(x)\frac{dY_\nu(x)}{dx} - Y_\nu(x)\frac{dJ_\nu(x)}{dx} = \frac{2}{\pi x}.$$

2. $$J_{\nu+1}(x)Y_\nu(x) - J_\nu(x)Y_{\nu+1}(x) = \frac{2}{\pi x}.$$

ASYMPTOTIC EXPANSIONS FOR LARGE VALUES OF x

9.120

1. $$J_\nu(x) = \sqrt{\frac{2}{\pi x}}\left\{P\ (x)\cos\left(x - \frac{2\nu+1}{4}\pi\right) - Q_\nu(x)\sin\left(x - \frac{2\nu+1}{4}\pi\right)\right\},$$

2. $$Y_\nu(x) = \sqrt{\frac{2}{\pi x}}\left\{P_\nu(x)\sin\left(x - \frac{2\nu+1}{4}\pi\right) + Q_\nu(x)\cos\left(x - \frac{2\nu+1}{4}\pi\right)\right\},$$

3. $H_\nu^{\mathrm{I}}(x) = e^{i\left(x - \frac{2\nu+1}{4}\pi\right)} \sqrt{\frac{2}{\pi x}} \left\{ P_\nu(x) + iQ_\nu(x) \right\},$

4. $H_\nu^{\mathrm{II}}(x) = e^{-i\left(x - \frac{2\nu+1}{4}\pi\right)} \sqrt{\frac{2}{\pi x}} \left\{ P_\nu(x) - iQ_\nu(x) \right\},$

where

$$P_\nu(x) = 1 + \sum_{k=1}^{\infty} (-1)^k \frac{(4\nu^2 - 1^2)(4\nu^2 - 3^2) \ldots\ldots (4\nu^2 - \overline{4k-1}^2)}{(2k)!\ 2^{6k}\ x^{2k}},$$

$$Q_\nu(x) = \sum_{k=1}^{\infty} (-1)^{k+1} \frac{(4\nu^2 - 1^2)(4\nu^2 - 3^2) \ldots\ldots (4\nu^2 - \overline{4k-3}^2)}{(2k-1)!\ 2^{6k-3}\ x^{2k-1}}.$$

SPECIAL VALUES

9.130

1. $J_0(x) = 1 - \frac{1}{(1!)^2}\left(\frac{x}{2}\right)^2 + \frac{1}{(2!)^2}\left(\frac{x}{2}\right)^4 - \frac{1}{(3!)^2}\left(\frac{x}{2}\right)^6 + \ldots.$

2. $J_1(x) = -\frac{dJ_0(x)}{dx} = \frac{x}{2}\left\{ 1 - \frac{1}{1!2!}\left(\frac{x}{2}\right)^2 + \frac{1}{2!3!}\left(\frac{x}{2}\right)^4 - \frac{1}{3!4!}\left(\frac{x}{2}\right)^6 + \ldots \right\}.$

3. $$\begin{aligned} \frac{\pi}{2} Y_0(x) &= \left(\log\frac{x}{2} + \gamma\right) J_0(x) + \left(\frac{x}{2}\right)^2 - \frac{1}{(2!)^2}\left(1 + \frac{1}{2}\right)\left(\frac{x}{2}\right)^4 \\ &\qquad + \frac{1}{(3!)^2}\left(1 + \frac{1}{2} + \frac{1}{3}\right)\left(\frac{x}{2}\right)^6 - \ldots \\ &= \left(\log\frac{x}{2} + \gamma\right) J_0(x) + 4\left\{ \frac{1}{2} J_2(x) - \frac{1}{4} J_4(x) + \frac{1}{6} J_6(x) - \ldots \right\}. \end{aligned}$$

4. $$\begin{aligned} \frac{\pi}{2} Y_1(x) &= \left(\log\frac{x}{2} + \gamma\right) J_1(x) - \frac{1}{x} J_0(x) - \frac{x}{2}\left\{ 1 - \frac{1}{1!2!}\left(1 + \frac{1}{2}\right)\left(\frac{x}{2}\right)^2 \right. \\ &\qquad \left. + \frac{1}{2!3!}\left(1 + \frac{1}{2} + \frac{1}{3}\right)\left(\frac{x}{2}\right)^4 - \ldots \right\} \\ &= \left(\log\frac{x}{2} + \gamma\right) J_1(x) - \frac{1}{x} J_0(x) + \frac{3}{1\cdot 2} J_3(x) - \frac{5}{2\cdot 3} J_5(x) \\ &\qquad + \frac{7}{3\cdot 4} J_7(x) - \ldots\ldots \end{aligned}$$

$\gamma = 0.5772157$ (**6.602**).

9.131 Limiting values for $x = 0$:

$$J_0(x) = 1,$$

$$J_1(x) = 0,$$

$$Y_0(x) = \frac{2}{\pi}\left(\log\frac{x}{2} + \gamma\right),$$

$$Y_1(x) = -\frac{2}{\pi x}.$$

9.132 Limiting values for $x = \infty$:

$$J_0(x) = \frac{\cos\left(x - \frac{\pi}{4}\right)}{\sqrt{\frac{\pi x}{2}}}, \qquad Y_0(x) = \frac{\sin\left(x - \frac{\pi}{4}\right)}{\sqrt{\frac{\pi x}{2}}},$$

$$J_1(x) = \frac{\sin\left(x - \frac{\pi}{4}\right)}{\sqrt{\frac{\pi x}{2}}}, \qquad Y_1(x) = -\frac{\cos\left(x - \frac{\pi}{4}\right)}{\sqrt{\frac{\pi x}{2}}}.$$

9.140 Bessel's Addition Formula:

$$J_\nu(x + h) = \left(\frac{x + h}{x}\right)^\nu \sum_{k=0}^{\infty} (-1)^k \frac{h^k}{k!} \left(\frac{2x + h}{2x}\right)^k J_{\nu+k}(x).$$

9.141 Multiplication formula:

$$J_\nu(\alpha x) = \alpha^\nu \sum_{k=0}^{\infty} \frac{(1 - \alpha^2)^k}{k!} \left(\frac{x}{2}\right)^k J_{\nu+k}(x).$$

9.142

$$J_\nu(\alpha x) J_\mu(\beta x) = \sum_{k=0}^{\infty} (-1)^k A_k \left(\frac{x}{2}\right)^{\mu+\nu+2k},$$

where

$$A_k = \sum_{s=0}^{k} \frac{\alpha^{2k-2s}\beta^{2s}}{s!(k - s)!\Gamma(\nu + k - s + 1)\Gamma(\mu + s + 1)}.$$

9.143

$$J_\nu(x) J_\mu(x) = \sum_{k=0}^{\infty} \frac{(-1)^k}{\Gamma(\nu + k + 1)\Gamma(\mu + k + 1)} \binom{\mu + \nu + 2k}{k} \left(\frac{x}{2}\right)^{\mu+\nu+2k}.$$

DEFINITE INTEGRAL EXPRESSIONS FOR BESSEL'S FUNCTIONS

9.150

$$J_\nu(x) = \frac{2\left(\frac{x}{2}\right)^\nu}{\sqrt{\pi}\,\Gamma\left(\nu + \frac{1}{2}\right)} \int_0^{\frac{\pi}{2}} \cos(x \sin\phi) \cos^{2\nu}\phi \cdot d\phi.$$

9.151

$$J_\nu(x) = \frac{2\left(\frac{x}{2}\right)}{\sqrt{\pi}\,\Gamma\left(\nu + \frac{1}{2}\right)} \int_0^{\pi} \cos(x \cos\phi) \sin^{2\nu}\phi \cdot d\phi.$$

9.152

$$J_\nu(x) = \frac{\left(\frac{x}{2}\right)^\nu}{\sqrt{\pi}\,\Gamma\left(\nu+\frac{1}{2}\right)} \int_0^\pi e^{ix\cos\phi} \sin^{2\nu}\phi \cdot d\phi.$$

If n is an integer:

9.153

$$J_{2n}(x) = \frac{1}{\pi}\int_0^\pi \cos(x\sin\phi)\cos(2n\phi)d\phi = \frac{2}{\pi}\int_0^{\frac{\pi}{2}}.$$

9.154

$$J_{2n}(x) = \frac{(-1)^n}{\pi}\int_0^\pi \cos(x\cos\phi)\cos(2n\phi)d\phi = \frac{2(-1)^n}{\pi}\int_0^{\frac{\pi}{2}}.$$

9.155

$$J_{2n+1}(x) = \frac{1}{\pi}\int_0^\pi \sin(x\sin\phi)\sin(2n+1)\phi\, d\phi = \frac{2}{\pi}\int_0^{\frac{\pi}{2}}.$$

9.156

$$J_{2n+1}(x) = \frac{(-1)^n}{\pi}\int_0^\pi \sin(x\cos\phi)\cos(2n+1)\phi d\phi = \frac{2(-1)^n}{\pi}\int_0^{\frac{\pi}{2}}.$$

9.157

$$J_n(x) = \frac{1}{2\pi}\int_{-\pi}^{+\pi} e^{-in\phi+ix\sin\phi}\, d\phi = \frac{1}{2\pi}\int_0^{2\pi} e^{-in\phi+ix\sin\phi}\, d\phi.$$

INTEGRAL PROPERTIES

9.160 If $C_\nu(\mu x)$ is any one of the particular integrals:

$$J_\nu(\mu x),\ Y_\nu(\mu x),\ H_\nu^{\mathrm{I}}(\mu x),\ H_\nu^{\mathrm{II}}(\mu x),$$

of the differential equation:

$$\frac{d^2y}{dx^2} + \frac{1}{x}\frac{dy}{dx} + \left(\mu^2 - \frac{\nu^2}{x^2}\right)y = 0,$$

$$\int_a^b C_\nu(\mu_k x)C_\nu(\mu_l x)xdx$$

$$= \frac{1}{\mu_k^2 - \mu_l^2}\left[x\left\{\mu_l C_\nu(\mu_k x)C_\nu'(\mu_l x) - \mu_k C_\nu(\mu_l x)C_\nu'(\mu_k x)\right\}\right]_a^b;\ \mu_k \neq \mu_l.$$

9.161 If μ_k and μ_l are two different roots of

$$C_\nu(\mu b) = 0,$$

$$\int_a^b C_\nu(\mu_k x)C_\nu(\mu_l x)x\,dx = \frac{a}{\mu_k^2 - \mu_l^2}\left\{\mu_k C_\nu(\mu_l a)C_\nu'(\mu_k a) - \mu_l C_\nu(\mu_k a)C_\nu'(\mu_l a)\right\}.$$

9.162 If μ_k and μ_l are two different roots of

$$a\frac{C_\nu'(\mu a)}{C_\nu(\mu a)} = p\mu + q\frac{1}{\mu},$$

and

$$C_\nu(\mu b) = 0,$$

$$\int^b C_\nu(\mu_k x)C_\nu(\mu_l x)xdx = pC_\nu(\mu_k a)C_\nu(\mu_l a).$$

If $\mu_k = \mu_l$:

$$\int^b C_\nu(\mu_k x)C_\nu(\mu_l x)xdx = \frac{1}{2}\left\{b^2C_\nu'^2(\mu_k b) - a^2C_\nu'^2(\mu_k a) - \left(a^2 - \frac{\nu^2}{\mu_k^2}\right)C_\nu^2(\mu_k a)\right\}.$$

EXPANSIONS IN BESSEL'S FUNCTIONS

9.170 Schlömilch's Expansion. Any function $f(x)$ which has a continuous differential coefficient for all values of x in the closed range $(0, \pi)$ may be expanded in the series:

$$f(x) = a_0 + \sum_{k=1} a_k J_0(kx),$$

where

$$a_0 = f(0) + \frac{1}{\pi}\int_0^{\pi} u \int_0^{\frac{\pi}{2}} f'(u \sin\theta) d\theta du,$$

$$a_k = \frac{2}{\pi}\int_0^{\pi} u \cos ku \int_0^{\frac{\pi}{2}} f'(u \sin\theta)\, d\theta du.$$

9.171

$$f(x) = a_0 x^n + \sum_{k=1}^{\infty} a_k J_n(\alpha_k x) \qquad 0 < x < 1,$$

where

$$J_{n+1}(\alpha_k) = 0,$$

$$a_0 = 2(n+1)\int^{1} f(x) x^{n+1}\, dx,$$

$$a_k = \frac{2}{[J_n(\alpha_k)]^2}\int_0^1 x f(x) J_n(\alpha_k x) dx.$$

(Bridgman, Phil. Mag. 16, p. 947, 1908)

9.172

$$f(x) = \sum_{k=1}^{\infty} A_k J_0(\mu_k x) \qquad a < x < b,$$

where:

$$a\frac{J_0'(\mu_k a)}{J_0(\mu_k a)} = p\mu_k + \frac{q}{\mu_k},$$

and

$$J_0(\mu_k b) = 0,$$

$$A_k = 2\,\frac{\int_a^b x f(x) J_0(\mu_k x) dx - p f(a) J_0(\mu_k a)}{b^2 J_0'^2(\mu_k b) - a^2 J_0'^2(\mu_k a) - (a^2 + 2p) J_0^2(\mu_k a)}.$$

(Stephenson, Phil. Mag. 14, p. 547, 1907)

SPECIAL EXPANSIONS IN BESSEL'S FUNCTIONS

9.180

1. $\sin x = 2\sum_{k=0}^{\infty} (-1)^k J_{2k+1}(x),$

2. $\cos x = J_0(x) + 2\sum_{k=1}^{\infty} (-1)^k J_{2k}(x).$

9.181

1. $$\cos(x\sin\theta) = J_0(x) + 2\sum_{k=1}^{\infty} J_{2k}(x)\cos 2k\theta,$$

2. $$\sin(x\sin\theta) = 2\sum_{k=0}^{\infty} J_{2k+1}(x)\sin(2k+1)\theta.$$

9.182

1. $$\left(\frac{x}{2}\right)^n = \sum_{k=0}^{\infty} \frac{(n+2k)\,(n+k-1)!}{k!} J_{n+2k}(x),$$

2. $$\sqrt{\frac{2x}{\pi}} = \sum_{k=0}^{\infty} \frac{(4k+1)\,(2k)!}{2^{2k}(k!)^2} J_{2k+\frac{1}{2}}(x).$$

9.183

$$\frac{dJ_\nu(x)}{d\nu} = \left\{\log\frac{x}{2} - \psi(\nu+1)\right\} J\ (x) + \sum_{k=1}^{\infty} (-1)^{k-1}\frac{\nu+2k}{k(\nu+k)} J_{\nu+2k}(x)$$

$$= J_\nu(x)\log\frac{x}{2} - \sum_{k=0}^{\infty} (-1)^k \frac{\psi(\nu+k+1)}{k!\ \Gamma(\nu+k+1)}\left(\frac{x}{2}\right)^{\nu+2k}. \qquad \text{(see } \mathbf{6.61}\text{)}$$

9.200 The differential equation:

$$\frac{d^2y}{dx^2} + \frac{2}{x}\frac{dy}{dx} + \left(\mu^2 - \frac{n(n+1)}{x^2}\right)y = 0$$

with the substitution:

$$z = y\sqrt{x}, \qquad \mu x = \rho$$

becomes:

$$\frac{d^2z}{d\rho^2} + \frac{1}{\rho}\frac{dz}{d\rho} + \left(1 - \frac{(n+\frac{1}{2})^2}{\rho^2}\right)z = 0$$

which is Bessel's equation of order $n + \frac{1}{2}$.

9.201 Two independent solutions are:

$$z = J_{n+\frac{1}{2}}(\rho).$$

$$z = J_{-n-\frac{1}{2}}(\rho).$$

The former remains finite for $\rho = 0$; the latter becomes infinite for $\rho = 0$.

9.202 Special values.

$$J_{\frac{1}{2}}(x) = \sqrt{\frac{2}{\pi x}} \sin x,$$

$$J\ (x) = \sqrt{\frac{2}{\pi x}} \left(\frac{\sin x}{x} - \cos x \right),$$

$$J_{\frac{5}{2}}(x) = \sqrt{\frac{2}{\pi x}} \left\{ \left(\frac{3}{x^2} - 1 \right) \sin x - \frac{3}{x} \cos x \right\},$$

$$J_{\frac{7}{2}}(x) = \sqrt{\frac{2}{\pi x}} \left\{ \left(\frac{15}{x^3} - \frac{6}{x} \right) \sin x - \left(\frac{15}{x^2} - 1 \right) \cos x \right\},$$

$$J_{\frac{9}{2}}(x) = \sqrt{\frac{2}{\pi x}} \left\{ \left(\frac{105}{x^4} - \frac{45}{x^2} + 1 \right) \sin x - \left(\frac{105}{x^3} - \frac{10}{x} \right) \cos x \right\}.$$

9.203

$$J_{-\frac{1}{2}}(x) = \sqrt{\frac{2}{\pi x}} \cos x,$$

$$J_{-\frac{3}{2}}(x) = -\sqrt{\frac{2}{\pi x}} \left(\sin x + \frac{\cos x}{x} \right),$$

$$J_{-\frac{5}{2}}(x) = \sqrt{\frac{2}{\pi x}} \left\{ \frac{3}{x} \sin x + \left(\frac{3}{x^2} - 1 \right) \cos x \right\},$$

$$J_{-\frac{7}{2}}(x) = -\sqrt{\frac{2}{\pi x}} \left\{ \left(\frac{15}{x^2} - 1 \right) \sin x + \left(\frac{15}{x^3} - \frac{6}{x} \right) \cos x \right\},$$

$$J_{-\frac{9}{2}}(x) = \sqrt{\frac{2}{\pi x}} \left\{ \left(\frac{105}{x^3} - \frac{10}{x} \right) \sin x + \left(\frac{105}{x^4} - \frac{45}{x^2} + 1 \right) \cos x \right\}.$$

9.204

$$H^{\mathrm{I}}_{\frac{1}{2}}(x) = -i\sqrt{\frac{2}{\pi x}} e^{ix},$$

$$H^{\mathrm{I}}_{\frac{3}{2}}(x) = -\sqrt{\frac{2}{\pi x}} e^{ix} \left(1 + \frac{i}{x} \right),$$

$$H^{\mathrm{I}}_{\frac{5}{2}}(x) = -\sqrt{\frac{2}{\pi x}} e^{ix} \left\{ \frac{3}{x} + i\left(\frac{3}{x^2} - 1 \right) \right\}.$$

9.205

$$H^{\mathrm{II}}_{\frac{1}{2}}(x) = i\sqrt{\frac{2}{\pi x}} e^{-ix},$$

$$H^{\mathrm{II}}_{\frac{3}{2}}(x) = -\sqrt{\frac{2}{\pi x}} e^{-ix} \left(1 - \frac{i}{x} \right),$$

$$H^{\mathrm{II}}_{\frac{5}{2}}(x) = -\sqrt{\frac{2}{\pi x}} e^{-ix} \left\{ \frac{3}{x} - i\left(\frac{3}{x^2} - 1 \right) \right\}.$$

9.210 The differential equation:

$$\frac{d^2y}{dx^2} + \frac{1}{x}\frac{dy}{dx} - \left(1 + \frac{\nu^2}{x^2}\right) y = 0,$$

with the substitution,

$$x = iz,$$

becomes Bessel's equation.

9.211 Two independent solutions of **9.210** are:

$$I_\nu (x) = i^{-\nu} J_\nu (ix),$$

$$K^\nu (x) = e^{\frac{\nu+1}{2}\pi i} \frac{\pi}{2} H^1_\nu (ix).$$

9.212 If $\nu = n$, an integer:

$$I_n (x) = \sum_{k=0}^{\infty} \frac{1}{k!\,(n+k)!} \left(\frac{x}{2}\right)^{n+2k},$$

$$K_n (x) = i^{n+1} \frac{\pi}{2} H^I_n (x).$$

9.213

$$I_\nu (x) = \frac{1}{\sqrt{\pi}\Gamma(\nu + \frac{1}{2})} \left(\frac{x}{2}\right)^\nu \int_0^\pi \cosh (x \cos \phi) \sin^{2\nu} \phi d\phi,$$

$$K_\nu (x) = \frac{\sqrt{\pi}}{\Gamma(\nu + \frac{1}{2})} \left(\frac{x}{2}\right)^\nu \int^\infty \sinh^{2\nu} \phi e^{-x \cosh \phi} d\phi.$$

9.214 If x is large, to a first approximation:

$$I_n (x) = (2\pi x \cosh \beta)^{-\frac{1}{2}} e^{x (\cosh \beta - \beta \sinh \beta)},$$

$$K_n (x) = \pi (2\pi x \cosh \beta)^{-\frac{1}{2}} e^{-x (\cosh \beta - \beta \sinh \beta)},$$

$$n = x \sinh \beta.$$

9.215 Ber and Bei Functions.

$$\text{ber } x + i \text{ bei } x = I\,(x\sqrt{i}),$$

$$\text{ber } x - i \text{ bei } x = I_0(ix\sqrt{i}),$$

$$\text{ber } x = 1 - \frac{1}{(2!)^2}\left(\frac{x}{2}\right)^4 + \frac{1}{(4!)^2}\left(\frac{x}{2}\right)^8 - \ldots$$

$$\text{bei } x = \left(\frac{x}{2}\right)^2 - \frac{1}{(3!)^2}\left(\frac{x}{2}\right)^6 + \frac{1}{(5!)^2}\left(\frac{x}{2}\right)^{10} - \ldots$$

9.216 Ker and Kei Functions:

$$\ker x + i \operatorname{kei} x = K_0(x\sqrt{i}),$$
$$\ker x - i \operatorname{kei} x = K_0(ix\sqrt{i}),$$

$$\ker x = \left(\log \frac{2}{x} - \gamma\right) \operatorname{ber} x + \frac{\pi}{4} \operatorname{bei} x - \frac{1}{(2!)^2}\left(1 + \frac{1}{2}\right)\left(\frac{x}{2}\right)^4 + \frac{1}{(4!)^2}\left(1 + \frac{1}{2} + \frac{1}{3} + \frac{1}{4}\right)\left(\frac{x}{2}\right)^8 - \ldots$$

$$\operatorname{kei} x = \left(\log \frac{2}{x} - \gamma\right) \operatorname{bei} x - \frac{\pi}{4} \operatorname{ber} x + \left(\frac{x}{2}\right)^2 - \frac{1}{(3!)^2}\left(1 + \frac{1}{2} + \frac{1}{3}\right)\left(\frac{x}{2}\right)^6 + \ldots.$$

9.220 The Bessel-Clifford Differential Equation:

$$x\frac{d^2y}{dx^2} + (\nu + 1)\frac{dy}{dx} + y = 0.$$

With the substitution:

$$z = x^{\nu/2}y \qquad u = 2\sqrt{x},$$

the differential equation reduces to Bessel's equation.

9.221 Two independent solutions of **9.220** are:

$$C_\nu(x) = x^{-\frac{\nu}{2}} J_\nu(2\sqrt{x}) = \sum_{k=0}^{\infty} (-1)^k \frac{x^k}{k!\Gamma(\nu + k + 1)},$$

$$D_\nu(x) = x^{-\frac{\nu}{2}} Y_\nu(2\sqrt{x}).$$

9.222

$$C_{\nu+1}(x) = -\frac{d}{dx} C_\nu(x),$$

$$xC_{\nu+2}(x) = (\nu + 1)C_{\nu+1}(x) - C_\nu(x).$$

9.223 If $\nu = n$, an integer:

$$C_n(x) = (-1)^n \frac{d^n}{dx^n} C_0(x),$$

$$C_0(x) = \sum_{k=0}^{\infty} (-1)^k \frac{x^k}{(k!)^2}$$

9.224 Changing the sign of ν, the corresponding solution of:

$$x\frac{d^2y}{dx^2} - (\nu - 1)\frac{dy}{dx} + y = 0,$$

$$y = x^\nu C_\nu(x).$$

9.225 If ν is half an odd integer:

$$C_{\frac{1}{2}}(x) = \frac{\sin(2\sqrt{x} + \epsilon)}{2\sqrt{x}},$$

$$C_{\frac{3}{2}}(x) = -\frac{d}{dx} C_{\frac{1}{2}}(x) = \frac{\sin(2\sqrt{x} + \epsilon)}{4x^{\frac{3}{2}}} - \frac{\cos(2\sqrt{x} + \epsilon)}{2x},$$

$$C_{\frac{5}{2}}(x) = -\frac{d}{dx} C_{\frac{3}{2}}(x) = \frac{3 - 4x}{8x^{\frac{5}{2}}} \sin(2\sqrt{x} + \epsilon) - \frac{3\cos(2\sqrt{x} + \epsilon)}{4x^2},$$

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$$C_{-\frac{1}{2}}(x) = -\cos(2\sqrt{x} + \epsilon),$$

$$C_{-\frac{3}{2}}(x) = x^{\frac{3}{2}} C_{\frac{3}{2}}(x),$$

$$C_{-\frac{5}{2}}(x) = x^{\frac{5}{2}} C_{\frac{5}{2}}(x).$$

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ϵ is arbitrary so as to give a second arbitrary constant.

9.226 For x negative, the solution of the equation:

$$x\frac{d^2y}{dx^2} + (\pm\nu + 1)\frac{dy}{dx} - y = 0,$$

when ν is half an odd integer, is obtained from the values in **9.225** by changing sin and cos to sinh and cosh respectively.

9.227

$$(m + n + 1)\int C_{m+1}(x)C_{n+1}(x)\,dx = -xC_{m+1}(x)C_{n+1}(x) - C_m(x)C_n(x),$$

$$(m + n + 1)\int x^{m+n}C_m(x)C_n(x)\,dx = x^{m+n+1}\left\{xC_{m+1}(x)C_{n+1}(x) + C_m(x)C_n(x)\right\}.$$

9.228

1. $$\int_0^\pi C_{-\frac{1}{2}}(x\cos^2\phi)\,d\phi = \pi C_0(x).$$

2. $$\int_0^\pi C_{\frac{1}{2}}(x\cos^2\phi)\,d\phi = \pi C_1(x).$$

3. $$\int_0^\pi C_0(x\sin^2\phi)\sin\phi\,d\phi = C_{\frac{1}{2}}(x).$$

4. $$\int_0^\pi C_1(x\sin^2\phi)\sin^3\phi\,d\phi = C_{\frac{3}{2}}(x).$$

5. $$\int_0^\pi C_1(x\sin^2\phi)\sin\phi\,d\phi = \frac{1 - \cos 2\sqrt{x}}{x}.$$

9.229 Many differential equations can be solved in a simpler form by the use of the C_n functions than by the use of Bessel's functions.

(Greenhill, Phil. Mag. 38, p. 501, 1919)

9.240 The differential equation:

$$\frac{d^2y}{dx^2} + \frac{2(n+1)}{x}\frac{dy}{dx} + y = 0,$$

with the change of variable:

$$y = zx^{-n-\frac{1}{2}},$$

becomes Bessel's equation **9.200.**

9.241 Solutions of **9.240** are:

1. $$y = x^{-n-\frac{1}{2}}\, J_{n+\frac{1}{2}}(x).$$
2. $$y = x^{-n-\frac{1}{2}}\, Y_{n+\frac{1}{2}}(x).$$
3. $$y = x^{-n-\frac{1}{2}}\, H^{\mathrm{I}}_{n+\frac{1}{2}}(x).$$
4. $$y = x^{-n-\frac{1}{2}}\, H^{\mathrm{II}}_{n+\frac{1}{2}}(x).$$

9.242 The change of variable:

$$x = 2\sqrt{z},$$

transforms equation **9.240** into the Bessel-Clifford differential equation **9.220.** This leads to a general solution of **9.240:**

$$y = C_{n+\frac{1}{2}}\left(\frac{x^2}{4}\right).$$

When n is an integer the equations of **9.225** may be employed.

$$C_1\left(\frac{x^2}{4}\right) = \frac{\sin(x+\epsilon)}{x},$$

$$C_{\frac{3}{2}}\left(\frac{x^2}{4}\right) = \frac{2\sin(x+\epsilon)}{x^3} - \frac{\cos(x+\epsilon)}{x}.$$

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9.243 The solution of

$$\frac{d^2y}{dx^2} + \frac{2(n+1)}{x}\frac{dy}{dx} - y = 0,$$

may be obtained from **9.242** by writing sinh and cosh for sin and cos respectively.

9.244 The differential equation **9.240** is also satisfied by the two independent functions (when n is an integer):

$$\psi_n(x) = \left(-\frac{1}{x}\frac{d}{dx}\right)^n \frac{\sin x}{x}$$

$$= \frac{1}{1\cdot 3\cdot 5\,..\,(2n+1)}\sum_{k=0}^{\infty}(-1)^k\frac{x^{2k}}{2^k k!\,(2n+3)\,......\,(2n+2k+1)},$$

$$\Psi_n(x) = \left(-\frac{1}{x}\frac{d}{dx}\right)^n \frac{\cos x}{x}$$

$$= \frac{1\cdot 3\cdot 5\ldots(2n-1)}{x^{2n+1}} \sum_{k=0}^{\infty} (-1)^k \frac{x^{2k}}{2^k k!(1-2n)(3-2n)\ldots(2k-2n-1)}.$$

9.245 The general solution of **9.240** may be written:

$$y = \left(\frac{1}{x}\frac{d}{dx}\right)^n \frac{Ae^{ix} + Be^{-ix}}{x}.$$

9.246 Another particular solution of **9.240** is:

$$y = f_n(x) = \left(-\frac{1}{x}\frac{d}{dx}\right)^n \frac{e^{-ix}}{x} = \Psi_n(x) - i\psi_n(x),$$

$$f_n(x) = \frac{i^n e^{-ix}}{x^{n+1}}\left\{1 + \frac{n(n+1)}{2ix} + \frac{(n-1)n(n+1)(n+2)}{2\cdot 4\cdot (ix)^2} + \ldots + \frac{1\cdot 2\cdot 3\ldots 2n}{2\cdot 4\cdot 6\ldots 2n(ix)^n}\right\}.$$

9.247 The functions $\psi_n(x)$, $\Psi_n(x)$, $f_n(x)$ satisfy the same recurrence formulae:

$$\frac{d\psi_n(x)}{dx} = -x\psi_{n+1}(x),$$

$$x\frac{d\psi_n(x)}{dx} + (2n+1)\psi_n(x) = \psi_{n-1}(x).$$

9.260 The differential equation:

$$\frac{d^2y}{dx^2} - \frac{n(n+1)}{x^2}y + y = 0,$$

with the change of variable:

$$y = u\sqrt{x}$$

is transformed into Bessel's equation of order $n + \frac{1}{2}$.

9.261 Solutions of **9.260** are:

1. $$S_n(x) = \sqrt{\frac{\pi x}{2}}\, J_{n+\frac{1}{2}}(x) = x^{n+1}\left(-\frac{1}{x}\frac{d}{dx}\right)^n \frac{\sin x}{x}.$$

2. $$C_n(x) = (-1)^n\sqrt{\frac{\pi x}{2}}\, J_{-n-\frac{1}{2}}(x) = x^{n+1}\left(-\frac{1}{x}\frac{d}{dx}\right)^n \frac{\cos x}{x}.$$

3. $$E_n(x) = C_n(x) - iS_n(x) = x^{n+1}\left(-\frac{1}{x}\frac{d}{dx}\right)^n \frac{e^{-ix}}{x}.$$

9.262 The functions $S_n(x)$, $C_n(x)$, $E_n(x)$ satisfy the same recurrence formulae:

1. $$\frac{dS_n(x)}{dx} = \frac{n+1}{x}S_n(x) - S_{n+1}(x).$$

$$2.\quad \frac{dS_n(x)}{dx} = S_{n-1}(x) - \frac{n}{x}S_n(x).$$

$$3.\quad S_{n+1}(x) = \frac{2n+1}{x}S_n(x) - S_{n-1}(x).$$

9.30 The hypergeometric differential equation:

$$x(1-x)\frac{d^2y}{dx^2} + \left\{\gamma - (\alpha+\beta+1)x\right\}\frac{dy}{dx} - \alpha\beta y = 0.$$

9.31 The equation **9.30** is satisfied by the hypergeometric series:

$$F(\alpha, \beta, \gamma, x) = 1 + \frac{\alpha}{1}\frac{\beta}{\gamma}x + \frac{\alpha(\alpha+1)}{1\cdot 2}\frac{\beta(\beta+1)}{\gamma(\gamma+1)}x^2 + \frac{\alpha(\alpha+1)(\alpha+2)}{1\cdot 2\cdot 3}\frac{\beta(\beta+1)(\beta+2)}{\gamma(\gamma+1)(\gamma+2)}x^3 + \ldots\ldots$$

The series converges absolutely when $x<1$ and diverges when $x>1$. When $x=+1$ it converges only when $\alpha+\beta-\gamma<0$, and then absolutely. When $x=-1$ it converges only when $\alpha+\beta-\gamma-1<0$, and absolutely if $\alpha+\beta-\gamma<0$.

9.32

$$\frac{d}{dx}F(\alpha, \beta, \gamma, x) = \frac{\alpha\beta}{\gamma}F(\alpha+1, \beta+1, \gamma+1, x).$$

$$F(\alpha, \beta, \gamma, 1) = \frac{\Gamma(\gamma)\Gamma(\gamma-\alpha-\beta)}{\Gamma(\gamma-\alpha)\Gamma(\gamma-\beta)}.$$

9.33 Representation of various functions by hypergeometric series.

$$(1+x)^n = F(-n, \beta, \beta, -x),$$

$$\log(1+x) = xF(1, 1, 2, -x),$$

$$e^x = \underset{\beta=\infty}{\text{Limit}}\, F\left(1, \beta, 1, \frac{x}{\beta}\right),$$

$$(1 + x)^n + (1 - x)^n = 2\,F\left(-\frac{n}{2}, -\frac{n}{2} + \frac{1}{2}, \frac{1}{2}, x^2\right),$$

$$\log\frac{1 + x}{1 - x} = 2xF\left(\frac{1}{2}, 1, \frac{3}{2}, x^2\right),$$

$$\cos nx = F\left(\frac{n}{2}, -\frac{n}{2}, \frac{1}{2}, \sin^2 x\right),$$

$$\sin nx = n\sin xF\left(\frac{n+1}{2}, \frac{1-n}{2}, \frac{3}{2}, \sin^2 x\right),$$

$$\cosh x = \underset{\alpha = \beta = \infty}{\text{Limit}} F\left(\alpha, \beta, \frac{1}{2}, \frac{x^2}{4\alpha\beta}\right),$$

$$\sin^{-1} x = xF\left(\frac{1}{2}, \frac{1}{2}, \frac{3}{2}, x^2\right),$$

$$\tan^{-1} x = xF\left(\frac{1}{2}, 1, \frac{3}{2}, -x^2\right),$$

$$P_n(x) = F\left(-n, n+1, 1, \frac{1-x}{2}\right),$$

$$Q_n(x) = \frac{\sqrt{\pi}\,\Gamma(n+1)}{2^{n+1}\Gamma\left(n+\frac{3}{2}\right)}\frac{1}{x^{n+1}}F\left(\frac{n+1}{2}, \frac{n+2}{2}, n+\frac{3}{2}, \frac{1}{x^2}\right).$$

9.4 Heaviside's Operational Methods of Solving Partial Differential Equations.

9.41 The partial differential equation,

$$a\frac{\partial^2 u}{\partial x^2} = \frac{\partial u}{\partial t},$$

where a is a constant, may be solved by Heaviside's operational method.

Writing $\frac{\partial}{\partial t} = p$, and $\frac{p}{a} = q^2$, the equation becomes,

$$\frac{\partial^2 u}{\partial x^2} = q^2 u,$$

whose complete solution is $u = e^{qx}A + e^{-qx}B$, where A and B are integration constants to be determined by the boundary conditions. In many applications the solution $u = e^{-qx}B$, only, is required: and the boundary conditions will lead to $u = e^{-qx}f(q)u_0$, where u_0 is a constant. If $e^{-qx}f(q)$ be expanded in an infinite power series in q, and the integral and fractional, positive and negative powers of p be interpreted as in **9.42,** the resulting series will be a solution of the differential equation, satisfying the boundary conditions, and reducing to $u = 0$ at $t = 0$. The expansion of $e^{-qx}f(q)$ may be carried out in two or more ways, leading to series suitable for numerical calculation under different conditions.

9.42 Fractional Differentiation and Integration.

In the following expressions, 1 stands for a function of t which is zero up to $t = 0$, and equal to 1 for $t>0$.

9.421

$$p^{\frac{1}{2}}1 = \frac{1}{\sqrt{\pi t}}$$

$$p^{\frac{3}{2}}1 = \frac{1}{2t\sqrt{\pi t}} \qquad p^{\frac{2n+1}{2}}1 = (-1)^n \frac{1\cdot 3\cdot 5\ \ldots\ (2n-1)}{2^n t^n \sqrt{\pi t}}$$

$$p^{\frac{5}{2}}1 = \frac{3}{2^2 t^2 \sqrt{\pi t}}$$

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9.422

$$p\,1 = 0$$
$$p^2 1 = 0 \qquad p^n 1 = 0$$
$$p^3 1 = 0$$

. . .

. . .

9.423

$$p^{-\frac{1}{2}} = 2\sqrt{\frac{t}{\pi}}$$

$$p^{-\frac{3}{2}} = \frac{2^2 t}{3}\sqrt{\frac{t}{\pi}} \qquad p^{-\frac{2n+1}{2}}1 = \frac{2^{2n-1}t^n}{1\cdot 3\cdot 5\ \ldots\ (2n+1)}\sqrt{\frac{t}{\pi}}$$

$$p^{-\frac{5}{2}} = \frac{2^3 t^2}{3\cdot 5}\sqrt{\frac{t}{\pi}}$$

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9.424

$$\frac{1}{p^\nu} = \frac{t^\nu}{\Gamma(1+\nu)},$$

where ν may have any real value, except a negative integer. (Conjectural.)

9.425

$$\frac{p}{p-a}1 = e^{at}$$

$$\frac{1}{p-a}1 = \frac{1}{a}(e^{at}-1)$$

9.426 With $p = aq^2$,

$$q^{2n+1}1 = (-1)^n \frac{1\cdot 3\cdot 5\ \ldots\ (2n-1)}{(2at)^n\sqrt{\pi at}}$$

$$q^{-2n}1 = \frac{(at)^n}{n!}.$$

9.427

$$qe^{-qx}1 = \frac{1}{\sqrt{\pi at}} e^{-\frac{x^2}{4at}}$$

9.428 If $z = \dfrac{x}{2\sqrt{at}}$,

$$e^{-qx} = \frac{2}{\sqrt{\pi}} \int_z^\infty e^{-v^2} dv$$

$$\frac{1}{q} e^{-qx} = \frac{x}{\sqrt{\pi}} \int_z^\infty e^{-v^2} \frac{dv}{v^2}.$$

9.43 Many examples of the use of this method are given by Heaviside: Electromagnetic Theory, Vol. II. Bromwich, Proceedings Cambridge Philosophical Society, XX, p. 411, 1921, has justified its application by the method of contour integration and applied it to the solution of a problem in the conduction of heat.

9.431 Herlitz, Arkiv for Matematik, Astronomi och Fysik, XIV, 1919, has shown that the same methods may be applied to the more general partial differential equations of the type,

$$\sum_{\alpha, \beta} A_{\alpha, \beta}(x) \frac{\partial^{\alpha+\beta}(u)}{\partial x^\alpha \, \partial t^\beta} = 0,$$

and the relations of **9.42** are valid.

9.44 Heaviside's Expansion Theorem.

The operational solution of the differential equation of **9.41,** or the more general equation, **9.431,** satisfying the given boundary conditions, may be written in the form,

$$u = \frac{F(p)}{\Delta(p)} u_0,$$

where $F(p)$ and $\Delta(p)$ are known functions of $p = \dfrac{\partial}{\partial t}$. Then Heaviside's Expansion Theorem is:

$$u = u_0 \left\{ \frac{F(0)}{\Delta(0)} + \sum \frac{F(\alpha)}{\alpha \Delta'(\alpha)} e^{\alpha t} \right\},$$

where α is any root, except 0, of $\Delta(p) = 0$, $\Delta'(p)$ denotes the first derivative of $\Delta(p)$ with respect to p, and the summation is to be taken over all the roots of $\Delta(p) = 0$. This solution reduces to $u = 0$ at $t = 0$.

Many applications of this expansion theorem are given by Heaviside, Electromagnetic Theory, II, and III; Electrical Papers, Vol. II. Herlitz, **9.431,** has also applied this expansion theorem to the solution of the problem of the distribution of magnetic induction in cylinders and plates.

9.45 Bromwich's Expansion Theorem. Bromwich has extended Heaviside's Expansion Theorem as follows. If the operational solution of the partial differential equation of **9.41,** obtained to satisfy the boundary conditions, is

$$u = \frac{F(p)}{\Delta(p)} (Gt)$$

where G is a constant, then the solution of the differential equation is

$$u = G\left\{N_0 t + N_1 + \sum \frac{F(\alpha)}{\alpha^2 \Delta'(\alpha)} e^{\alpha t}\right\},$$

where N_0 and N_1 are defined by the expansion,

$$\frac{F(p)}{\Delta(p)} = N_0 + N_1 p + N_2 p^2 + \ldots;$$

α is any root of $\Delta(p) = 0$, $\Delta'(p)$ is the first derivative of $\Delta(p)$ with respect to p, and the summation is over all the roots, α. This solution reduces to $u = 0$ at $t = 0$. Phil. Mag. 37, p. 407, 1919; Proceedings London Mathematical Society, 15, p. 401, 1916.

9.9 References to Bessel Functions.

Nielsen: Handbuch der Theorie der Cylinder Funktionen.
Leipzig, 1904.

The notation and definitions given by Nielsen have been adopted in the present collection of formulae. The only difference is that Nielsen uses an upper index, $J^n(x)$, to denote the order, where the more usual custom of writing $J_n(x)$ is here employed. In place of H_1^n and H_2^n used by Nielsen for the cylinder functions of the third kind, H_n^{I} and H_n^{II} are employed in this collection.

Gray and Mathews: Treatise on Bessel Functions.
London, 1895.[1]

The Bessel Function of the second kind, $Y_n(x)$, employed by Gray and Mathews is the function

$$\frac{\pi}{2} Y_n(x) + (\log 2 - \gamma) J_n(x),$$

of Nielsen.

Schafheitlin: Die Theorie der Besselschen Funktionen.
Leipzig, 1908.

Schafheitlin defines the function of the second kind, $Y_n(x)$, in the same way as Nielsen, except that its sign is changed.

NOTE. A Treatise on the Theory of Bessel Functions, by G. N. Watson, Cambridge University Press, 1922, has been brought out while this volume is in press. This Treatise gives by far the most complete account of the theory and properties of Bessel Functions that exists, and should become the standard work on the subject with respect to notation. A particularly valuable feature is the Collection of Tables of Bessel Functions at the end of the volume and the Bibliography, giving references to all the important works on the subject.

9.91 Tables of Legendre, Bessel and allied functions.

$P_n(x)$ **(9.001)**.

[1] A second edition of Gray and Mathews' Treatise, prepared by A. Gray and T. M. MacRobert, has been published (1922) while this volume is in press. The notation of the first edition has been altered in some respects.

B. A. Report, 1879, pp. 54–57. Integral values of n from 1 to 7; from $x = 0.01$ to $x = 1.00$, interval 0.01, 16 decimal places.

Jahnke and Emde: Funktionentafeln, p. 83; same to 4 decimal places.

$P_n(\cos\theta)$

Phil. Trans. Roy. Soc. London, 203, p. 100, 1904. Integral values of n from 1 to 20, from $\theta = 0$ to $\theta = 90$, interval 5, 7 decimal places.

Phil. Mag. 32, p. 512, 1891. Integral values of n from 1 to 7, $\theta = 0$ to $\theta = 90$, interval 1; 4 decimal places. Reproduced in Jahnke and Emde, p. 85.

Tallquist, Acta Soc. Sc. Fennicae, Helsingfors, 33, pp. 1–8. Integral values of n from 1 to 8; $\theta = 0$ to $\theta = 90$, interval 1, 10 decimal places.

Airey, Proc. Roy. Soc. London, 96, p. 1, 1919. Tables by means of which zonal harmonics of high order may be calculated.

Lodge, Phil. Trans. Roy. Soc. London, 203, 1904, p. 87. Integral values of n from 1 to 20; $\theta = 0$ to $\theta = 90$, interval 5, 7 decimal places. Reprinted in Rayleigh, Collected Works, Volume V, p. 162.

$\dfrac{\partial P_n(\cos\theta)}{\partial\theta}$.

Farr, Proc. Roy. Soc. London, 64, 199, 1899. Integral values of n from 1 to 7; $\theta = 0$ to $\theta = 90$, interval 1, 4 decimal places. Reproduced in Jahnke and Emde, p. 88.

$J_0(x)$, $J_1(x)$ (**9.101**).

Meissel's tables, $x = 0.01$ to $x = 15.50$, interval 0.01, to 12 decimal places, are given in Table I of Gray and Mathews' Treatise on Bessel's Functions.

Aldis, Proc. Roy. Soc. London 66, 40, 1900. $x = 0.1$ to $x = 6.0$, interval 0.1, 21 decimal places.

Jahnke and Emde, Funktionentafeln, Table III. $x = 0.01$ to $x = 15.50$, interval 0.01, 4 decimal places.

$J_n(x)$ (**9.101**).

Gray and Mathews, Table II. Integral values of n from $n = 0$ to $n = 60$; integral values of x from $x = 1$ to $x = 24$, 18 decimal places.

Jahnke and Emde, Table XXIII, same, to 4 significant figures.

B. A. Report, 1915, p. 29; $n = 0$ to $n = 13$.

$x = 0.2$ to $x = 6.0$	interval 0.2	6 decimal places,
$x = 6.0$ to $x = 16.0$	interval 0.5	10 decimal places.

Hague, Proc. London Physical Soc. 29, 211, 1916–17, gives graphs of $J_n(x)$ for integral values of n from 0 to 12, and $n = 18$, x ranging from 0 to 17.

$-\frac{\pi}{2} Y_0(x) = G_0(x)$; $-\frac{\pi}{2} Y_1(x) = G_1(x)$.

B. A. Report, 1913, pp. 116–130. $x = 0.01$ to $x = 16.0$, interval 0.01, 7 decimal places.

B. A. Report, 1915, $x = 6.5$ to $x = 15.5$, interval 0.5, 10 decimal places.

Aldis, Proc. Roy. Soc. London, 66, 40, 1900: $x = 0.1$ to $x = 6.0$. Interval 0.1, 21 decimal places.

Jahnke and Emde, Tables VII and VIII, functions denoted $K_0(x)$ and $K_1(x)$, $x = 0.1$ to $x = 6.0$, interval 0.1; $x = 0.01$ to $x = 0.99$, interval 0.01; $x = 1.0$ to $x = 10.3$, interval 0.1; 4 decimal places.

$$-\frac{\pi}{2} Y_n(x) = G_n(x).$$

B. A. Report, 1914, p. 83. Integral values of n from 0 to 13. $x = 0.01$ to $x = 6.0$, interval 0.1; $x = 6.0$ to $x = 16.0$, interval 0.5; 5 decimal places.

$$\frac{\pi}{2} Y_0(x) + (\log 2 - \gamma)J_0(x),$$ Denoted $Y_0(x)$ and $Y_1(x)$

$$\frac{\pi}{2} Y_1(x) + (\log 2 - \gamma)J_1(x).$$ respectively in the tables.

B. A. Report, 1914, p. 76, $x = 0.02$ to $x = 15.50$, interval 0.02, 6 decimal places.

B. A. Report, 1915, p. 33, $x = 0.1$ to $x = 6.0$, interval 0.1; $x = 6.0$ to $x = 15.5$, interval 0.5, 10 decimal places.

Jahnke and Emde, Table VI, $x = 0.01$ to $x = 1.00$, interval 0.01; $x = 1.0$ to $x = 10.2$, interval 0.1, 4 decimal places.

$Y_0(x)$, $Y_1(x)$. Denoted $N_0(x)$ and $N_1(x)$ respectively.

Jahnke and Emde, Table IX, $x = 0.1$ to $x = 10.2$, interval 0.1, 4 decimal places.

$$\frac{\pi}{2} Y_n(x) + (\log 2 - \gamma)\, J_n(x).$$ Denoted $Y_n(x)$ in tables.

B. A. Report, 1915. Integral values of n from 1 to 13. $x = 0.2$ to $x = 6.0$, interval 0.2; $x = 6.0$ to $x = 15.5$, interval 0.5, 6 decimal places.

$J_{n+\frac{1}{2}}(x)$.

Jahnke and Emde, Table II. Integral values of n from $n = 0$ to $n = 6$, and $n = -1$ to $n = -7$; $x = 0$ to $x = 50$, interval 1.0, 4 figures.

$J_{\frac{1}{3}}(x)$, $J_{-\frac{1}{3}}(x)$.

Watson, Proc. Roy. Soc. London, 94, 204, 1918.

$x = 0.05$ to $x = 2.00$ interval 0.05,
$x = 2.0$ to $x = 8.0$ interval 0.2,

4 decimal places.

$J_\alpha(\alpha)$, $J_{\alpha-1}(\alpha)$

$$-\frac{\pi}{2}Y_\alpha(\alpha),\ -\frac{\pi}{2} Y_{\alpha-1}(\alpha).$$ Denoted $G_\alpha(\alpha)$ and $G_{\alpha-1}(\alpha)$ respectively.

$\frac{\pi}{2} Y_\alpha(\alpha) + (\log 2 - \gamma)J_\alpha(\alpha),$

$\frac{\pi}{2} Y_{\alpha-1}(\alpha) + (\log 2 - \gamma)J_{\alpha-1}(\alpha).$ Denoted $-Y_\alpha(\alpha)$ and $-Y_{\alpha-1}(\alpha)$.

Tables of these six functions are given in the B. A. Report, 1916, as follows:

From α	to α	Interval
1	50	1.
50	100	5
100	200	10
200	400	20
400	1000	50
1000	2000	100
2000	5000	500
5000	20000	1000
20000	30000	10000

100,000
500,000
1,000,000

$I_0(x)$, $I_1(x)$ **(9.211)**.

Aldis, Proc. Roy. Soc. London, 64, pp. 218–223, 1899; $x = 0.1$ to $x = 6.0$, interval 0.1; $x = 6.0$ to $x = 11.0$, interval 1.0, 21 decimal places.

Jahnke and Emde, Tables XI and XII, 4 places:

$x = 0.01$ to $x = 5.10$. interval 0.01,
$x = 5.10$ to $x = 6.0$ interval 0.1,
$x = 6.0$ to $x = 11.0$ interval 1.0.

$\mathrm{I}_0(x)$ **(9.211)**.

B. A. Report, 1896; $x = 0.001$ to $x = 5.100$, interval 0.001, 9 decimal places.

$\mathrm{I}_1(x)$ **(9.211)**.

B. A. Report, 1893; $x = 0.001$ to $x = 5.100$, interval 0.001, 9 decimal places.

Gray and Mathews, Table V, $x = 0.01$ to $x = 5.10$, interval 0.01, 9 decimal places.

$\mathrm{I}_n(x)$ **(9.211)**.

B. A. Report, 1889, pp. 28–32; integral values of n from 0 to 11, $x = 0.2$ to $x = 6.0$, interval 0>2, 12 decimal places. These tables are reproduced in Gray and Mathews, Table VI.

Jahnke and Emde, Table XXIV; same ranges, to 4 places.

$J_0(x\sqrt{i}) = X - iY,$

$\sqrt{2}J_1(x\sqrt{i}) = X_1 + iY_1$

Aldis, Proc. Roy. Soc. London, 66, 142, 1900; $x = 0.1$ to $x = 6.0$, interval 0.1, 21 decimal places.

Jahnke and Emde, Tables XV and XVI, same range, to 4 places.

$J_0(x\sqrt{i})$.

Gray and Mathews, Table IV; $x = 0.2$ to $x = 6.0$, interval 0.2, 9 decimal places.

$Y_0(x\sqrt{i})$ **(9.104)** Denoted $N_0(x\sqrt{i})$ in table.

$H_0^{\mathrm{I}}(x\sqrt{i})$, $H_1^{\mathrm{I}}(x\sqrt{i})$.

Jahnke and Emde, Tables XVII and XVIII; $x = 0.2$ to $x = 6.0$, interval 0.2, 4–7 figures.

$$\left.\begin{aligned} \frac{i\pi}{2} H_0^{\mathrm{I}}(ix) &= K_0(x), \\ -\frac{\pi}{2} H_0^{\mathrm{I}}(ix) &= K_1(x), \end{aligned}\right\} \quad \textbf{(9.212)}.$$

Aldis, Proc. Roy. Soc. London, 64, 219–223, 1899; $x = 0.1$ to $x = 12.0$, interval 0.1, 21 decimal places.

Jahnke and Emde, Table XIV; same, to 4 places.

$iH_0^{\mathrm{I}}(ix)$, $-H_0^{\mathrm{I}}(ix)$ **(9.107)**.

Jahnke and Emde, Table XIII; $x = 0.12$ to $x = 6.0$, interval 0.2, 4 figures.

$$\left.\begin{aligned} &\operatorname{ber} x,\ \operatorname{ber}' x, \\ &\operatorname{bei} x,\ \operatorname{bei}' x, \end{aligned}\right\} \quad \textbf{(9.215)}.$$

B. A. Report, 1912; $x = 0.1$ to $x = 10.0$, interval 0.1, 9 decimal places.

Jahnke and Emde, Table XX; $x = 0.5$ to $x = 6.0$, interval 0.5, and $x = 8$, 10, 15, 20, 4 decimal places.

$$\left.\begin{aligned} &\operatorname{ker} x,\ \operatorname{ker}' x, \\ &\operatorname{kei} x,\ \operatorname{kei}' x, \end{aligned}\right\} \quad \textbf{(9.216)}.$$

B. A. Report, 1915; $x = 0.1$ to $x = 10.0$, interval 0.1, 7–10 decimal places.

$$\begin{aligned} &\operatorname{ber}^2 x + \operatorname{bei}^2 x, \\ &\operatorname{ber}'^2 x + \operatorname{bei}'^2 x, \\ &\operatorname{ber} x \operatorname{bei}' x - \operatorname{bei} x \operatorname{ber}' x, \\ &\operatorname{ber} x \operatorname{ber}' x + \operatorname{bei} x \operatorname{bei}' x, \end{aligned}$$

and the corresponding ker and kei functions.

B. A. Report, 1916; $x = 0.2$ to $x = 10.0$, interval 0.2, decimal places.

$$\left.\begin{aligned} &S_n(x),\ S'_n(x),\ \log S_n(x),\ \log S'_n(x), \\ &C_n(x),\ C'_n(x),\ \log C_n(x),\ \log C'_n(x), \\ &E_n(x),\ E'_n(x),\ \log E_n(x),\ \log E'_n(x), \end{aligned}\right\} \quad \textbf{(9.261)}.$$

B. A. Report, 1916; integral values of n from 0 to 10, $x = 1.1$ to $x = 1.9$, interval 0.1, 7 decimal places.

$$G(x) = -\sqrt{2}\,\Pi\left(\frac{1}{4}\right) x^{-\frac{1}{4}} J_{\frac{1}{4}}\left(\frac{x}{2}\right) = -\frac{1}{0.78012}\, x^{-\frac{1}{4}} J_{\frac{1}{4}}\left(\frac{x}{2}\right)$$

$$D(x) = \frac{1}{\sqrt{2}}\,\Pi\left(-\frac{1}{4}\right) x^{\frac{1}{4}} J_{-\frac{1}{4}}\left(\frac{x}{2}\right) = \frac{1}{1.15407}\, x^{\frac{1}{4}} J_{-\frac{1}{4}}\left(\frac{x}{2}\right)$$

Table I of Jahnke and Emde gives these two functions to 3 decimal places for $x = 0.2$ to $x = 8.0$, interval 0.2, and $x = 8.0$ to $x = 12.0$, interval 1.0.

Roots of $J_0(x) = 0$.

Airey, Phil. Mag. 36, p. 241, 1918: First 40 roots (ρ) with corresponding values of $J_1(\rho)$, 7 decimal places.

Jahnke and Emde, Table IV, same, to 4 decimal places.

Roots of $J_1(x) = 0$.

Gray and Mathews, Table III, first 50 roots, with corresponding values of $J_0(x)$, 16 decimal places.

Airey, Phil. Mag. 36, p. 241: First 40 roots (r) with corresponding values of $J_0(r)$, 7 decimal places.

Jahnke and Emde, Table IV, same, to 4 decimal places.

Roots of $J_n(x) = 0$.

B. A. Report, 1917, first 10 roots, to 6 figures, for the following integral values of n: 0–10, 15, 20, 30, 40, 50, 75, 100, 200, 300, 400, 500, 750, 1000.

Jahnke and Emde, Table XXII, first 9 roots, 3 decimal places, integral values of n 0–9.

Roots of:

$(\log 2 - \gamma)J_n(x) + \frac{\pi}{2} Y_n(x) = 0.$ Denoted $Y_n(x) = 0$ in table.

Airey: Proc. London Phys. Soc. 23, p. 219, 1910–11. First 40 roots for $n = 0, 1, 2$, 5 decimal places.

Jahnke and Emde, Table X, first 4 roots for $n = 0, 1$. E decimal places.

Roots of:

$Y_0(x) = 0,$

$Y_1(x) = 0.$ Denoted $N_0(x)$ and $N_1(x)$ in tables.

Airey: l. c. First 10 roots, 5 decimal places.

Roots of:

$J_0(x) \pm (\log 2 - \gamma)J_0(x) + \frac{\pi}{2} Y_0(x) = 0.$ Denoted $J_0(x) \pm Y_0(x) = 0.$

$J_1(x) + (\log 2 - \gamma)J_1(x) + \frac{\pi}{2} Y_1(x) = 0.$ Denoted $J_1(x) + Y_1(x) = 0.$

$J_0(x) - 2(\log 2 - \gamma)J_0(x) + \frac{\pi}{2} Y_0(x) = 0.$ Denoted $J_0(x) - 2Y_0(x) = 0.$

$10J_0(x) \pm (\log 2 - \gamma)J_0(x) + \frac{\pi}{2} Y_0(x) = 0.$ Denoted $10J_0(x) \pm Y_0(x) = 0.$

Airey, l. c. First 10 roots, 5 decimal places.

Roots of

$$\frac{J_{n+1}(x)}{J_n(x)} + \frac{I_{n+1}(x)}{I_n(x)} = 0.$$

Airey, l. c. First 10 roots: $n = 0$, 4 decimal places, $n = 1, 2, 3$, 3 decimal places.

Jahnke and Emde, Table XXV, first 5 roots for $n = 0$, 3 for $n = 1$, 2 for $n = 2$: 4 figures.

Airey, l. c. gives roots of some other equations involving Bessel's functions connected with the vibration of circular plates.

Roots of:

$$J_\nu(x) Y_\nu(x) = J_\nu(kx) Y_\nu(kx).$$

Jahnke and Emde, Table XXVI, first 6 roots, 4 decimal places, for $\nu = 0, 1/2, 1, 3/2, 2, 5/2$: $k = 1.2, 1.5, 2.0$.

Table XXVIII, first root, multiplied by $(k - 1)$ for $k = 1, 1.2, 1.5, 2-11, 19, 39, \infty$: ν same as above.

Table XXIX, first 4 roots, multiplied by $(k - 1)$ for certain irrational values of k, and $\nu = 0, 1$.

X. NUMERICAL SOLUTION OF DIFFERENTIAL EQUATIONS

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INTRODUCTION

Differential equations are usually first encountered in the final chapter of a book on integral calculus. The methods which are there given for solving them are essentially the same as those employed in the calculus. Similar methods are used in the first special work on the subject. That is, numerous types of differential equations are given in which the variables can be separated by suitable devices; little or nothing is said about the existence of solutions of other types, or about methods of finding the solutions. The false impression is often left that only exceptionally can differential equations be solved. Whatever satisfaction there may be in learning that some problems in geometry and physics lead to standard forms of differential equations is more than counterbalanced by the discovery that most practical problems do not lead to such forms.

10.01 The point of view adopted here and the methods which are developed can be best understood by considering first some simpler and better known mathematical theories. Suppose

1. $$F(x) = x^n + a_1 x^{n-1} + \ldots\ldots + a_{n-1}x + a_n = 0$$

is a polynomial equation in x having real coefficients $a_1, a_2, \ldots, a_n$. If n is 1, 2, 3, or 4 the values of x which satisfy the equation can be expressed as explicit functions of the coefficients. If n is greater than 4, formulas for the solution can not in general be written down. Nevertheless, it is possible to prove that n solutions exist and that at least one of them is real if n is odd. If the coefficients are given numbers, there are straightforward, though somewhat laborious, methods of finding the solutions. That is, even though general formulas for the solutions are not known, yet it is possible both to prove the existence of the solutions and also to find them in any special numerical case.

10.02 Consider as another illustration the definite integral

1. $$I = \int_a^b f(x)\, dx,$$

where $f(x)$ is continuous for $a \leqslant x \leqslant b$. If $F(x)$ is such a function that

2. $$\frac{dF}{dx} = f(x),$$

then $I = F(b) - F(a)$. But suppose no $F(x)$ can be found satisfying (2). It is nevertheless possible to prove that the integral I exists, and if the value of (x) is given for every value of x in the interval $a \leqslant x \leqslant b$, it is possible to find the numerical value of I with any desired degree of approximation. That is, it is not necessary that the primitive of the integrand of a definite integral be known in order to prove the existence of the integral, or even to find its value in any particular example.

10.03 The facts are analogous in the case of differential equations. Those having numerical coefficients and prescribed initial conditions can be solved regardless of whether or not their variables can be separated. They need to satisfy only mild conditions which are always fulfilled in physical problems. It is with a sense of relief that one finds he can solve, numerically, any particular problem which can be expressed in terms of differential equations.

10.04 This chapter will contain an account of a method of solving ordinary differential equations which is applicable to a broad class including all those which arise in physical problems. A large amount of experience has shown that the method is very convenient in practice. It must be understood that there is for it an underlying logical basis, involving refinements of modern analysis, which fully justifies the procedure. In other words, it can be proved that the process is capable of furnishing the solution with any desired degree of accuracy. The proofs of these facts belong to the domain of pure analysis and will not be given here.

10.10 Simpson's Method of Computing Definite Integrals. The method of solving differential equations which will be given later involves the computation of definite integrals by a special process which will be developed in this and the following sections.

Let t be the variable of integration, and consider the definite integral

1. $$F = \int_a^b f(t)\,dt.$$

This integral can be interpreted as the area between the t-axis and the curve $y = f(t)$ and bounded by the ordinates $t = a$ and $t = b$, figure 1.

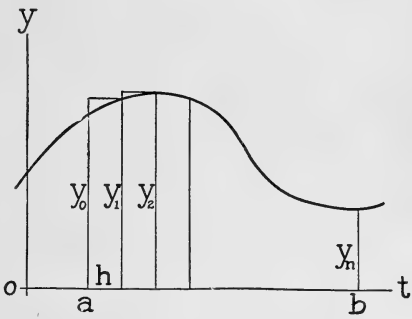

FIG. 1

Let $t_0 = a$, $t_n = b$, $y_i = f(t_i)$, and divide the interval $a \leqslant t \leqslant b$ up into n equal parts, each of length $h = (b - a)/n$. Then an approximate value of F is

2. $$F_0 = h(y_1 + y_2 + \ldots + y_n).$$

This is the sum of rectangles whose ordinates, figure 1, are $y_1, y_2, \ldots, y_n$.

10.11 A more nearly exact value can be obtained for the first two intervals, for example, by putting a curve of the second degree through the three points

y_0, y_1, y_2, and finding the area between the t-axis and this curve and bounded by the ordinates t_0 and t_2. The equation of the curve is

1. $$y = a_0 + a_1(t - t_0) + a_2(t - t_0)^2,$$

where the coefficients a_0, a_1, and a_2 are determined by the conditions that y shall equal y_0, y_1, and y_2 at t equal to t_0, t_1 and t_2 respectively; or

2. $$\begin{cases} y_0 = a_0, \\ y_1 = a_0 + a_1(t_1 - t_0) + a_2(t_1 - t_0)^2, \\ y_2 = a_0 + a_1(t_2 - t_0) + a_2(t_2 - t_0)^2. \end{cases}$$

It follows from these equations and $t_2 - t_1 = t_1 - t_0 = h$ that

3. $$\begin{cases} a_0 = y_0, \\ a_1 = -\dfrac{1}{2h}(3y_0 - 4y_1 + y_2), \\ a_2 = \dfrac{1}{2h^2}(y_0 - 2y_1 + y_2). \end{cases}$$

The definite integral $\int_{t_0}^{t_2} ydt$ is approximately

$$I = \int_{t_0}^{t_2}\left[a_0 + a_1(t - t_0) + a_2(t - t_0)^2\right] dt = 2h\left[a_0 + a_1h + \frac{4}{3}\,a_2h^2\right],$$

which becomes as a consequence of (3)

4. $$I = \frac{h}{3}\,(y_0 + 4y_1 + y_2).$$

10.12 The value of the integral over the next two intervals, or from t_2 to t_4, can be computed in the same way. If n is even, the approximate value of the integral from t_0 to t_n is therefore

$$F_1 = \frac{h}{3}\,[y_0 + 4y_1 + 2y_2 + 4y_3 + 2y_4 + \cdots\cdots + 4y_{n-1} + y_n].$$

This formula, which is due to Simpson, gives results which are usually remarkably accurate considering the simplicity of the arithmetical operations.

10.13 If a curve of the third degree had been passed through the four points y_0, y_1, y_2, and y_3, the integral corresponding to (4), but over the first three intervals, would have been found to be

$$I = \frac{3h}{8}\,[y_0 + 3y_1 + 3y_2 + y_3].$$

10.20 Digression on Difference Functions. For later work it will be necessary to have some properties of the successive differences of the values of a function for equally spaced values of its argument.

As before, let y_i be the value of $f(t)$ for $t = t_i$. Then let

$$
\begin{aligned}
\Delta_1 y_1 &= y_1 - y_0, \\
\Delta_1 y_2 &= y_2 - y_1, \\
&\cdots\cdots \\
\Delta_1 y_n &= y_n - y_{n-1}, \\
&\cdots\cdots\cdots\cdots
\end{aligned}
$$

These are the first differences of the values of the function y for successive values of t. All the successive intervals for t are supposed to be equal.

10.21 In a similar way the second differences are defined by

$$
\begin{aligned}
\Delta_2 y_2 &= \Delta_1 y_2 - \Delta_1 y_1, \\
\Delta_2 y_3 &= \Delta_1 y_3 - \Delta_1 y_2, \\
&\cdots\cdots\cdots\cdots \\
\Delta_2 y_n &= \Delta_1 y_n - \Delta_1 y_{n-1}, \\
&\cdots\cdots\cdots\cdots
\end{aligned}
$$

10.22 In a similar way third differences are defined by

$$
\begin{aligned}
\Delta_3 y_3 &= \Delta_2 y_3 - \Delta_2 y_2, \\
\Delta_3 y_4 &= \Delta_2 y_4 - \Delta_2 y_3, \\
&\cdots\cdots \\
\Delta_3 y_n &= \Delta_2 y_n - \Delta_2 y_{n-1}, \\
&\cdots\cdots\cdots\cdots,
\end{aligned}
$$

and obviously the process can be repeated as many times as may be desired.

10.23 The table of successive differences can be formed conveniently from the tabular values of the function and can be arranged in a table as follows:

TABLE I

y	$\Delta_1 y$	$\Delta_2 y$	$\Delta_3 y$
y_0			
y_1	$\Delta_1 y_1$		
y_2	$\Delta_1 y_2$	$\Delta_2 y_2$	
y_3	$\Delta_1 y_3$	$\Delta_2 y_3$	$\Delta_3 y_3$
....	....	....	....

In this table the numbers in each column are subtracted from those immediately below them and the remainders are placed in the next column to the right on the same line as the minuends. Variations from this precise arrangement could be, and indeed often have been, adopted.

10.24 A very important advantage of a table of differences is that it is almost sure to reveal any errors that may have been committed in computing the y_i. If a single y_i has an error ϵ, it follows from **10.20** that the first difference $\Delta_1 y_i$ will contain the error $+\epsilon$ and $\Delta_1 y_{i+1}$ will contain the error $-\epsilon$. But the second differences $\Delta_2 y_i$, $\Delta_2 y_{i+1}$, and $\Delta_2 y_{i+2}$ will contain the respective errors $+\epsilon$, -2ϵ, $+\epsilon$. Similarly, the third differences $\Delta_3 y_i$, $\Delta_3 y_{i+1}$, $\Delta_3 y_{i+2}$, and $\Delta_3 y_{i+3}$ will contain the respective errors $+\epsilon$, -3ϵ, $+3\epsilon$, $-\epsilon$. An error in a single y_i affects $j + 1$ differences of order j, and the coefficients of the error are the binomial coefficients with alternating signs. The algebraic sums of the errors in the affected numbers in the various difference columns are zero. Now in such functions as ordinarily occur in practice the numerical values of the differences, if the intervals are not too great, decrease with rapidity and run smoothly. If an error is present, however, the differences of higher order become very irregular.

10.25 As an illustration, consider the function $y = \sin t$ for t equal to $10°$, $15°$, ... The following table gives the function and its successive differences, expressed in terms of units of the fourth decimal:[1]

TABLE II

t	$\sin t$	$\Delta_1 \sin t$	$\Delta_2 \sin t$	$\Delta_3 \sin t$
10°	1736			
15	2588	852		
20	3420	832	−20	
25	4226	806	−26	−6
30	5000	774	−32	−6
35	5736	736	−38	−6
40	6428	692	−44	−6
45	7071	643	−49	−5
50	7660	589	−54	−5
55	8191	531	−58	−4
60	8660	469	−62	−4
65	9063	403	−66	−4
70	9397	334	−69	−3

Suppose, however, that an error of two units had been made in determining the sine of 45° and that 7073 had been taken in place of 7071. Then the part of the table adjacent to this number would have been the following:

TABLE III

t	$\sin t$	$\Delta_1 \sin$	$\Delta_2 \sin t$	$\Delta_3 \sin t$
25°	4226			
30	5000	774		
35	5736	736	−38	
40	6428	692	−44	− 6
45	7073	645	−47	− 3
50	7660	587	−58	−11
55	8191	531	−56	+ 2
60	8660	469	−62	− 6
65	9063	403	−66	− 4

The irregularity in the numbers of the last column shows the existence of an error, and, in fact, indicates its location. In the third differences four numbers

[1] Often it is not necessary to carry along the decimal and zeros to the left of the first significant figure.

will be affected by an error in the value of the function. The erroneous numbers in the last column are clearly the second, third, fourth, and fifth. The algebraic sum of these four numbers equals the sum of the four correct numbers, or -18. Their average is -4.5. Hence the central numbers are probably -5 and -4. Since the errors in these numbers are -3ϵ and $+3\epsilon$, it follows that ϵ is probably $+2$. The errors in the second and fifth numbers are $+\epsilon$ and $-\epsilon$ respectively. On making these corrections and working back to the first column, it is found that 7073 should be replaced by 7071.

10.30 Computation of Definite Integrals by Use of Difference Functions.

Suppose the values of $f(t)$ are known for $t = t_{n-2}, t_{n-1}, t_n$, and t_{n+1}. Suppose it is desired to find the integral

1. $$I_n = \int_{t_n}^{t_{n+1}} f(t)\, dt.$$

The coefficients b_0, b_1, b_2, and b_3 of the polynomial can be determined, as above, so that the function

2. $$y = b_0 + b_1(t - t_n) + b_2(t - t_n)^2 + b_3(t - t_n)^3$$

shall take the same values as $f(t)$ for $t = t_{n-2}, t_{n-1}, t_n$, and t_{n+1}.
With this approximation to the function $f(t)$, the integral becomes (since $t_{n+1} - t_n = h$)

3. $$I_n = \int_{t_n}^{t_{n+1}} [b_0 + b_1(t - t_n) + b_2(t - t_n)^2 + b_3(t - t_n)^3]\, dt$$

$$= h[b_0 + \frac{1}{2} b_1 h + \frac{1}{3} b_2 h^2 + \frac{1}{4} b_3 h^3].$$

The coefficients b_0, b_1, b_2, and b_3 will now be expressed in terms of y_{n+1}, $\Delta_1 y_{n+1}$, $\Delta_2 y_{n+1}$, and $\Delta_3 y_{n+1}$. It follows from (2) that

4. $$\begin{cases} y_{n-2} = b_0 - 2b_1 h + 4b_2 h^2 - 8b_3 h^3, \\ y_{n-1} = b_0 - b_1 h + b_2 h^2 - b_3 h^3, \\ y_n \quad = b_0, \\ y_{n+1} = b_0 + b_1 h + b_2 h^2 + b_3 h^3. \end{cases}$$

Then it follows from the rules for determining the difference functions that

5. $$\begin{cases} \Delta_1 y_{n-1} = b_1 h - 3b_2 h^2 + 7b_3 h^3, \\ \Delta_1 y_n \quad = b_1 h - b_2 h^2 + b_3 h^3, \\ \Delta_1 y_{n+1} = b_1 h + b_2 h^2 + b_3 h^3. \end{cases}$$

6. $$\begin{cases} \Delta_2 y_n \quad = 2b_2 h^2 - 6b_3 h^3, \\ \Delta_2 y_{n+1} = 2b_2 h^2. \end{cases}$$

7. $$\Delta_3 y_{n+1} = 6b_3 h^3.$$

It follows from the last equations of these four sets of equations that

8. $$\begin{cases} b_0 &= y_{n+1} - \Delta_1 y_{n+1}, \\ b_1 h &= \Delta_1 y_{n+1} - \frac{1}{2}\Delta_2 y_{n+1} - \frac{1}{6}\Delta_3 y_{n+1}, \\ b_2 h^2 &= \frac{1}{2}\Delta_2 y_{n+1}, \\ b_3 h^3 &= \frac{1}{6}\Delta_3 y_{n+1}. \end{cases}$$

Therefore the integral (3) becomes

9. $$I_n = h\left[y_{n+1} - \frac{1}{2}\Delta_1 y_{n+1} - \frac{1}{12}\Delta_2 y_{n+1} - \frac{1}{24}\Delta_3 y_{n+1} - \cdots\right].$$

The coefficients of the higher order terms $\Delta_4 y_{n+1}$ and $\Delta_5 y_{n+1}$ are $-\frac{19}{720}$ and $\frac{1}{48}$ respectively.

10.31 Obviously, if it were desired, the integral from t_{n-2} to t_{n-1}, or over any other part of this interval, could be computed by the same methods. For example, the integral from t_{n-1} to t_n is

$$\begin{aligned} I_{n-1} &= \int_{t_{n-1}}^{t_n} f(t)\,dt, \\ &= h\left[y_{n+1} - \frac{3}{2}\Delta_1 y_{n+1} + \frac{5}{12}\Delta_2 y_{n+1} + \frac{1}{24}\Delta_3 y_{n+1} + \cdots\right]. \end{aligned}$$

NUMERICAL ILLUSTRATIONS

10.32 Consider first the application of Simpson's method. Suppose it is required to find

$$I = \int_{25°}^{55°} \sin t\,dt = -\left[\cos t\right]_{25°}^{55°} = 0.3327.$$

On applying **10.12** with the numbers taken from Table I, it is found that

$$I_1 = \frac{5°}{3}[.4226 + 2.0000 + 1.1472 + 2.5712 + 1.4142 + 3.0640 + .8191],$$

which becomes, on reducing 5° to radians,

$$I_1 = 0.3327,$$

agreeing to four places with the correct result.

10.33 On applying **10.11** (4) and omitting alternate entries in Table II, it is found that

$$I = \int_{25°}^{45°} \sin t\,dt = \frac{10°}{3}[.4226 + 2.2944 + .7071] = 0.1992,$$

which is also correct to four places. These formulas could hardly be surpassed in ease and convenience of application.

10.34 Now consider the application of **10.30** (9). As it stands it furnishes the integral over the single interval t_n to t_{n+1}. If it is desired to find the integral from t_n to t_{n+m}, the formula for doing so is obviously the sum of m formulas such as (9), the value of the subscript going from $n + 1$ to $n + m + 1$, or

$$I_{n,\,m} = h\Big[\left(y_{n+1} + \dots\dots + y_{n+m+1}\right) - \frac{1}{2}\left(\Delta_1 y_{n+1} + \dots\dots + \Delta_1 y_{n+m+1}\right)$$

$$- \frac{1}{12}\left(\Delta_2 y_{n+1} + \dots\dots + \Delta_2 y_{n+m+1}\right) - \frac{1}{24}\left(\Delta_3 y_{n+1} + \dots\dots + \Delta_3 y_{n+m+1}\right) + \dots\Big].$$

On applying this formula to the numbers of Table I, it is found that

$$\begin{aligned} I = \int_{25^\circ}^{55^\circ} \sin t\, dt = 5^\circ\Big[&(.5000 + .5736 + .6428 + .7071 + .7660 + .8191) \\ &- \frac{1}{2}(.0774 + .0736 + .0692 + .0643 + .0589 + .0531) \\ &+ \frac{1}{12}(.0032 + .0038 + .0044 + .0049 + .0054 + .0058) \\ &+ \frac{1}{24}(.0006 + .0006 + .0006 + .0005 + .0005 + .0004)\Big] \\ &= 0.3327, \end{aligned}$$

agreeing to four places with the exact value. When a table of differences is at hand covering the desired range this method involves the simplest numerical operations. It must be noted, however, that some of the required differences necessitate a knowledge of the value of the function for earlier values of the argument than the lower limit of the integral.

10.40 Reduced Form of the Differential Equations. Differential equations which arise from physical problems usually involve second derivatives. For example, the differential equation satisfied by the motion of a vibrating tuning fork has the form

$$\frac{d^2x}{dt^2} = -kx,$$

where k is a constant depending on the tuning fork.

10.41 The differential equations for the motion of a body subject to gravity and a retardation which is proportional to its velocity are

$$\begin{cases} \dfrac{d^2x}{dt^2} = -c\dfrac{dx}{dt}, \\[2ex] \dfrac{d^2y}{dt^2} = -c\dfrac{dy}{dt} - g, \end{cases}$$

where c is a constant depending on the resisting medium and the mass and shape of the body, while g is the acceleration of gravity.

10.42 The differential equations for the motion of a body moving subject to the law of gravitation are

$$\begin{cases} \dfrac{d^2x}{dt^2} = -k^2\dfrac{x}{r^3}, \\ \dfrac{d^2y}{dt^2} = -k^2\dfrac{y}{r^3}, \\ \dfrac{d^2z}{dt^2} = -k^2\dfrac{z}{r^3}, \\ r^2 = x^2 + y^2 + z^2. \end{cases}$$

10.43 These examples illustrate sufficiently the types of differential equations which arise in practical problems. The number of the equations depends on the problem and may be small or great. In the problem of three bodies there are nine equations. The equations are usually not independent as is illustrated in **10.42,** where each equation involves all three variables x, y, and z through r. On the other hand, equations **10.41** are mutually independent for the first does not involve y or its derivatives and the second does not involve x or its derivatives. The right members may involve x, y, and z as is the case in **10.42,** or they may involve the first derivatives, as is the case in **10.41,** or they may involve both the coördinates and their first derivatives. In some problems they also involve the independent variable t.

10.44 Hence physical problems usually lead to differential equations which are included in the form

$$\begin{cases} \dfrac{d^2x}{dt^2} = f\left(x, y, \dfrac{dx}{dt}, \dfrac{dy}{dt}, t\right), \\ \dfrac{d^2y}{dt^2} = g\left(x, y, \dfrac{dx}{dt}, \dfrac{dy}{dt}, t\right), \end{cases}$$

where f and g are functions of the indicated arguments. Of course, the number of equations may be greater than two.

10.45 If we let

$$x' = \frac{dx}{dt}, \quad y' = \frac{dy}{dt},$$

equations **10.44** can be written in the form

$$\begin{cases} \dfrac{dx}{dt} = x', \\ \dfrac{dx'}{dt} = f(x, y, x', y', t), \\ \dfrac{dy}{dt} = y', \\ \dfrac{dy'}{dt} = g(x, y, x', y', t). \end{cases}$$

10.46 If we let $x = x_1,\ x' = x_2,\ y = x_3,\ y' = x_4, \ldots\ldots$ equations **10.45** are included in the form

$$\begin{cases} \dfrac{dx_1}{dt} = f_1(x_1, x_2, \ldots, x_n, t), \\ \ldots\ldots\ldots\ldots\ldots \\ \ldots\ldots\ldots\ldots\ldots \\ \dfrac{dx_n}{dt} = f_n(x_1, x_2, \ldots, x_n, t). \end{cases}$$

This is the final standard form to which it will be supposed the differential equations are reduced.

10.50 Definition of a Solution of Differential Equations. For simplicity in writing, suppose the differential equations are two in number and write them in the form

1. $$\begin{cases} \dfrac{dx}{dt} = f(x, y, t), \\ \dfrac{dy}{dt} = g(x, y, t), \end{cases}$$

where f and g are known functions of their arguments. Suppose $x = a,\ y = b$ at $t = 0$. Then

2. $$\begin{cases} x = \phi(t), \\ y = \psi(t), \end{cases}$$

is the solution of (1) satisfying these initial conditions if ϕ and ψ are such functions that

3. $$\begin{aligned} \phi(0) &= a, \\ \psi(0) &= b, \\ \frac{d\phi}{dt} &= f(\phi, \psi, t), \\ \frac{d\psi}{dt} &= g(\phi, \psi, t), \end{aligned}$$

the last two equations being satisfied for all $0 \leqslant t \leqslant T$, where T is a positive constant, the largest value of t for which the solution is determined. It is not necessary that ϕ and ψ be given by any formulas — it is sufficient that they have the properties defined by (3). Solutions *always exist*, though it will not be proved here, *if f and g are continuous functions of t and have derivatives with respect to both x and y.*

10.51 Geometrical Interpretation of a Solution of Differential Equations. Geometrical interpretations of definite integrals have been of great value not only in leading to an understanding of their real meaning but also in suggesting practical means of obtaining their numerical values. The same things are true in the case of differential equations.

For simplicity in the geometrical representation, consider a single equation

1. $$\frac{dx}{dt} = f(x, t),$$

where $x = a$ at $t = 0$. Suppose the solution is

2. $$x = \phi(t),$$

Equation (2) defines a curve whose coördinates are x and t. Suppose it is represented by figure 2. The value of the tangent to the curve at every point on it is given by equation (1), for there is, corresponding to each point, a pair of values of x and t which gives $\frac{dx}{dt}$, the value of the tangent, when substituted in the right member of equation (1).

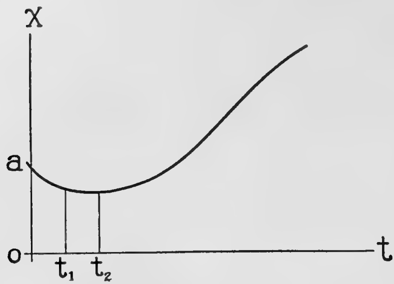

FIG. 2

Consider the initial point on the curve, viz. $x = a$, $t = 0$. The tangent at this point is $f(a, 0)$. The curve lies close to the tangent for a short distance from the initial point. Hence an approximate value of x at $t = t_1$, t_1 being small, is the ordinate of the point where the tangent at a intersects the line $t = t_1$, or

$$x_1 = f(a, 0)t_1.$$

The tangent at x_1, t_1 is defined by (1), and a new step in the solution can be made in the same way. Obviously the process can be continued as long as x and t have values for which the right member of (1) is defined. And the same process can be applied when there are any number of equations. While the steps of this process can be taken so short that it will give the solution with any desired degree of accuracy, it is not the most convenient process that may be employed. It is the one, however, which makes clearest to the intuitions the nature of the solution.

10.6 Outline of the Method of Solution. Consider equations **10.50** (1) and their solution (2). The problem is to find functions ϕ and ψ having the properties (2). If we integrate the last two equations of **10.50** (3) we shall have

1. $$\begin{cases} \phi = a + \int_0^t f(\phi, \psi, t)\, dt, \\ \psi = b + \int_0^t g(\phi, \psi, t)\, dt. \end{cases}$$

The difficulty arises from the fact that ϕ and ψ are not known in advance and the integrals on the right can not be formed. Since ϕ and ψ are the solution values of x and y, we may replace them by the latter in order to preserve the original notation, and we have

2.
$$\begin{cases} x = a + \int_0^t f(x, y, t)\,dt, \\ y = b + \int_0^t g(x, y, t)\,dt. \end{cases}$$

If x and y do not change rapidly in numerical value, then $f(x, y, t)$ and $g(x, y, t)$ will not in general change rapidly, and a first approximation to the values of x and y satisfying equations (2) is

3.
$$\begin{cases} x_1 = a + \int_0^t f(a, b, t)\,dt, \\ y_1 = b + \int_0^t g(a, b, t)\,dt, \end{cases}$$

at least for values of t near zero. Since a and b are constants, the integrands in (3) are known and the integrals can be computed. If the primitives can not be found the integrals can be computed by the methods of **10.1** or **10.3.**

After a first approximation has been found a second approximation is given by

4.
$$\begin{cases} x_2 = a + \int_0^t f(x_1, y_1, t)\,dt, \\ y_2 = b + \int_0^t g(x_1, y_1, t)\,dt. \end{cases}$$

The integrands are again known functions of t because x_1 and y_1 were determined as functions of t by equations (3). Consequently x_2 and y_2 can be computed. The process can evidently be repeated as many times as is desired. The nth approximation is

5.
$$\begin{cases} x_n = a + \int_0^t f(x_{n-1}, y_{n-1}, t)\,dt, \\ y_n = b + \int_0^t g(x_{n-1}, y_{n-1}, t)\,dt. \end{cases}$$

There is no difficulty in carrying out the process, but the question arises whether it converges to the solution. The answer, first established by Picard, is that, as n increases, x_n and y_n tend toward the solution for all values of t for which all the approximations belong to those values of x, y, and t for which f and g have the properties of continuity with respect to t and differentiability with respect to x and y. If, for example, $f = \dfrac{\sin x}{x^2}$ and the value of x_n tends towards zero for $t = T$, then the solution can not be extended beyond $t = T$.

It is found in practice that the longer the interval over which the integration is extended in the successive approximations, the greater the number of approximations which must be made in order to obtain a given degree of accuracy. In fact, it is preferable to take first a relatively short interval and to find the solution over this interval with the required accuracy, and then to continue from the end values of this interval over a new interval. This is what is done in actual work. The details of the most convenient methods of doing it will be explained in the succeeding sections.

10.7 The Step-by-Step Construction of the Solution. Suppose the differential equations are

1 $$\begin{cases} \dfrac{dx}{dt} = f(x, y, t), \\ \dfrac{dy}{dt} = g(x, y, t), \end{cases}$$

with the initial conditions $x = a$, $y = b$ at $t = 0$. It is more difficult to start a solution than it is to continue one after the first few steps have been made. Therefore, it will be supposed in this section that the solution is well under way, and it will be shown how to continue it. Then the method of starting a solution will be explained in the next section, and the whole process will be illustrated numerically in the following one.

Suppose the values of x and y have been found for $t = t_1, t_2, \ldots, t_n$. Let them be respectively x_1, y_1; x_2, y_2; . . .; x_n, y_n, care being taken not to confuse the subscripts with those used in section **10.6** in a different sense. Suppose the intervals $t_2 - t_1, t_3 - t_2, \ldots, t_n - t_{n-1}$ are all equal to h and that it is desired to find the values of x and y at t_{n+1}, where $t_{n+1} - t_n = h$.

It follows from this notation and equations (2) of **10.6** that the desired quantities are

2. $$\begin{cases} x_{n+1} = x_n + \displaystyle\int_{t_n}^{t_{n+1}} f(x, y, t)\, dt, \\ y_{n+1} = y_n + \displaystyle\int_{t_n}^{t_{n+1}} g(x, y, t)\, dt. \end{cases}$$

The values of x and y in the integrands are of course unknown. They can be found by successive approximations, and if the interval is short, as is supposed, the necessary approximations will be few in number.

A fortunate circumstance makes it possible to reduce the number of approximations. The values of x and y are known at $t = t_n, t_{n-1}, t_{n-2}, \ldots$ From these values it is possible to determine in advance, by extrapolation, very close approximations to x and y for $t = t_{n+1}$. The corresponding values of f and g can be computed because these functions are given in terms of x, y, and t. They are also given for $t = t_n, t_{n-1}, \ldots$. Consequently, curves for f and g agreeing with their values at $t = t_{n+1}, t_n, t_{n-1}, \ldots$ can be constructed and the integrals (2) can be computed by the methods of **10.1** and **10.3.**

The method of extrapolating values of x_{n+1} and y_{n+1} must be given. Since the method is the same for both, consider only the former. Since, by hypothesis, x is known for $t = t_n, t_{n-1}, t_{n-2}, \ldots$ the values of x_n, $\Delta_1 x_n$, $\Delta_2 x_n$, and $\Delta_3 x_n$ are known. If the interval h is not too large the value of $\Delta_3 x_{n+1}$ is very nearly equal to $\Delta_3 x_n$. As an approximation $\Delta_3 x_{n+1}$ may be taken equal to $\Delta_3 x_n$, or perhaps a closer value may be determined from the way the third differences

$\Delta_3 x_{n-3}, \Delta_3 x_{n-2}, \Delta_3 x_{n-1}$, and $\Delta_3 x_n$ vary. For example, in Table II it is easy to see that $\Delta_3 \sin 75°$ is almost certainly -3. It follows from **10.20, 1, 2** that

3. $$\begin{cases} \Delta_2 x_{n+1} = \Delta_3 x_{n+1} + \Delta_2 x_n, \\ \Delta_1 x_{n+1} = \Delta_2 x_{n+1} + \Delta_1 x_n, \\ x_{n+1} = \Delta_1 x_{n+1} + x_n. \end{cases}$$

After the adopted value of $\Delta_3 x_{n+1}$ has been written in its column the successive entries to the left can be written down by simple additions to the respective numbers on the line of t_n. For example, it is found from Table II that $\Delta_2 \sin 75° = -72$, $\Delta_1 \sin 75° = 262$, $\sin 75° = 9659$. This is, indeed, the correct value of $\sin 75°$ to four places.

Now having extrapolated approximate values of x_{n+1} and y_{n+1} it remains to compute f and g for $x = x_{n+1}$, $y = y_{n+1}$, $t = t_{n+1}$. The next step is to pass curves through the values of f and g for $t = t_{n+1}, t_n, t_{n-1}, \ldots$ and to compute the integrals (2). This is the precise problem that was solved in **10.30,** the only difference being that in that section the integrand was designated by y. On applying equation **10.30** (9) to the computation of the integrals (2), the latter give

4. $$\begin{cases} x_{n+1} = x_n + h\left[f_{n+1} - \frac{1}{2}\Delta_1 f_{n+1} - \frac{1}{12}\Delta_2 f_{n+1} - \frac{1}{24}\Delta_3 f_{n+1} \ldots\right], \\ y_{n+1} = y_n + h\left[g_{n+1} - \frac{1}{2}\Delta_1 g_{n+1} - \frac{1}{12}\Delta_2 g_{n+1} - \frac{1}{24}\Delta_3 g_{n+1} \ldots\right], \end{cases}$$

where

5. $$\begin{cases} f_{n+1} = f(x_{n+1}, y_{n+1}, t_{n+1}), \\ g_{n+1} = g(x_{n+1}, y_{n+1}, t_{n+1}). \end{cases}$$

The right members of (4) are known and therefore x_{n+1} and y_{n+1} are determined.

It will be recalled that f_{n+1} and g_{n+1} were computed from extrapolated values of x_{n+1} and y_{n+1}, and hence are subject to some error. They should now be recomputed with the values of x_{n+1} and y_{n+1} furnished by (4). Then more nearly correct values of the entire right members of (4) are at hand and the values of x_{n+1} and y_{n+1} should be corrected if necessary. If the interval h is small it will not generally be necessary to correct x_{n+1} and y_{n+1}. But if they require corrections, then new values of f_{n+1} and g_{n+1} should be computed. In practice it is advisable to take the interval h so small that one correction to f_{n+1} and g_{n+1} is sufficient.

After x_{n+1} and y_{n+1} have been obtained, values of x and y at t_{n+2} can be found in precisely the same manner, and the process can be continued to $t = t_{n+3}, t_{n+4}$, ... If the higher differences become large and irregular it is advisable to interpolate values at the mid-intervals of the last two steps and to continue with an interval half as great. On the other hand, if the higher differences become very small it is advisable to proceed with an interval twice as great as that used in the earlier part of the computation.

The foregoing, expressed in words, seems rather complicated. As a matter of fact, it goes very simply in practice, as will be shown in section **10.9.**

10.8 The Start of the Construction of the Solution. Suppose the differential equations are again

1.
$$\begin{cases} \dfrac{dx}{dt} = f(x, y, t), \\ \dfrac{dy}{dt} = g(x, y, t), \end{cases}$$

with the initial conditions $x = a$, $y = b$ at $t = 0$. Only the initial values of x and y are known. But it follows from (1) that the rates of change of x and y at $t = 0$ are $f(a, b, 0)$ and $g(a, b, 0)$ respectively. Consequently, first approximations to values of x and y at $t = t_1 = h$ are

2.
$$\begin{cases} x_1^{(1)} = a + hf(a, b, 0), \\ y_1^{(1)} = b + hg(a, b, 0). \end{cases}$$

Now it follows from (1) that the rates of change of x and y at $x = x_1$, $y = y_1$, $t = t_1$ are approximately $f(x_1^{(1)}, y_1^{(1)}, t_1)$ and $g(x_1^{(1)}, y_1^{(1)}, t_1)$. These rates will be different from those at the beginning, and the average rates of change for the first interval will be nearly the average of the rates at the beginning and at the end of the interval. Therefore closer approximations than those given in (2) to the values of x and y at $t = t_1$ are

3.
$$\begin{cases} x_1^{(2)} = a + \tfrac{1}{2}h\,[f(a, b, 0) + f(x_1^{(1)}, y_1^{(1)}, t_1)], \\ y_1^{(2)} = b + \tfrac{1}{2}h\,[g(a, b, 0) + g(x_1^{(1)}, y_1^{(1)}, t_1)]. \end{cases}$$

The process could be repeated on the first interval, but it is not advisable when the interval is taken as short as it should be.

The rates of change at the beginning of the second interval are approximately $f(x_1^{(2)}, y_1^{(2)}, t_1)$ and $g(x_1^{(2)}, y_1^{(2)}, t_1)$ respectively. Consequently, first approximations to the values of x and y at $t = t_2$, where $t_2 - t_1 = h$, are

4.
$$\begin{cases} x_2^{(1)} = x_1^{(2)} + hf(x_1^{(2)}, y_1^{(2)}, t_1), \\ y_2^{(1)} = y_1^{(2)} + hg(x_1^{(2)}, y_1^{(2)}, t_1). \end{cases}$$

With these values of x and y approximate values of f_2 and g_2 are computed. Since f_0, g_0; f_1, g_1 are known, it follows that $\Delta_1 f_2$, $\Delta_1 g_2$; $\Delta_2 f_2$, and $\Delta_2 g_2$ are also known. Hence equations (4) of **10.7,** for $n + 1 = 2$, can be used, with the exception of the last terms in the right members, for the computation of x_2 and y_2.

At this stage of work $x_0 = a$, $y_0 = b$; x_1, y_1; x_2, y_2 are known, the first pair exactly and the last two pairs with considerable approximation. After f_2 and g_2 have been computed, x_1 and y_1 can be corrected by **10.31** for $n = 1$. Then approximate values of x_3 and y_3 can be extrapolated by the method explained in the preceding section, after which approximate values of f_3 and g_3 can be computed. With these values and the corresponding difference functions, x_2 and y_2 can be corrected by using **10.31.** Then after correcting all the corresponding differences of all the functions, the solution is fully started and proceeds by the method given in the preceding section.

10.9 Numerical Illustration. In this section a numerical problem will be treated which will illustrate both the steps which must be taken and also the method of arranging the work. A convenient arrangement of the computation which preserves a complete record of all the numerical work is very important.

Suppose the differential equation is

1. $$\begin{cases} \dfrac{d^2x}{dt^2} = -(1 + \kappa^2)x + 2\kappa^2 x^3, \\ x = 0, \dfrac{dx}{dt} = 1 \text{ at } t = 0. \end{cases}$$

The problem of the motion of a simple pendulum takes this form when expressed in suitable variables. This problem is chosen here because it has an actual physical interpretation, because it can be integrated otherwise so as to express t in terms of x, and because it will illustrate sufficiently the processes which have been explained.

Equation (1) will first be integrated so as to express t in terms of x. On multiplying both sides of (1) by $2\dfrac{dx}{dt}$ and integrating, it is found that the integral which satisfies the initial conditions is

2. $$\left(\frac{dx}{dt}\right)^2 = (1 - x^2)\,(1 - \kappa^2 x^2).$$

On separating the variables this equation gives

3. $$t = \int_0^x \frac{dx}{\sqrt{(1 - x^2)\,(1 - \kappa^2 x^2)}}.$$

Suppose $\kappa^2 < 1$ and that the upper limit x does not exceed unity. Then

4. $$\frac{1}{\sqrt{1 - \kappa^2 x^2}} = 1 + \frac{1}{2}\kappa^2 x^2 + \frac{3}{8}\kappa^4 x^4 + \frac{5}{16}\kappa^6 x^6 + \ldots.$$

where the right member is a converging series. On substituting (4) into (3) and integrating, it is found that

5. $$t = \sin^{-1} x + \tfrac{1}{4}[-x\sqrt{1 - x^2} + \sin^{-1} x]\kappa^2 + \tfrac{3}{8}[-x^3\sqrt{1 - x^2} - \tfrac{3}{4}x(1 - x^2)^{\frac{3}{2}} + \tfrac{3}{8}x\sqrt{1 - x^2} + \tfrac{3}{8}\sin^{-1} x]\kappa^4 + \ldots\ldots].$$

When $x = 1$ this integral becomes

6. $$T = \frac{\pi}{2}\left[1 + \left(\frac{1}{2}\right)^2\kappa^2 + \left(\frac{1\cdot 3}{2\cdot 4}\right)^2\kappa^4 + \left(\frac{1\cdot 3\cdot 5}{2\cdot 4\cdot 6}\right)^2\kappa^6 + \ldots\right].$$

Equation (5) gives t for any value of x between -1 and $+1$. But the problem is to determine x in terms of t. Of course, if a table is constructed giving t for many values of x, it may be used inversely to obtain the value of x corresponding to any value of t. The labor involved is very great. When κ^2 is given numerically it is simpler to compute the integral (3) by the method of **10.1** or **10.3.**

In mathematical terms, t is an elliptical integral of x of the first kind, and the inverse function, that is, x as a function of t, is the sine-amplitude function, which has the real period $4T$.

Suppose $\kappa^2 = \frac{1}{2}$ and let $y = \frac{dx}{dt}$. Then equation (1) is equivalent to the two equations

7.
$$\begin{cases} \dfrac{dx}{dt} = y, \\ \dfrac{dy}{dt} = -\dfrac{3}{2}x + x^3, \end{cases}$$

which are of the form **10.50** (1), where

8.
$$\begin{cases} f = y, \\ g = -\dfrac{3}{2}x + x^3, \end{cases}$$

and $x = 0$, $y = 1$ at $t = 0$.

The first step is to determine the interval which is to be used in the start of the solution. No general rule can be given. The larger f_0 and g_0 the smaller must the interval be taken. A fairly good rule is in general to take h so small that hf_0 and hg_0 shall not be greater than 1000 times the permissible error in the results. In the present instance we may take $h = 0.1$.

First approximations to x and y at $t = 0.1$ are found from the initial conditions and equations **10.8** (2) to be

9.
$$\begin{cases} x_1^{(1)} = 0 + \dfrac{1}{10} \cdot 1 = 0.1000, \\ y_1^{(1)} = 1 + \dfrac{1}{10}\, 0 = 1.0000. \end{cases}$$

It follows from (8) and these values of x_1 and y_1 that

10.
$$\begin{cases} f(x_1^{(1)}, y_1^{(1)}, t_1) = 1.0000, \\ g(x_1^{(1)}, y_1^{(1)}, t_1) = -0.1490. \end{cases}$$

Hence the more nearly correct values of x_1 and y_1, which are given by **10.8** (3), are

11.
$$\begin{cases} x_1^{(2)} = 0 + \dfrac{0 \cdot 1}{2}\left[1.0000 + 1.0000\right] = 0.1000, \\ y_1^{(2)} = 1 + \dfrac{0 \cdot 1}{2}\left[0.0000 - 0.1490\right] = 0.9925. \end{cases}$$

Since in this particular problem $x = \int y\, dt$, it is not necessary to compute both f and g by the exact process explained in section **10.8**, for after y has been determined x is given by the integral. It follows from (7), (8), (10), and (11) that a first approximation to the value of y at $t = t_2 = 0.2$ is

12.
$$y_2^{(1)} = .0025 - \frac{1}{10}.1490 = .9776.$$

With the values of y at 0, .1, .2 given by the initial conditions and in equations (9) and (12), the first trial y-table is constructed as follows:

First Trial y-Table

t	y	$\Delta_1 y$	$\Delta_2 y$
0	1.0000		
.1	.9925	−.0075	
.2	.9776	−.0149	−.0074

Since $y = f$ it now follows from the first equations of (11) and **10.7** (4) for $n = 1$ that an approximate value of x_2 is

13. $$x_2^{(1)} = 0.1000 + \frac{1}{10}\left[.9776 + \frac{1}{2}.0149 + \frac{1}{12}.0074\right] = .1986.$$

With this value of x_2 it is found from the second of (8) that $g_2 = .2901$. Then the first trial g-table constructed from the values of g at $t = 0, 0.1, 0.2$, is:

First Trial g-Table

t	g	$\Delta_1 g$	$\Delta_2 g$
0	.0000		
.1	−.1490	−.1490	
.2	−.2901	−.1411	+.0079

Then the second equation of **10.7** (4) gives for $n = 1$ the more nearly correct value of y_2,

14. $$y_2 = .9925 + \frac{1}{10}\left[-.2901 + \frac{1}{12}.1411 - \frac{1}{12}.0079\right] = .9705.$$

This value of y_2 should replace the last entry in the first trial y-table. When this is done it is found that $\Delta_1 y_2 = -.0220$, $\Delta_2 y_2 = -.0145$. Then the first equation of **10.7** (4) gives

15. $$x_2 = .1000 + \frac{1}{10}\left[.9705 + \frac{1}{2}.0220 + \frac{1}{12}.0145\right] = .1983.$$

The computation is now well started although x_1, y_1, x_2, and y_2 are still subject to slight errors. The values of x_1 and y_1 can be corrected by applying **10.31** for $n = 1$. It is necessary first to compute a more nearly correct value of g_2 by using the value of x_2 given in (15). The result is $g_2 = -.2896$, $\Delta_1 g_2 = -.1406$, $\Delta_2 g_2 = +.0084$. Then the second equation of **10.7** (4) gives

16. $$y_2 = .9925 + \frac{1}{10}\left[-.2896 + \frac{1}{2}.1406 - \frac{1}{12}.0084\right] = .9705,$$

agreeing with (14). This value of y_2 is therefore essentially correct. An application of **10.31** then gives

17. $$x_1 = .0000 + \frac{1}{10}\left[.9705 + \frac{3}{2}.0220 - \frac{5}{12}.0145\right] = .0997,$$

after which it is found that $g_1 = -.1486$, $\Delta_1 g_1 = -.1486$. Now the first trial y-table can be corrected by using the value of y_2 given in (14). The result is:

Second Trial y-Table

t	y	$\Delta_1 y$	$\Delta_2 y$
0	1.0000		
.1	.9925	−.0075	
.2	.9705	−.0220	−.0145

In order to correct x_2 and y_2 by the same method, which is the most convenient one to follow, it is necessary first to obtain approximate values of g_3 and y_3. The trial g-table can be corrected by computing g with the values of x given by (17) and (15). Then the line for g_3 can be extrapolated. The results are:

Second Trial g-Table

t	g	$\Delta_1 g$	$\Delta_2 g$
0	.0000		
.1	−.1486	−.1486	
.2	−.2896	−.1410	+.0076
.3	−.4230	−.1334	+.0076

Then the second equation of **10.7** (4) gives for $n = 2$,

18. $$y_3 = .9705 + \frac{1}{10}\left[-.4230 + \frac{1}{2}.1334 - \frac{1}{12}.0076\right] = .9348.$$

When this is added to the second trial y-table, it is found that

19. $$y_3 = .9348,\ \Delta_1 y_3 = -.0357,\ \Delta_2 y_3 = -.0137,\ \Delta_3 y_3 = +.0008.$$

Now x_2 and y_2 can be corrected by applying **10.31** to these numbers and those in the last line of the second trial g-table. The results are

20. $$\begin{cases} x_2 = .0997 + \dfrac{1}{10}\left[.9348 + \dfrac{3}{2}.0357 - \dfrac{5}{12}.0137 + \dfrac{1}{24}.0008\right] = .1980, \\ y_2 = .9925 + \dfrac{1}{10}\left[-.4230 + \dfrac{3}{2}.1334 + \dfrac{5}{12}.0076\right] = .9705. \end{cases}$$

The preliminary work is finished and x and y have been determined for $t = 0$, .1, and .2 with an error of probably not more than one unit in the last place. As the process is read over it may seem somewhat complicated, but this is largely because on the printed page preliminary values of the unknown quantities can not be erased and replaced by more nearly correct ones. As a matter of fact, the first steps are very simple and can be carried out in practice in a few minutes if the chosen time-interval is not too great.

The problem now reduces to simple routine. There are an x-table, a y-table (which in this problem serves also as an f-table), a g-table, and a schedule for computing g. It is advisable to use large sheets so that all the computations except the schedule for computing g can be kept side by side on the same sheet. The process consists of six steps: (1) Extrapolate a value of g_{n+1} and its differences in the g-table; (2) compute y_{n+1} by the second equation of **10.7** (4); (3) enter the result in the y-table and write down the differences; (4) use these results to compute x_{n+1} by the first equation of **10.7** (4); (5) with this value of x_{n+1} compute g_{n+1} by the g-computation schedule; and (6) correct the extrapolated value of g_{n+1} in the g-table.

Usually the correction to g_{n+1} will not be great enough to require a sensible correction to y_{n+1}. But if a correction is required, it should, of course, be made. It follows from the integration formulas **10.7** (4) and the way that the difference functions are formed that an error ϵ in g_{n+1} produces the error $\frac{3}{8}h\epsilon$ in y_{n+1}, and the corresponding error in x_{n+1} is $\dfrac{9}{64}h^2\epsilon$. It is never advisable to use so large a value of h that the error in x_{n+1} is appreciable. On the other hand, if the differences in the g-table and the y-table become so small that the second differences are insensible the interval may be doubled.

The following tables show the results of the computations in this problem reduced from five to four places.

Final x-Table

t	x	$\Delta_1 x$	$\Delta_2 x$	$\Delta_3 x$
0	.0000			
.1	.0997	.0997		
.2	.1980	.0983	−.0014	
.3	.2934	.0954	−.0029	−.0015
.4	.3847	.0913	−.0041	−.0012
.5	.4708	.0861	−.0052	−.0011
.6	.5508	.0800	−.0061	−.0009
.7	.6243	.0735	−.0065	−.0004
.8	.6909	.0666	−.0069	−.0004
.9	.7505	.0596	−.0070	−.0001
1.0	.8030	.0525	−.0071	−.0001
1.1	.8486	.0456	−.0069	+.0002
1.2	.8877	.0391	−.0065	+.0004
1.3	.9205	.0328	−.0063	+.0002
1.4	.9472	.0267	−.0061	+.0002
1.5	.9682	.0210	−.0057	+.0004
1.6	.9837	.0155	−.0055	+.0002
1.7	.9940	.0103	−.0052	+.0003
1.8	.9993	.0053	−.0050	+.0002
1.9	.9995	.0002	−.0051	−.0001

Final y-Table

t	y	$\Delta_1 y$	$\Delta_2 y$	$\Delta_3 y$
0	1.0000			
.1	.9925	−.0075		
.2	.9705	−.0220	−.0145	
.3	.9352	−.0353	−.0133	+.0012
.4	.8882	−.0470	−.0117	+.0016
.5	.8320	−.0562	−.0092	+.0025
.6	.7687	−.0633	−.0071	+.0019
.7	.7009	−.0678	−.0045	+.0016
.8	.6308	−.0701	−.0023	+.0022
.9	.5602	−.0706	−.0005	+.0008
1.0	.4906	−.0696	+.0010	+.0015
1.1	.4231	−.0675	+.0021	+.0011
1.2	.3584	−.0647	+.0028	+.0007
1.3	.2968	−.0616	+.0031	+.0003
1.4	.2382	−.0586	+.0030	−.0001
1.5	.1824	−.0558	+.0028	−.0002
1.6	.1290	−.0534	+.0024	−.0004
1.7	.0775	−.0515	+.0019	−.0005
1.8	.0271	−.0504	+.0011	−.0008
1.9	−.0230	−.0501	+.0003	−.0008

Final g-Schedule

t	.1	.2	.3	.4	.5	.6	.7	.8	.9
$\log x$	8.9989	9.2967	9.4675	9.5851	9.6728	9.7410	9.7954	9.8394	9.8753
$\log x^3$	6.9967	7.8901	8.4025	8.7553	9.0184	9.2230	9.3862	9.5182	9.6259
$3x$	.2992	.5941	.8802	1.1541	1.4124	1.6524	1.8729	2.0727	2.2515
$-\frac{3}{2}x$	−.1496	−.2970	−.4401	−.5770	−.7062	−.8262	−.9365	−1.0364	−1.1257
x^3	.0010	.0077	.0252	.0569	.1044	.1671	.2434	.3298	.4227
g	−.1486	−.2893	−.4149	−.5201	−.6018	−.6591	−.6931	−.7066	−.7030

Final g-Table

t	g	$\Delta_1 g$	$\Delta_2 g$	$\Delta_3 g$
0	.0000			
.1	−.1486	−.1486		
.2	−.2893	−.1407	+.0079	
.3	−.4149	−.1256	+.0151	+.0072
.4	−.5201	−.1052	+.0204	+.0053
.5	−.6018	−.0817	+.0235	+.0031
.6	−.6591	−.0573	+.0244	+.0009
.7	−.6931	−.0340	+.0233	−.0011
.8	−.7066	−.0135	+.0205	−.0028
.9	−.7030	+.0036	+.0171	−.0034
1.0	−.6867	+.0163	+.0127	−.0044
1.1	−.6618	+.0249	+.0086	−.0041
1.2	−.6320	+.0298	+.0049	−.0037
1.3	−.6008	+.0312	+.0014	−.0035
1.4	−.5710	+.0298	−.0014	−.0028
1.5	−.5447	+.0263	−.0035	−.0021
1.6	−.5236	+.0211	−.0052	−.0017
1.7	−.5088	+.0148	−.0063	−.0011
1.8	−.5011	+.0077	−.0071	−.0008
1.9	−.5008	+.0003	−.0074	−.0003

Final g-Schedule — *Continued*

1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9
9.9047	9.9287	9.9483	9.9640	9.9764	9.9860	9.9929	9.9974	9.9997	9.9998
9.7141	9.7861	9.8449	9.8920	9.9292	9.9580	9.9787	9.9922	9.9991	9.9994
2.4090	2.5458	2.6631	2.7615	2.8416	2.9046	2.9511	2.9820	2.9979	2.9985
−1.2045	−1.2729	−1.3316	−1.3807	−1.4208	−1.4523	−1.4756	−1.4910	−1.4989	−1.4992
.5178	.6111	.6996	.7799	.8498	.9076	.9520	.9822	.9978	.9984
− .6867	− .6618	− .6320	− .6008	− .5710	− .5447	− .5236	− .5088	− .5011	− .5008

As has been remarked, large sheets should be used so that the x, y, and g-tables can be put side by side on one sheet. Then the t-column need be written but once for these three tables. The g-schedule, which is of a different type, should be on a separate sheet.

The differential equation (1) has an integral which becomes for $\kappa^2 = \frac{1}{2}$ and $\frac{dx}{dt} = y$.

21. $$y^2 + \frac{3}{2}x^2 - \frac{1}{4}x^4 = 1,$$

and which may be used to check the computation because it must be satisfied at every step. It is found on trial that (21) is satisfied to within one unit in the fourth place by the results given in the foregoing tables for every value of t.

The value of t for which $x = 1$ and $y = 0$ is given by (6). When $\kappa^2 = \frac{1}{2}$ it is found that $T = 1.8541$. It is found from the final x-table by interpolation based on first and second differences that x rises to its maximum unity for almost exactly this value of t; and, similarly, that y vanishes for this value of t.

XI ELLIPTIC FUNCTIONS

By Sir George Greenhill, F. R. S.

INTRODUCTION TO THE TABLES OF ELLIPTIC FUNCTIONS

By Sir George Greenhill

In the integral calculus, $\int \frac{dx}{\sqrt{X}}$, and more generally, $\int \frac{M + N\sqrt{X}}{P + Q\sqrt{X}}\,dx$, where M, N, P, Q are rational algebraical functions of x, can always be expressed by the elementary functions of analysis, the algebraical, circular, logarithmic or hyperbolic, so long as the degree of X does not exceed the second. But when X is of the third or fourth degree, new functions are required, called elliptic functions, because encountered first in the attempt at the rectification of an ellipse by means of an integral.

To express an elliptic integral numerically, when required in an actual question of geometry, mechanics, or physics and electricity, the integral must be normalised to a standard form invented by Legendre before the Tables can be employed; and these Tables of the Elliptic Functions have been calculated as an extension of the usual tables of the logarithmic and circular functions of trigonometry. The reduction to a standard form of any assigned elliptic integral that arises is carried out in the procedure described in detail in a treatise on the elliptic functions.

11.1. Legendre's Standard Elliptic Integral of the First Kind (E. I. I) is

$$F\phi = \int_0^\phi \frac{d\phi}{\sqrt{1 - \kappa^2 \sin^2 \phi}} = \int_0^x \frac{dx}{\sqrt{(1 - x^2)(1 - \kappa^2 x^2)}} = u,$$

defining ϕ as the amplitude of u, to the modulus κ, with the notation,

$$\begin{aligned} \phi &= \operatorname{am} u \\ x &= \sin \phi = \sin \operatorname{am} u \end{aligned}$$

abbreviated by Gudermann to,

$$\begin{aligned} x &= \operatorname{sn} u \\ \cos \phi &= \operatorname{cn} u \\ \Delta \phi &= \sqrt{(1 - \kappa^2 \sin^2 \phi)} = \Delta \operatorname{am} u = \operatorname{dn} u, \end{aligned}$$

and sn u, cn u, dn u are the three elliptic functions. Their differentiations are,

$$\frac{d\phi}{du} = \Delta\phi \qquad \text{or} \qquad \frac{d \operatorname{am} u}{du} = \operatorname{dn} u$$

$$\frac{d \sin \phi}{du} = \cos \phi \cdot \Delta\phi \qquad \text{or} \qquad \frac{d \operatorname{sn} u}{du} = \operatorname{cn} u \operatorname{dn} u$$

$$\frac{d\cos\phi}{du} = -\sin\phi\,\Delta\phi \quad \text{or} \quad \frac{d\,\mathrm{cn}\,u}{du} = -\,\mathrm{sn}\,u\,\mathrm{dn}\,u$$

$$\frac{d\Delta\phi}{du} = -\,\kappa^2\sin\phi\cos\phi \quad \text{or} \quad \frac{d\,\mathrm{dn}\,u}{du} = -\,\kappa^2\,\mathrm{sn}\,u\,\mathrm{cn}\,u$$

11.11. The complete integral over the quadrant, $0 < \phi < \frac{\pi}{2}$, $0 < x < 1$, defines the (quarter) period, K,

$$K = F\frac{\pi}{2} = \int_0^{\frac{1}{2}\pi}\frac{d\phi}{\Delta\phi},$$

making

$$\mathrm{sn}\,K = 1$$
$$\mathrm{cn}\,K = 0$$
$$\mathrm{dn}\,K = \kappa'.$$

κ' is the comodulus to κ, $\kappa^2 + \kappa'^2 = 1$, and the coperiod, K', is,

$$K' = \int_0^{\frac{\pi}{2}}\frac{d\phi}{\sqrt{(1 - \kappa'^2\sin^2\phi)}}.$$

11.12.

$$\mathrm{sn}^2\,u + \mathrm{cn}^2\,u = 1$$
$$\mathrm{cn}^2\,u + \kappa^2\,\mathrm{sn}^2\,u = 1$$
$$\mathrm{dn}^2\,u - \kappa^2\,\mathrm{cn}^2\,u = \kappa'^2.$$
$$\mathrm{sn}\;0 = 0, \quad \mathrm{cn}\;0 = \mathrm{dn}, \qquad 0 = 1.$$
$$\mathrm{sn}\,K = 1, \quad \mathrm{cn}\,K = 0, \qquad \mathrm{dn}\,K = \kappa'.$$

11.13. Legendre has calculated for every degree of θ, the modular angle, $\kappa = \sin\theta$, the value of $F\phi$ for every degree in the quadrant of the amplitude ϕ, and tabulated them in his Table IX, Fonctions elliptiques, t. II, $90 \times 90 = 8100$ entries.

But in this new arrangement of the Table, we take $u = F\phi$ as the independent variable of equal steps, and divide it into 90 degrees of a quadrant K, putting

$$u = eK = \frac{r^\circ}{90^\circ}K, \qquad r^\circ = 90^\circ e.$$

As in the ordinary trigonometrical tables, the degrees of r run down the left of the page from 0° to 45°, and rise up again on the right from 45° to 90°. Then columns II, III, X, XI are the equivalent of Legendre's Table of $F\phi$ and ϕ, but rearranged so that $F\phi$ proceeds by equal increments 1° in r°, and the increments in ϕ are unequal, whereas Legendre took equal increments of ϕ giving unequal increments in $u = F\phi$.

The reason of this rearrangement was the great advance made in elliptic function theory when Abel pointed out that $F\phi$ was of the nature of an inverse function, as it would be in a degenerate circular integral with zero modular angle. On Abel's recommendation, the notation is reversed, and ϕ is to be considered a function of u, denoted already by $\phi = \text{am}\ u$, instead of looking at u, in Legendre's manner, as a function, $F\phi$, of ϕ. Jacobi adopted the idea in his Fundamenta nova, and employs the elliptic functions

$$\sin\phi = \sin \text{am}\ u, \qquad \cos\phi = \cos \text{am}\ u, \qquad \Delta\phi = \Delta\ \text{am}\ u,$$

single-valued, uniform, periodic functions of the argument u, with (quarter) period K, as ϕ grows from 0 to $\frac{1}{2}\pi$. Gudermann abbreviated this notation to the one employed usually today.

11.2. The E. I. I is encountered in its simplest form, not as the elliptic arc, but in the expression of the time in the pendulum motion of finite oscillation, unrestricted to the small invisible motion of elementary treatment.

The compound pendulum, as of a clock, is replaced by its two equivalent particles, one at O in the centre of suspension, and the other at the centre of oscillation, P; the particles are adjusted so as to have the same total weight as the pendulum, the same centre of gravity at G, and the same moment of inertia about G or O; the two particles, if rigidly connected, are then the kinetic equivalent of the compound pendulum and move in the same way in the same field of force (Maxwell, Matter and Motion, CXXI).

Putting $OP = l$, called the simple equivalent pendulum length, and P starting from rest at B, in Figure 1, the particle P will move in the circular arc BAB' as if sliding down a smooth curve; and P will acquire the same velocity as if it fell vertically $KP = ND$; this is all the dynamical theory required.

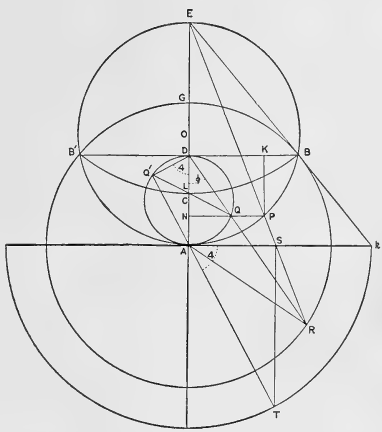

FIG. 1

$$(\text{velocity of } P)^2 = 2g \cdot KP,$$

$$(\text{velocity of } N)^2 = 2g \cdot ND \cdot \sin^2 AOP$$

$$= 2g \cdot ND \cdot \frac{NP^2}{OP^2} = \frac{g2}{l^2} \cdot ND \cdot NA \cdot NE,$$

and with $AD = h$, $AN = y$, $ND = h - y$, $AE = 2l$, $NE = 2l - y$,

$$\left(\frac{dy}{dt}\right)^2 = \frac{2g}{l^2}(hy - y^2)(2l - y) = \frac{2g}{l^2}Y,$$

where Y is a cubic in y. Then t is given by an elliptic integral of the form $\int \frac{dy}{\sqrt{Y}}$. This integral is normalised to Legendre's standard form of his E. I. I by putting $y = h \sin^2 \phi$, making $AOQ = \phi$, $h - y = h \cos^2 \phi$, $2l - y = 2l(1 - \kappa^2 \sin^2 \phi)$,

$$\kappa^2 = \frac{h}{2l} = \frac{AD}{AE} = \sin^2 AEB.$$

κ is called the modulus, AEB the modular angle which Legendre denoted by θ; $\sqrt{(1 - \kappa^2 \sin^2 \phi)}$ he denoted by $\Delta\phi$.

With $g = ln^2$, and reckoning the time t from A, this makes

$$nt = \int_0^\phi \frac{d\phi}{\Delta\phi} = F\phi,$$

in Legendre's notation. Then the angle ϕ is called the amplitude of nt, to be denoted am nt, the particle P starting up from A at time $t = 0$; and with $u = nt$,

$$\text{sn } u = \frac{AP}{AB} = \frac{AQ}{AD} \qquad \text{sn}^2 u = \frac{AN}{AD}$$

$$\text{cn } u = \frac{DQ}{AD} \qquad \text{cn}^2 u = \frac{PK}{AD}$$

$$\text{dn } u = \frac{EP}{EA} \qquad \text{dn}^2 u = \frac{NE}{AE}$$

Velocity of $P = n \cdot AB \cdot \text{cn } u = \sqrt{BP \cdot PB'}$, with an oscillation beat of T seconds in $u = eK$, $e = 2t/T$.

11.21. The numerical values of sn, cn, dn, tn (u, κ) are taken from a table to modulus $\kappa = \sin$ (modular angle, θ) by means of the functions Dr, Ar, Br, Cr, in columns V, VI, VII, VIII, by the quotients,

$$\sqrt{\kappa'} \text{ sn } eK = \frac{A}{D}$$

$$\text{cn } eK = \frac{B}{D}$$

$$\frac{\text{dn } eK}{\sqrt{\kappa'}} = \frac{C}{D}$$

$$\sqrt{\kappa'} \text{ tn } eK = \frac{A}{B}$$

$$r^\circ = 90^\circ e$$

$$u = eK.$$

These D, A, B, C are the Theta Functions of Jacobi, normalised, defined by

$$D(r) = \frac{\Theta u}{\Theta o}, \qquad A(r) = \frac{Hu}{HK},$$

$$B(r) = A(90^\circ - r) \qquad C(r) = D(90^\circ - r).$$

They were calculated from the Fourier series of angles proceeding by multiples of r°, and powers of q as coefficients, defined by

$$q = e^{-\pi \frac{k'}{k}}$$

$$\Theta u = 1 - 2q \cos 2r + 2q^4 \cos 4r - 2q^9 \cos 6r + \dots .$$

$$Hu = 2q^{\frac{1}{4}} \sin r - 2q^{\frac{9}{4}} \sin 3r + 2q^{\frac{25}{4}} \sin 5r - \dots .$$

11.3. The Elliptic Integral of the Second Kind (E. I. II) arose first historically in the rectification of the ellipse, hence the name. With $BOP = \phi$ in Figure 2, the minor eccentric angle of P, and s the arc BP from B to P at $x = a \sin \phi$, $y = b \cos \phi$,

$$\frac{ds}{d\phi} = \sqrt{a^2 \cos^2 \phi + b^2 \sin^2 \phi} = a\Delta(\phi, \kappa),$$

to the modulus κ, the eccentricity of the ellipse. Then $s = a\,E\phi$, where $\int_0^\phi \Delta\phi \cdot d\phi$ is denoted by $E\phi$ in Legendre's notation of his standard E. I. II; it is tabulated in his Table IX alongside of $F\phi$ for every degree of the modular angle θ, and to every degree in the quadrant of the amplitude ϕ.

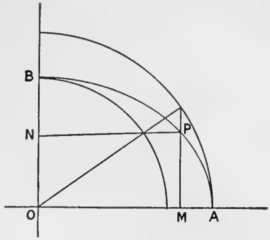

FIG. 2

But it is not possible to make the inversion and express ϕ as a single-valued function of $E\phi$.

11.31. The E. I. II, $E\phi$, arises also in the expression of the time, t, in the oscillation of a particle, P, on the arc of a parabola, as $F\phi$ was required on the arc of a circle. Starting from B along the parabola BAB', Figure 3, and with $AO = h$, $OB = b$, $BOQ = \phi$, $AN = y = h \cos^2 \phi$, $NP = x = b \cos \phi$ and with $OS = 2h = b \tan \alpha$, $OA' = SB = b \sec \alpha$, the parabola cutting the horizontal at B at an angle α, the modular angle, $BRA'B'$ is a semi-ellipse, with focus at S, and eccentricity $\kappa = \sin \alpha$.

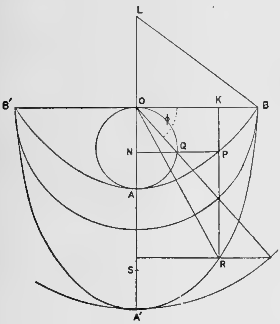

FIG. 3

$$(\text{Velocity of } P)^2 = \left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2$$

$$= (b^2 \cos^2 \phi + 4h^2 \sin^2 \phi \cos^2 \phi) \left(\frac{d\phi}{dt}\right)^2$$

$$= a^2(1 - \sin^2 \alpha \sin^2 \phi) \cos^2 \phi \left(\frac{d\phi}{dt}\right)^2 = 2gy = 2gh \cos^2 \phi$$

$$= V^2 \cos^2 \phi,$$

if V denotes the velocity of P at A, and $OA' = a$. Then with s the elliptic arc BR,

$$V \frac{dt}{d\phi} = a\Delta\phi = a \frac{ds}{d\phi}, \quad Vt = s,$$

and so the point R moves round the ellipse with constant velocity V, and accompanies the point P on the same vertical, oscillating on the parabola from B to B'.

In the analogous case of the circular pendulum, the time t would be given by the arc of an Elastica, in Kirchhoff's Kinetic Analogue, and this can be placed as a bow on Figure 1, with the cord along AE and vertex at B.

Legendre has shown also how in the oscillation of R on the semi-ellipse BRB' in a gravity field the time t is expressible by elliptic integrals, two of the first and two of the second kind, to complementary modulus (Fonctions elliptiques, I, p. 183).

11.32. In these tables, $E\phi$ is replaced by the columns IV, IX, of $E(r)$ and $G(r) = E(90 - r)$, defined, in Jacobi's notation, by

$$E(r) = \text{zn}\, eK = E\phi - eE$$
$$G(r) = \text{zn}\, (1 - e)K, \quad r = 90e.$$

This is the periodic part of $E\phi$ after the secular term $eE = \dfrac{E}{K} u$ has been set aside, E denoting the complete E. I. II,

$$E = E\tfrac{1}{2}\pi = \int^{\frac{1}{2}\pi} \Delta\phi \cdot d\phi.$$

The function zn u, or Zu in Jacobi's notation, or $E(r)$ in our notation, is calculated from the series,

$$Er = Zu = \frac{\pi}{K} \sum_{m=1}^{\infty} \frac{\sin 2mr}{\sinh m\pi \dfrac{K'}{K}} = \frac{2\pi}{K} \sum_{m=1}^{\infty} (q^m + q^{3m} + q^{5m} + \ldots) \sin 2mr.$$

This completes the explanation of the twelve columns of the tables.

11.4. The Double Periodicity of the Elliptic Functions.

This can be visualised in pendulum motion if gravity is supposed reversed suddenly at B (Figure 1) the end of a swing; as if by the addition of a weight to bring the centre of gravity above O, or by the movement of a weight, as in the metronome. The point P then oscillates on the arc BEB', and beats the elliptic function to the complementary modulus κ', as if in imaginary time, to imaginary argument $nti = fK'i$: and it reaches P' on AX produced, where tan AEP' = tan $AEB \cdot$cn $(nt'i, \kappa)$, or tan EAP' = tan $EAB \cdot$cn (nt', κ'); or with nt$' = v$, $DR' = DB \cdot$cn (iv, κ'), $DR = DB \cdot$cn (v, κ'), with $DR \cdot DR' = DB^2$, EP' crossing DB in R'.

$$\text{cn}\,(iv, \kappa) = \frac{1}{\text{cn}\,(v, \kappa')}$$
$$\text{sn}\,(iv, \kappa) = \frac{i\,\text{sn}\,(v, \kappa')}{\text{cn}\,(v, \kappa')} = i\,\text{tn}\,(v, \kappa')$$
$$\text{dn}\,(iv, \kappa) = \frac{\text{dn}\,(v, \kappa')}{\text{cn}\,(v, \kappa')} = \frac{1}{\text{sn}\,(K' - v, \kappa')}$$

where K' denotes the complementary (quarter) period to comodulus κ'.

If m, m' are any integers, positive or negative, including 0,

$$\text{sn}\,(u + 4mK + 2m'iK') = \text{sn}\, u$$
$$\text{cn}\,[u + 4mK + 2m'(K + iK')] = \text{cn}\, u$$
$$\text{dn}\,(u + 2mK + 4m'iK') = \text{dn}\, u$$

11.41. The Addition Theorem of the Elliptic Functions.

$$\text{sn}\,(u \pm v) = \frac{\text{sn}\, u\, \text{cn}\, v\, \text{dn}\, v \pm \text{sn}\, v\, \text{cn}\, u\, \text{dn}\, u}{1 - \kappa^2\, \text{sn}^2 u\, \text{sn}^2 v}$$
$$\text{cn}\,(v \pm u) = \frac{\text{cn}\, u\, \text{cn}\, v \mp \text{sn}\, u\, \text{dn}\, u\, \text{sn}\, v\, \text{dn}\, v}{1 - \kappa^2\, \text{sn}^2 u\, \text{sn}^2 v}$$
$$\text{dn}\,(v \pm u) = \frac{\text{dn}\, u\, \text{dn}\, v \mp \kappa^2\, \text{sn}\, u\, \text{cn}\, u\, \text{sn}\, v\, \text{cn}\, v}{1 - \kappa^2\, \text{sn}^2 u\, \text{sn}^2 v}$$

11.42. Coamplitude Formulas, with $v = \pm K$,

$$\mathrm{sn}\,(K - u) = \frac{\mathrm{cn}\,u}{\mathrm{dn}\,u} = \mathrm{sn}\,(K + u)$$

$$\mathrm{cn}\,(K - u) = \frac{\kappa'\,\mathrm{sn}\,u}{\mathrm{dn}\,u} \qquad \mathrm{cn}\,(K + u) = -\frac{\kappa'\,\mathrm{sn}\,u}{\mathrm{dn}\,u}$$

$$\mathrm{dn}\,(K - u) = \frac{\kappa'}{\mathrm{dn}\,u} = \mathrm{dn}\,(K + u)$$

$$\mathrm{tn}\,(K - u) = \frac{1}{\kappa'\,\mathrm{tn}\,u} \qquad \mathrm{tn}\,(K + u) = -\frac{}{\kappa'\,\mathrm{tn}\,u}$$

11.43. Legendre's Addition Formula for his E. I. II,

$$E\phi = \int \Delta\phi \cdot d\phi = \int \mathrm{dn}^2\,u \cdot du, \qquad \phi = \int \mathrm{dn}\,u \cdot du = \mathrm{am}\,u.$$

$$E\phi + E\psi - E\sigma = \kappa^2 \sin\phi \sin\psi \sin\sigma,\ \psi = \mathrm{am}\,v,\ \sigma = \mathrm{am}\,(v + u)$$

or, in Jacobi's notation,

$$\mathrm{zn}\,u + \mathrm{zn}\,v - \mathrm{zn}\,(u + v) = \kappa^2\,\mathrm{sn}\,u\,\mathrm{sn}\,v\,\mathrm{sn}\,(v + u),$$

the secular part cancelling.

Another form of the Addition Theorem for Legendre's E. I. II,

$$E\sigma - E\theta - 2E\psi = \frac{-2\kappa^2 \sin\psi \cos\psi\, \Delta\psi \sin^2\phi}{1 - \kappa^2 \sin^2\phi \sin^2\psi},\ \theta = \mathrm{am}\,(v - u)$$

or, in Jacobi's notation,

$$\mathrm{zn}\,(v + u) + \mathrm{zn}\,(v - u) - 2\,\mathrm{zn}\,v = \frac{-2\kappa^2\,\mathrm{sn}\,v\,\mathrm{cn}\,v\,\mathrm{dn}\,v\,\mathrm{sn}^2\,u}{1 - \kappa^2\,\mathrm{sn}^2\,u\,\mathrm{sn}^2\,v}.$$

11.5. The Elliptic Integral of the Third Kind (E. I. III) is given by the next integration with respect to u, and introduces Jacobi's Theta Function, Θu, defined by,

$$\frac{d \log \Theta u}{du} = Zu = \mathrm{zn}\,u$$

$$\frac{\Theta u}{\Theta o} = \exp.\ \int_0 \mathrm{zn}\,u \cdot du.$$

Integrating then with respect to u,

$$\log \Theta\,(v + u) - \log \Theta\,(v - u) - 2u\,\mathrm{zn}\,v = \int_0 \frac{-2\kappa^2\,\mathrm{sn}\,v\,\mathrm{cn}\,v\,\mathrm{dn}\,v\,\mathrm{sn}^2\,u}{1 - \kappa^2\,\mathrm{sn}^2\,u\,\mathrm{sn}^2\,v}\,du,$$

and this integral is Jacobi's standard form of the E. I. III, and is denoted by $-2\Pi\,(u, v)$; thus,

$$\Pi\,(u, v) = \int \frac{\kappa^2\,\mathrm{sn}\,v\,\mathrm{cn}\,v\,\mathrm{dn}\,v\,\mathrm{sn}^2\,u}{1 - \kappa^2\,\mathrm{sn}^2\,u\,\mathrm{sn}^2\,v}\,du = u\,\mathrm{zn}\,v + \tfrac{1}{2} \log \frac{\Theta\,(v - u)}{\Theta\,(v + u)}.$$

Jacobi's Eta Function, $\mathrm{H}v$, is defined by

$$\frac{\mathrm{H}v}{\Theta v} = \sqrt{\kappa}\,\mathrm{sn}\,v,$$

and then

$$\frac{d \log \mathrm{H}v}{dv} = \frac{\mathrm{cn}\,v\,\mathrm{dn}\,v}{\mathrm{sn}\,v} + \mathrm{zn}\,v, \text{ denoted by zs } v;$$

so that

$$\int_0 \frac{\frac{\operatorname{cn} v \operatorname{dn} v}{\operatorname{sn} v} du}{1 - \kappa^2 \operatorname{sn}^2 u \operatorname{sn}^2 v} = u \frac{\operatorname{cn} v \operatorname{dn} v}{\operatorname{sn} v} + \Pi(u, v)$$

$$= u \operatorname{zs} v + \frac{1}{2} \log \frac{\Theta(v-u)}{\Theta(v+u)}$$

$$= \frac{1}{2} \log \frac{\Theta(v-u)}{\Theta(v+u)} e^{2u \cdot \operatorname{zs} v}$$

This gives Legendre's standard E. I. III,

$$\int \frac{M}{1 + n \sin^2 \phi} \frac{d\phi}{\Delta\phi},$$

where we put $n = -\kappa^2 \operatorname{sn}^2 v = -\kappa^2 \sin^2 \psi$,

$$M^2 = -\left(1 + \frac{\kappa^2}{n}\right)(1+n) = \frac{\cos^2 \psi \Delta^2 \psi}{\sin^2 \psi} = \frac{\operatorname{cn}^2 v \operatorname{dn}^2 v}{\operatorname{sn}^2 v};$$

the normalising multiplier, M.

The E. I. III arises in the dynamics of the gyroscope, top, spherical pendulum, and in Poinsot's herpolhode. It can be visualized in the solid angle of a slant cone, or in the perimeter of the reciprocal cone, a sphero-conic, or in the magnetic potential of the circular base.

11.51. We arrive here at the definitions of the functions in the tables. Jacobi's Θu and $\mathrm{H} u$ are normalised by the divisors Θo and $\mathrm{H}K$, and with $r = 90e$,

$$D(r) \text{ denotes } \frac{\Theta eK}{\Theta K}, \qquad A(r) \text{ denotes } \frac{\mathrm{H}eK}{\mathrm{H}K}$$

while $B(r) = A(90 - r)$, $C(r) = D(90 - r)$, and $B(0) = A(90) = D(0) = C(90)$ $= 1$, $C(0) = D(90) = \frac{1}{\sqrt{\kappa}}$.

Then in the former definitions,

$$\frac{A(r)}{D(r)} = \frac{A(90)}{D(90)} \operatorname{sn} u = \sqrt{\kappa'} \operatorname{sn} eK$$

$$\frac{B(r)}{D(r)} = \frac{B(0)}{D(0)} \operatorname{cn} u = \operatorname{cn} eK$$

$$\frac{C(r)}{D(r)} = \frac{C(0)}{D(0)} \operatorname{dn} u = \frac{\operatorname{dn} eK}{\sqrt{\kappa'}}.$$

Then, with $u = eK$, $v = fK$, $r = 90e$, $s = 90f$,

$$(u, v) = eK \operatorname{zn} fK + \frac{1}{2} \log \frac{\Theta(f-e)K}{\Theta(f+e)K}$$

$$= eK\, E(s) + \frac{1}{2} \log \frac{D(s-r)}{D(s+r)}$$

$$\operatorname{zn} fK = E(s), \qquad \operatorname{zn}(1-f)K = E(90-s) = G(s).$$

The Jacobian multiplication relations of his theta functions can then be rewritten

$$D(r+s)D(r-s) = D^2rD^2s - \tan^2\theta A^2rA^2s,$$

$$A(r+s)A(r-s) = A^2rD^2s - D^2rA^2s,$$

$$B(r+s)B(r-s) = B^2rB^2s - A^2rA^2s.$$

But unfortunately for the physical applications the number s proves usually to be imaginary or complex, and Jacobi's expression is useless; Legendre calls this the circular form of the E. I. III, the logarithmic or hyperbolic form corresponding to real s. However, the complete E. I. III between the limits $0 < \phi < \frac{1}{2}\pi$, or $0 < u < K$, $0 < e < 1$, can always be expressed by the E. I. I and II, as Legendre pointed out.

11.6. The standard forms are given above to which an elliptic integral must be reduced when the result is required in a numerical form taken from the Tables. But in a practical problem the integral arises in a general algebraical form, and theory shows that the result can always be made, by a suitable substitution, to depend on three differential elements, of the I, II, III kind,

$$\text{I} \quad \frac{ds}{\sqrt{S}}$$

$$\text{II} \quad (s-a)\frac{ds}{\sqrt{S}}$$

$$\text{III} \quad \frac{1}{(s-\sigma)}\frac{ds}{\sqrt{S}}$$

where S is a cubic in the variable s which may be written, when resolved into three factors,

$$S = 4\cdot s - s_1\cdot s - s_2\cdot s - s_3$$

in the sequence $\infty > s_1 > s_2 > s_3 > -\infty$, and normalised to a standard form of zero degree these differential elements are

$$\text{I} \quad \frac{\sqrt{s_1 - s_3}\, ds}{\sqrt{S}}$$

$$\text{II} \quad \frac{s-a}{\sqrt{s_1 - s_3}}\frac{ds}{\sqrt{S}}$$

$$\text{III} \quad \frac{\frac{1}{2}\sqrt{\Sigma}}{s-\sigma}\frac{ds}{\sqrt{S}}$$

Σ denoting the value of S when $s = \sigma$.

The relative positions of s and σ in the intervals of the sequence require preliminary consideration before introducing the Elliptic Functions and their notation.

11.7. For the E. I. I and its representation in a tabular form with

$$\kappa^2 = \frac{s_2 - s_3}{s_1 - s_3}, \qquad \kappa'^2 = \frac{s_1 - s_2}{s_1 - s_3},$$

$$K = \int_{s_1, s_3}^{\infty, s_2} \frac{\sqrt{s_1 - s_3}\, ds}{\sqrt{S}}, \qquad K' = \int_{s_2, -\infty}^{s_1, s_3} \frac{\sqrt{s_1 - s_3}\, ds}{\sqrt{-S}},$$

and utilizing the inverse notation, then in the first interval of the sequence,

$$\infty > s > s_1$$

$$eK = \int_s^\infty \frac{\sqrt{s_1 - s_3}\, ds}{\sqrt{S}} = \mathrm{sn}^{-1}\sqrt{\frac{s_1 - s_3}{s - s_3}} = \mathrm{cn}^{-1}\sqrt{\frac{s - s_1}{s - s_3}} = \mathrm{dn}^{-1}\sqrt{\frac{s - s_2}{s - s_3}}$$

$$(1 - e)K = \int_{s_1}^{s} \frac{\sqrt{s_1 - s_3}\, ds}{\sqrt{S}} = \mathrm{sn}^{-1}\sqrt{\frac{s - s_1}{s - s_2}} = \mathrm{cn}^{-1}\sqrt{\frac{s_1 - s_2}{s - s_2}} = \mathrm{dn}^{-1}\sqrt{\frac{s_1 - s_2 \cdot s - s_3}{s_1 - s_3 \cdot s - s_2}}$$

indicating the substitutions,

$$\frac{s_1 - s_3}{s - s_3} = \sin^2 \phi = \mathrm{sn}^2\, eK, \qquad \frac{s - s_1}{s - s_2} = \sin^2 \psi = \mathrm{sn}^2\, (1 - e)K.$$

In the next interval S is negative, and the comodulus κ' is required.

$$s_1 > s > s_2$$

$$fK' = \int^{s_1} \frac{\sqrt{s_1 - s_3}\, ds}{\sqrt{-S}} = \mathrm{sn}^{-1}\sqrt{\frac{s_1 - s}{s_1 - s_2}} = \mathrm{cn}^{-1}\sqrt{\frac{s - s_2}{s_1 - s_2}} = \mathrm{dn}^{-1}\sqrt{\frac{s - s_3}{s_1 - s_3}}$$

$$(1 - f)K' = \int_{s_2}^{s} \frac{\sqrt{s_1 - s_3}\, ds}{\sqrt{-S}} = \mathrm{sn}^{-1}\sqrt{\frac{s_1 - s_3 \cdot s - s_2}{s_1 - s_2 \cdot s - s_3}} = \mathrm{cn}^{-1}\sqrt{\frac{s_2 - s_3 \cdot s_1 - s}{s_1 - s_2 \cdot s - s_1}}$$

$$= \mathrm{dn}^{-1}\sqrt{\frac{s_2 - s_3}{s - s_3}}$$

S is positive again in the next interval, and the modulus is κ.

$$s_2 > s > s_3$$

$$(1 - e)K = \int_s^{s_2} \frac{\sqrt{s_1 - s_3}\, ds}{\sqrt{S}} = \mathrm{sn}^{-1}\sqrt{\frac{s_1 - s_3 \cdot s_2 - s}{s_2 - s_3 \cdot s_1 - s}} = \mathrm{cn}^{-1}\sqrt{\frac{s_1 - s_2 \cdot s - s_3}{s_2 - s_3 \cdot s_1 - s}}$$

$$= \mathrm{dn}^{-1}\sqrt{\frac{s_1 - s_2}{s_1 - s}}$$

$$eK = \int_{s_3}^{s} \frac{\sqrt{s_1 - s_3}\, ds}{\sqrt{S}} = \mathrm{sn}^{-1}\sqrt{\frac{s - s_3}{s_2 - s_3}} = \mathrm{cn}^{-1}\sqrt{\frac{s_2 - s}{s_2 - s_3}} = \mathrm{dn}^{-1}\sqrt{\frac{s_1 - s}{s_1 - s_3}}$$

indicating the substitutions,

$$\frac{s_1 - s_2}{s_1 - s} = \Delta^2\psi = \mathrm{dn}^2\, (1 - e)K, \qquad \frac{s - s_3}{s_2 - s_3} = \sin^2 \phi = \mathrm{sn}^2\, eK$$

$$s = s_2 \sin^2 \phi + s_3 \cos^2 \phi.$$

S is negative again in the last interval, and the modulus κ'.

$$s_3 > s > -\infty$$

$$(1-f)K' = \int_s^{s_3} \frac{\sqrt{s_1 - s_3}\, ds}{\sqrt{-S}} = \mathrm{sn}^{-1}\sqrt{\frac{s_3 - s}{s_2 - s}} = \mathrm{cn}^{-1}\sqrt{\frac{s_2 - s_3}{s_2 - s}} = \mathrm{dn}^{-1}\sqrt{\frac{s_2 - s_3 \cdot s_1 - s}{s_1 - s_3 \cdot s_2 - s}}$$

$$fK' = \int_{-\infty}^{s} \frac{\sqrt{s_1 - s_3}\, ds}{\sqrt{-S}} = \mathrm{sn}^{-1}\sqrt{\frac{s_1 - s_3}{s_1 - s}} = \mathrm{cn}^{-1}\sqrt{\frac{s_3 - s}{s_1 - s}} = \mathrm{dn}^{-1}\sqrt{\frac{s_2 - s}{s_1 - s}}$$

11.8. For the notation of the E. I. II and the various reductions, take the treatment given in the Trans. Am. Math. Soc., 1907, vol. 8, p. 450. The Jacobian Zeta Function and the *Er*, *Gr* of the Tables, are defined by the standard integral

$$\int_{s_3}^{s} \frac{s_1 - s}{\sqrt{s_1 - s_3}} \frac{ds}{\sqrt{S}} = \int_0^{\phi} \Delta\phi \cdot d\phi = E\phi = \int_0^{e} \mathrm{dn}^2 (eK) \cdot d(eK) = E \,\mathrm{am}\, eK = eH + \mathrm{zn}\, eK,$$

or,

$$\int_{s_2}^{\sigma} \frac{\sigma - s_3}{\sqrt{s_1 - s_3}} \frac{d\sigma}{\sqrt{-\Sigma}} = \int_0^{f} \mathrm{dn}^2 (fK') \cdot d(fK') = E \,\mathrm{am}\, fK' = fH' + \mathrm{zn}\, fK',$$

where zn is Jacobi's Zeta Function, and H, H' the complete E. I. II to modulus κ, κ', defined by,

$$H = \int_0^{\frac{\pi}{2}} \Delta(\phi, \kappa)\, d\phi = \int_0^{1} \mathrm{dn}^2 (eK) \cdot d(eK)$$

$$H' = \int_0^{\frac{\pi}{2}} \Delta(\phi, \kappa')\, d\phi = \int_0^{1} \mathrm{dn}^2 (fK') \cdot d(fK').$$

The function zn u is derived by logarithmic differentiation of Θu,

$$\mathrm{zn}\, u = \frac{d \log \Theta u}{du}, \text{ or concisely,}$$

$$\Theta u = \exp. \int \mathrm{zn}\, u \cdot du,$$

and a function zs u is derived similarly from

$$\begin{aligned} \mathrm{zs}\, u &= \frac{d \log Hu}{du} \\ &= \frac{d \log \Theta u}{du} + \frac{d \log \mathrm{sn}\, u}{du} \\ &= \mathrm{zn}\, u + \frac{\mathrm{cn}\, u \,\mathrm{dn}\, u}{\mathrm{sn}\, u}. \end{aligned}$$

For the incomplete E. I. II in the regions,

$$\infty > s > s_1 > s_2 > s > s_3$$

and

$$\mathrm{sn}^2\, eK = \frac{s_1 - s_3}{s - s_3} \text{ or } \frac{s - s_3}{s_2 - s_3},$$

$$\int_s^{s_1} \frac{s - s_1}{\sqrt{s_1 - s_3}} \frac{ds}{\sqrt{S}} = \int_s^{s_2} \frac{s_2 - s}{s - s_3} \frac{\sqrt{s - s_3}}{\sqrt{S}} ds = -(1 - e)H + \text{zs}\, eK$$

$$\int \frac{s - s_2}{\sqrt{s_1 - s_3}} \frac{ds}{\sqrt{S}} = \kappa^2 \int \frac{s_1 - s}{s - s_3} \frac{\sqrt{s_1 - s_3}}{\sqrt{S}} ds = -(1 - e)(H - \kappa'^2 K) + \text{zs}\, eK$$

$$\int \frac{s - s_3}{\sqrt{s_1 - s_3}} \frac{ds}{\sqrt{S}} = \int \frac{s_2 - s_3}{s - s_3} \frac{\sqrt{s_1 - s_3}}{\sqrt{S}} ds = (1 - e)(K - H) + \text{zs}\, eK$$

the integrals being ∞ at the upper limit, $s = \infty$, or at the lower limit, $s = s_3$ where $e = 0$ and $\text{zs}\, eK = \infty$.

So also,

$$\int_{s,\, s_1}^{\infty,\, s} \frac{s - s_2}{s - s_3} \frac{\sqrt{s_1 - s_3}}{\sqrt{S}} ds = \int_{s_3,\, s}^{s,\, s_2} \frac{s_1 - s}{\sqrt{s_1 - s_3}} \frac{ds}{\sqrt{S}} = \begin{matrix} eH + \text{zn}\, eK \\ (1 - e)H - \text{zn}\, eK \end{matrix}$$

$$\int \frac{s - s_1}{s - s_3} \frac{\sqrt{s_1 - s_3}}{\sqrt{S}} ds = \int \frac{s_2 - s}{\sqrt{s_1 - s_3}} \frac{ds}{\sqrt{S}} = \begin{matrix} e(H - \kappa'^2 K) + \text{zn}\, eK \\ (1 - e)(H - \kappa'^2 K) - \text{zn}\, eK \end{matrix}$$

$$\int \frac{s_2 - s_3}{s - s_3} \frac{\sqrt{s_1 - s_3}}{\sqrt{S}} ds = \int \frac{s - s_3}{\sqrt{s_1 - s_3}} \frac{ds}{\sqrt{S}} = \begin{matrix} e(K - H) - \text{zn}\, eK \\ (1 - e)(K - H) + \text{zn}\, eK \end{matrix}$$

Similarly, for the variable σ in the regions

$$s_1 > \sigma > s_2 > s_3 > \sigma > -\infty$$

Σ negative, and

$$\text{sn}^2 fK' = \frac{s_1 - \sigma}{s_1 - s_2} \text{ or } \frac{s_1 - s_3}{s_1 - \sigma}$$

$$\int_{\sigma,\, s_2}^{s_1,\, \sigma} \frac{s_1 - \sigma}{\sqrt{s_1 - s_3}} \frac{d\sigma}{\sqrt{-\Sigma}} = \int_{-\infty,\, \sigma}^{\sigma,\, s_3} \frac{s_1 - s_2}{s_1 - \sigma} \frac{\sqrt{s_1 - s_3}}{\sqrt{-\Sigma}} d\sigma = \begin{matrix} f(K' - H') - \text{zn}\, fK' \\ (1 - f)(K' - H') + \text{zn}\, fK' \end{matrix}$$

$$\int \frac{\sigma - s_2}{\sqrt{s_1 - s_3}} \frac{d\sigma}{\sqrt{-\Sigma}} = \int \frac{s_3 - \sigma}{s_1 - \sigma} \frac{\sqrt{s_1 - s_3}}{\sqrt{-\Sigma}} d\sigma = \begin{matrix} f(H' - \kappa'^2 K') + \text{zn}\, fK' \\ (1 - f)(H' - \kappa'^2 K') - \text{zn}\, fK' \end{matrix}$$

$$\int \frac{\sigma - s_3}{\sqrt{s_1 - s_3}} \frac{d\sigma}{\sqrt{-\Sigma}} = \int \frac{s_2 - \sigma}{s_1 - \sigma} \frac{\sqrt{s_1 - s_3}}{\sqrt{-\Sigma}} d\sigma = \begin{matrix} fH' + \text{zn}\, fK' \\ (1 - f)H' - \text{zn}\, fK' \end{matrix}$$

$$\int_{s_2}^{\sigma} \frac{s_1 - s_2}{s_1 - \sigma} \frac{\sqrt{s_1 - s_3}}{\sqrt{-\Sigma}} d\sigma = \int_{\sigma}^{s_3} \frac{s_1 - \sigma}{\sqrt{s_1 - s_3}} \frac{d\sigma}{\sqrt{-\Sigma}} = (1 - f)(K' - H') + \text{zs}\, fK'$$

$$\kappa'^2 \int \frac{s_3 - \sigma}{s_1 - \sigma} \frac{\sqrt{s_1 - s_3}}{\sqrt{-\Sigma}} d\sigma = \int \frac{s_2 - \sigma}{\sqrt{s_1 - s_3}} \frac{d\sigma}{\sqrt{-\Sigma}} = -(1 - f)(H' - \kappa^2 K') + \text{zs}\, fK'$$

$$\int \frac{s_2 - \sigma}{s_1 - \sigma} \frac{\sqrt{s_1 - s_3}}{\sqrt{-\Sigma}} d\sigma = \int \frac{s_3 - \sigma}{\sqrt{s_1 - s_3}} \frac{d\sigma}{\sqrt{-\Sigma}} = -(1 - f)H' + \text{zs}\, fK'$$

these last three integrals being infinite at the upper limit, $\sigma = s_1$, or lower limit $\sigma = -\infty$, where $f = 0$, $\text{zs}\, fK' = \infty$.

Putting $e = 1$ or $f = 1$ any of these forms will give the complete E. I. II, noticing that zn K' and zs K' are zero.

11.9. In dealing practically with an E. I. III it is advisable to study it first in the algebraical form of Weierstrass,

$$\int \frac{\frac{1}{2}\sqrt{\Sigma}\, ds}{(s-\sigma)\sqrt{S}},$$

where $S = 4\cdot s - s_1\cdot s - s_2\cdot s - s_3$, Σ the same function of σ, and begin by examining the sequence of the quantities s, σ, s_1, s_2, s_3

Then in the region

$$s > s_1 > s_2 > \sigma > s_3,$$

put

$$s - s_3 = \frac{s_1 - s_3}{\operatorname{sn}^2 u}, \quad \sigma - s_3 = (s_2 - s_3)\operatorname{sn}^2 v, \quad \kappa^2 = \frac{s_2 - s_3}{s_1 - s_3},$$

$$s - \sigma = \frac{s_1 - s_3}{\operatorname{sn}^2 u}(1 - \kappa^2 \operatorname{sn}^2 u \operatorname{sn}^2 v), \quad \frac{\sqrt{s_1 - s_3}\, ds}{\sqrt{S}} = du,$$

$$\sqrt{\Sigma} = \sqrt{s_1 - s_3}\,(s_2 - s_3)\operatorname{sn} v \operatorname{cn} v \operatorname{dn} v, \text{ making}$$

$$\int \frac{\frac{1}{2}\sqrt{\Sigma}}{s - \sigma}\frac{ds}{\sqrt{S}} = \int \frac{\kappa^2 \operatorname{sn} v \operatorname{cn} v \operatorname{dn} v \operatorname{sn}^2 u}{1 - \kappa^2 \operatorname{sn}^2 u \operatorname{sn}^2 v}\, du = \Pi(u, v).$$

But in the region,

$$\sigma > s_1 > s_2 > s > s_3,$$

$$s - s_3 = (s_2 - s_3)\operatorname{sn}^2 u, \quad \sigma - s_3 = \frac{s_1 - s_3}{\operatorname{sn}^2 v}, \quad \frac{1}{2}\sqrt{\Sigma} = (s_1 - s_3)^{\frac{3}{2}}\frac{\operatorname{cn} v \operatorname{dn} v}{\operatorname{sn}^3 v},$$

$$\sigma - s = \frac{s_1 - s_3}{\operatorname{sn}^2 v}(1 - \kappa^2 \operatorname{sn}^2 u \operatorname{sn}^2 v),$$

making,

$$\int \frac{\frac{1}{2}\sqrt{\Sigma}}{\sigma - s}\frac{ds}{\sqrt{S}} = \int \frac{\frac{\operatorname{cn} v \operatorname{dn} v}{\operatorname{sn} v}\, du}{1 - \kappa^2 \operatorname{sn}^2 u \operatorname{sn}^2 v} = \Pi_1 = \Pi(u, v) + u\frac{\operatorname{cn} v \operatorname{dn} v}{\operatorname{sn} v}.$$

In a dynamical application the sequence is usually

$$s > s_1 > \sigma > s_2 > s > s_3$$

or

$$s > s_1 > s_2 > s > s_3 > \sigma,$$

making Σ negative, and the E. I. III is then called circular; the parameter v is then imaginary, and the expression by the Theta function is illusory.

The complete E. I. III, however, was shown by Legendre to be tractable and falls into four classes, lettered (l') (m'), p. 138, (i'), (k'), pp. 133, 134 (Fonctions elliptiques, I).

$s_1 > \sigma > s_2$

$$\operatorname{sn}^2 fK' = \frac{s_1 - \sigma}{s_1 - s_2}$$

$$\operatorname{cn}^2 fK' = \frac{\sigma - s_2}{s_1 - s_2}$$

$$\operatorname{dn}^2 fK' = \frac{\sigma - s_3}{s_1 - s_3}$$

A.

$$\infty > s > s_1 \int_{s_1}^{\infty} \frac{\frac{1}{2}\sqrt{-\Sigma}}{s-\sigma} \frac{ds}{\sqrt{S}} = A(fK') = \tfrac{1}{2}\pi(1-f) - K \operatorname{zn} fK'$$

B.

$$s_2 > s > s_3 \int_{s_3}^{s_2} \frac{\frac{1}{2}\sqrt{-\Sigma}}{\sigma - s} \frac{ds}{\sqrt{S}} = B(fK') = \tfrac{1}{2}\pi f + K \operatorname{zn} fK'$$

$$A + B = \tfrac{1}{2}\pi.$$

$s_3 > \sigma > -\infty$

$$\operatorname{sn}^2 fK' = \frac{s_1 - s_3}{s_1 - \sigma}$$

$$\operatorname{cn}^2 fK' = \frac{s_3 - \sigma}{s_1 - \sigma}$$

$$\operatorname{dn}^2 fK' = \frac{s_2 - \sigma}{s_1 - \sigma}$$

C.

$$\infty > s > s_1 \int_{s_1}^{\infty} \frac{\frac{1}{2}\sqrt{-\Sigma}}{s-\sigma} \frac{ds}{\sqrt{S}} = C(fK') = K \operatorname{zs} fK' - \tfrac{1}{2}\pi(1-f)$$

D.

$$s_2 > s > s_3 \int_{s_3}^{s_2} \frac{\frac{1}{2}\sqrt{-\Sigma}}{s-\sigma} \frac{ds}{\sqrt{S}} = D(fK') = K \operatorname{zs} fK' + \tfrac{1}{2}\pi f$$

$$D - C = \tfrac{1}{2}\pi.$$

TABLES OF ELLIPTIC FUNCTIONS

By Col. R. L. Hippisley

K = 1.5737921309, K′ = 3.831742000, E = 1.5678090740, E′ = 1.012663506,

r	Fφ	φ		E(r)	D(r)	A(r)
0	0.00000 00000	0°	0′	0.00000 00000	1.00000 00000	0.00000 00000
1	0.01748 65792	1	0	0.00006 64649	1.00000 05812	0.01745 23906
2	0.03497 31585	2	0	0.00013 28485	1.00000 23240	0.03489 94650
3	0.05245 97377	3	0	0.00019 90699	1.00000 52264	0.05233 59088
4	0.06994 63169	4	0	0.00026 50480	1.00000 92847	0.06975 64107
5	0.08743 28962	5	1	0.00033 07023	1.00001 44942	0.08715 56642
6	0.10491 94754	6	1	0.00039 59525	1.00002 08483	0.10452 83693
7	0.12240 60546	7	1	0.00046 07190	1.00002 83393	0.12186 92343
8	0.13989 26338	8	1	0.00052 49226	1.00003 69582	0.13917 29770
9	0.15737 92131	9	1	0.00058 84849	1.00004 66945	0.15643 43264
10	0.17486 57923	10	1	0.00065 13283	1.00005 75362	0.17364 80247
11	0.19235 23716	11	1	0.00071 33760	1.00006 94702	0.19080 88283
12	0.20983 89508	12	1	0.00077 45523	1.00008 24819	0.20791 15101
13	0.22732 55300	13	1	0.00083 47824	1.00009 65555	0.22495 08603
14	0.24481 21092	14	2	0.00089 39929	1.00011 16738	0.24192 16887
15	0.26229 86885	15	2	0.00095 21114	1.00012 78184	0.25881 88257
16	0.27978 52677	16	2	0.00100 90670	1.00014 49696	0.27563 71244
17	0.29727 18469	17	2	0.00106 47903	1.00016 31066	0.29237 14618
18	0.31475 84262	18	2	0.00111 92132	1.00018 22072	0.30901 67404
19	0.33224 50054	19	2	0.00117 22694	1.00020 22482	0.32556 78900
20	0.34973 15846	20	2	0.00122 38941	1.00022 32051	0.34201 98690
21	0.36721 81639	21	2	0.00127 40244	1.00024 50525	0.35836 76658
22	0.38470 47431	22	2	0.00132 25992	1.00026 77636	0.37460 63009
23	0.40219 13223	23	2	0.00136 95594	1.00029 13109	0.39073 08277
24	0.41967 79016	24	2	0.00141 48476	1.00031 56657	0.40673 63347
25	0.43716 44808	25	3	0.00145 84087	1.00034 07982	0.42261 79464
26	0.45465 10600	26	3	0.00150 01897	1.00036 66779	0.43837 08251
27	0.47213 76393	27	3	0.00154 01398	1.00039 32731	0.45399 01723
28	0.48962 42185	28	3	0.00157 82103	1.00042 05516	0.46947 12303
29	0.50711 07977	29	3	0.00161 43549	1.00044 84801	0.48480 92833
30	0.52459 73770	30	3	0.00164 85297	1.00047 70246	0.49999 96593
31	0.54208 39562	31	3	0.00168 06931	1.00050 61502	0.51503 77311
32	0.55957 05354	32	3	0.00171 08062	1.00053 58215	0.52991 89180
33	0.57705 71147	33	3	0.00173 88322	1.00056 60024	0.54463 86870
34	0.59454 36939	34	3	0.00176 47373	1.00059 66561	0.55919 25543
35	0.61203 02731	35	3	0.00178 84901	1.00062 77451	0.57357 60867
36	0.62951 68524	36	3	0.00181 00617	1.00065 92318	0.58778 49028
37	0.64700 34316	37	3	0.00182 94261	1.00069 10776	0.60181 46744
38	0.66449 00108	38	3	0.00184 65599	1.00072 32438	0.61566 11280
39	0.68197 65900	39	3	0.00186 14423	1.00075 56912	0.62932 00458
40	0.69946 31693	40	3	0.00187 40556	1.00078 83803	0.64278 72670
41	0.71694 97485	41	4	0.00188 43845	1.00082 12712	0.65605 86895
42	0.73443 63278	42	4	0.00189 24166	1.00085 43239	0.66913 02706
43	0.75192 29070	43	4	0.00189 81424	1.00088 74981	0.68199 80287
44	0.76940 94862	44	4	0.00190 15552	1.00092 07533	0.69465 80439
45	78689 60655	45	4	0.00190 26510	1.00095 40492	0.70710 64600
90° r	Fψ	ψ		G(r)	C(r)	B(r)

$q = 0.000476569916867$, $\Theta 0 = 0.9990468602$, $H(K) = 0.2955029021$

B(r)	C(r)	G(r)	ψ		Fψ	90°-r
1.00000 00000	1.00190 80984	0.00000 00000	90°	0′	1.57379 21309	90
0.99984 76949	1.00190 75172	0.00006 63384	89	0	1.55630 55517	89
0.99939 08259	1.00190 57743	0.00013 25961	88	0	1.53881 89724	88
0.99862 95323	1.00190 28720	0.00019 86928	87	0	1.52133 23932	87
0.99756 40458	1.00189 88136	0.00026 45481	86	0	1.50384 58140	86
0.99619 46912	1.00189 36042	0.00033 00820	85	1	1.48635 92347	85
0.99452 18855	1.00188 72501	0.00039 52149	84	1	1.46887 26555	84
0.99254 61382	1.00187 97590	0.00045 98676	83	1	1.45138 60763	83
0.99026 80513	1.00187 11401	0.00052 39616	82	1	1.43389 94971	82
0.98768 83186	1.00186 14039	0.00058 74190	81	1	1.41641 29178	81
0.98480 77260	1.00185 05621	0.00065 01626	80	1	1.39892 63386	80
0.98162 71510	1.00183 86282	0.00071 21163	79	1	1.38143 97593	79
0.97814 75623	1.00182 56165	0.00077 32046	78	1	1.36395 31801	78
0.97437 00200	1.00181 15429	0.00083 33534	77	1	1.34646 66009	77
0.97029 56747	1.00179 64246	0.00089 24894	76	2	1.32898 00217	76
0.96592 57675	1.00178 02800	0.00095 05409	75	2	1.31149 34424	75
0.96126 16296	1.00176 31288	0.00100 74371	74	2	1.29400 68632	74
0.95630 46817	1.00174 49918	0.00106 31089	73	2	1.27652 02840	73
0.95105 64338	1.00172 58912	0.00111 74885	72	2	1.25903 37047	72
0.94551 84846	1.00170 58502	0.00117 05097	71	2	1.24154 71255	71
0.93969 25209	1.00168 48932	0.00122 21081	70	2	1.22406 05463	70
0.93358 03176	1.00166 30459	0.00127 22208	69	2	1.20657 39670	69
0.92718 37364	1.00164 03347	0.00132 07868	68	2	1.18908 73878	68
0.92050 47258	1.00161 67874	0.00136 77470	67	2	1.17160 08086	67
0.91354 53203	1.00159 24327	0.00141 30440	66	3	1.15411 42293	66
0.90630 76400	1.00156 73002	0.00145 66228	65	3	1.13662 76501	65
0.89879 38894	1.00154 14205	0.00149 84301	64	3	1.11914 10709	64
0.89100 63574	1.00151 48252	0.00153 84151	63	3	1.10165 44916	63
0.88294 74161	1.00148 75467	0.00157 65289	62	3	1.08416 79124	62
0.87461 95204	1.00145 96182	0.00161 27250	61	3	1.06668 13332	61
0.86602 52071	1.00143 10738	0.00164 69592	60	3	1.04919 47539	60
0.85716 70941	1.00140 19481	0.00167 91897	59	3	1.03170 81747	59
0.84804 78798	1.00137 22768	0.00170 93771	58	3	1.01422 15955	58
0.83867 03419	1.00134 20959	0.00173 74846	57	3	0.99673 50162	57
0.82903 73370	1.00131 14423	0.00176 34776	56	3	0.97924 84370	56
0.81915 17995	1.00128 03532	0.00178 73244	55	3	0.96176 18578	55
0.80901 67404	1.00124 88666	0.00180 89958	54	3	0.94427 52785	54
0.79863 52473	1.00121 70208	0.00182 84651	53	3	0.92678 86993	53
0.78801 04823	1.00118 48546	0.00184 57085	52	3	0.90930 21201	52
0.77714 56818	1.00115 24072	0.00186 07047	51	3	0.89181 55409	51
0.76604 41556	1.00111 97181	0.00187 34353	50	3	0.87432 89616	50
0.75470 92851	1.00108 68272	0.00188 38846	49	3	0.85684 23824	49
0.74314 45232	1.00105 37745	0.00189 20395	48	3	0.83935 58031	48
0.73135 33926	1.00102 06003	0.00189 78900	47	3	0.82186 92239	47
0.71933 94850	1.00098 73450	0.00190 14287	46	4	0.80438 26447	46
0.70710 64600	1.00095 40492	0.00190 26510	45	4	0.78689 60655	45
A(r)	D(r)	E(r)	φ		Fφ	r

K = 1.5828428043, K′ = 3.153385252, E = 1.5588871966, E′ = 1.040114396,

r	Fφ	φ		E(r)	D(r)	A(r)
0	0.00000 00000	0°	0′	0.00000 00000	1.00000 00000	0.00000 00000
1	0.01758 71423	1	0	0.00026 61187	1.00000 23404	0.01745 21509
2	0.03517 42845	2	1	0.00053 19095	1.00000 93587	0.03489 89861
3	0.05276 14268	3	1	0.00079 70448	1.00002 10463	0.05233 51918
4	0.07034 85691	4	2	0.00106 11979	1.00003 73890	0.06975 54570
5	0.08793 57113	5	2	0.00132 40433	1.00005 83670	0.08715 44758
6	0.10552 28536	6	3	0.00158 52573	1.00008 39546	0.10452 69489
7	0.12310 99959	7	3	0.00184 45182	1.00011 41206	0.12186 75849
8	0.14069 71382	8	4	0.00210 15066	1.00014 88284	0.13917 11019
9	0.15828 42804	9	4	0.00235 59064	1.00018 80356	0.15643 22298
10	0.17587 14227	10	5	0.00260 74044	1.00023 16945	0.17364 57109
11	0.19345 85650	11	5	0.00285 56913	1.00027 97518	0.19080 63023
12	0.21104 57072	12	5	0.00310 04619	1.00033 21491	0.20790 87771
13	0.22863 28495	13	6	0.00334 14153	1.00038 88224	0.22494 79261
14	0.24621 99918	14	6	0.00357 82555	1.00044 97028	0.24191 85595
15	0.26380 71340	15	7	0.00381 06920	1.00051 47160	0.25881 55080
16	0.28139 42763	16	7	0.00403 84394	1.00058 37829	0.27563 36252
17	0.29898 14186	17	7	0.00426 12186	1.00065 68193	0.29236 77883
18	0.31656 85609	18	8	0.00447 87567	1.00073 37362	0.30901 29003
19	0.33415 57031	19	8	0.00469 07873	1.00081 44399	0.32556 38912
20	0.35174 28454	20	8	0.00489 70511	1.00089 88322	0.34201 57197
21	0.36932 99877	21	9	0.00509 72961	1.00098 68100	0.35836 33745
22	0.38691 71299	22	9	0.00529 12778	1.00107 82664	0.37460 18764
23	0.40450 42722	23	9	0.00547 87596	1.00117 30898	0.39072 62791
24	0.42209 14145	24	10	0.00565 95131	1.00127 11647	0.40673 16711
25	0.43967 85568	25	10	0.00583 33185	1.00137 23717	0.42261 31771
26	0.45726 56990	26	10	0.00599 99643	1.00147 65874	0.43836 59597
27	0.47485 28413	27	11	0.00615 92485	1.00158 36848	0.45398 52206
28	0.49243 99836	28	11	0.00631 09780	1.00169 35336	0.46946 62019
29	0.51002 71258	29	11	0.00645 49693	1.00180 59998	0.48480 41881
30	0.52761 42681	30	11	0.00659 10484	1.00192 09464	0.49999 45073
31	0.54520 14104	31	12	0.00671 90513	1.00203 82334	0.51503 25321
32	0.56278 85526	32	12	0.00683 88242	1.00215 77178	0.52991 36820
33	0.58037 56949	33	12	0.00695 02232	1.00227 92542	0.54463 34239
34	0.59796 28372	34	12	0.00705 31150	1.00240 26944	0.55918 72740
35	0.61554 99795	35	12	0.00714 73769	1.00252 78880	0.57357 07990
36	0.63313 71217	36	13	0.00723 28968	1.00265 46826	0.58777 96173
37	0.65072 42640	37	13	0.00730 95735	1.00278 29236	0.60180 94008
38	0.66831 14063	38	13	0.00737 73166	1.00291 24548	0.61565 58756
39	0.68589 85485	39	13	0.00743 60469	1.00304 31183	0.62931 48239
40	0.70348 56908	40	13	0.00748 56962	1.00317 47551	0.64278 20847
41	0.72107 28331	41	13	0.00752 62073	1.00330 72046	0.65605 35555
42	0.73865 99754	42	13	0.00755 75345	1.00344 03056	0.66912 51936
43	0.75624 71176	43	13	0.00757 96433	1.00357 38959	0.68199 30169
44	0.77383 42599	44	13	0.00759 25102	1.00370 78127	0.69465 31055
45	0.79142 14022	45	13	0.00759 61235	1.00384 18928	0.70710 16026
90–r	Fψ	ψ		G(r)	C(r)	B(r)

$q = 0.00191359459017$, $\Theta\,0 = 0.9961728108$, $HK = 0.418305976553$

B(r)	C(r)	G(r)	ψ	Fψ	90−r
1.00000 00000	1.00768 37857	0.00000 00000	90° 0′	1.58284 28043	90
0.99984 76907	1.00768 14453	0.00026 40908	89 0	1.56525 56621	89
0.99939 08092	1.00767 44270	0.00052 78635	88 1	1.54766 85198	88
0.99862 94947	1.00766 27394	0.00079 10004	87 1	1.53008 13775	87
0.99756 39792	1.00764 63966	0.00105 31846	86 2	1.51249 42353	86
0.99619 45873	1.00762 54187	0.00131 41001	85 2	1.49490 70930	85
0.99452 17362	1.00759 98311	0.00157 34327	84 3	1.47731 99507	84
0.99254 59357	1.00756 96650	0.00183 08697	83 3	1.45973 28084	83
0.99026 77878	1.00753 49572	0.00208 61008	82 4	1.44214 56662	82
0.98768 79866	1.00749 57500	0.00233 88183	81 4	1.42445 85239	81
0.98480 73181	1.00745 20912	0.00258 87173	80 4	1.40697 13816	80
0.98162 66600	1.00740 40338	0.00283 54962	79 5	1.38938 42394	79
0.97814 69814	1.00735 16366	0.00307 88572	78 5	1.37179 70971	78
0.97436 93426	1.00729 49632	0.00331 85063	77 6	1.35420 99548	77
0.97029 48945	1.00723 40828	0.00355 41538	76 6	1.33662 28125	76
0.96592 48785	1.00716 90696	0.00378 55150	75 7	1.31903 56703	75
0.96126 06262	1.00710 00027	0.00401 23098	74 7	1.30144 85280	74
0.95630 35586	1.00702 69663	0.00423 42636	73 7	1.28386 13857	73
0.95105 51861	1.00695 00494	0.00445 11077	72 8	1.26627 42435	72
0.94551 71076	1.00686 93457	0.00466 25790	71 8	1.24868 71012	71
0.93969 10107	1.00678 49535	0.00486 84209	70 8	1.23109 99589	70
0.93357 86703	1.00669 69756	0.00506 83836	69 9	1.21351 28167	69
0.92718 19488	1.00660 55192	0.00526 22237	68 9	1.19592 56744	68
0.92050 27950	1.00651 06958	0.00544 97055	67 9	1.17833 85321	67
0.91354 32440	1.00641 26209	0.00563 06006	66 10	1.16075 13898	66
0.90630 54160	1.00631 14139	0.00580 46884	65 10	1.14316 42476	65
0.89879 15164	1.00620 71982	0.00597 17561	64 10	1.12557 71053	64
0.89100 38343	1.00610 01007	0.00613 15997	63 11	1.10798 99630	63
0.88294 47424	1.00599 02520	0.00628 40232	62 11	1.09040 28208	62
0.87461 66961	1.00587 77858	0.00642 88398	61 11	1.07281 56785	61
0.86602 22325	1.00576 28392	0.00656 58716	60 12	1.05522 85362	60
0.85716 39703	1.00564 55522	0.00669 49498	59 12	1.03764 13940	59
0.84804 46080	1.00552 60678	0.00681 59154	58 12	1.02005 42517	58
0.83866 69240	1.00540 45314	0.00692 86187	57 12	1.00246 71094	57
0.82903 37754	1.00528 10912	0.00703 29201	56 12	0.98487 99671	56
0.81914 80969	1.00515 58975	0.00712 86900	55 12	0.96729 28249	55
0.80901 29003	1.00502 91030	0.00721 58089	54 13	0.94970 56826	54
0.79863 12733	1.00490 08620	0.00729 41679	53 13	0.93211 85403	53
0.78800 63786	1.00477 13308	0.00736 36683	52 13	0.91453 13981	52
0.77714 14532	1.00464 06672	0.00742 42224	51 13	0.89694 42558	51
0.76603 98071	1.00450 90305	0.00747 57531	50 13	0.87935 71135	50
0.75470 48222	1.00437 65809	0.00751 81941	49 13	0.86176 99712	49
0.74313 99518	1.00424 34799	0.00755 14902	48 13	0.84418 28290	48
0.73134 87191	1.00410 98897	0.00757 55973	47 13	0.82659 56867	47
0.71933 47160	1.00397 59729	0.00759 04823	46 13	0.80900 85444	46
0.70710 16026	1.00384 18928	0.00759 61235	45 13	0.79142 14022	45
A(r)	D(r)	E(r)	φ	Fφ	r

$K = 1.5981420021$, $K' = K\sqrt{3} = 2.7680631454$, $E = 1.5441504969$, $E' = 1.076405113$,

r	$F\phi$	ϕ		E(r)	D(r)	A(r)
0	0.00000 00000	0°	0′	0.00000 00000	1.00000 00000	0.00000 00000
1	0.01775 71334	1	1	0.00059 97806	1.00000 53258	0.01745 10959
2	0.03551 42667	2	2	0.00119 88113	1.00002 12966	0.03489 68785
3	0.05327 14001	3	3	0.00179 63433	1.00004 78929	0.05233 20359
4	0.07102 85334	4	4	0.00239 16296	1.00008 50825	0.06975 12596
5	0.08878 56668	5	5	0.00298 39265	1.00013 28199	0.08714 92460
6	0.10654 28002	6	6	0.00357 24940	1.00019 10470	0.10452 06976
7	0.12429 99335	7	7	0.00415 65975	1.00025 96929	0.12186 03254
8	0.14205 70669	8	8	0.00473 55081	1.00033 86738	0.13916 28498
9	0.15981 42002	9	9	0.00530 85039	1.00042 78937	0.15642 30024
10	0.17757 13336	10	10	0.00587 48710	1.00052 72438	0.17363 55278
11	0.19532 84669	11	11	0.00643 39044	1.00063 66031	0.19079 51850
12	0.21308 56003	12	12	0.00698 49088	1.00075 58383	0.20789 67491
13	0.23084 27336	13	13	0.00752 71998	1.00088 48041	0.22493 50127
14	0.24859 98670	14	14	0.00806 01044	1.00102 33434	0.24190 47877
15	0.26635 70004	15	15	0.00858 29622	1.00117 12875	0.25880 09068
16	0.28411 41337	16	16	0.00909 51263	1.00132 84561	0.27561 82249
17	0.30187 12671	17	17	0.00959 59638	1.00149 46577	0.29235 16211
18	0.31962 84004	18	18	0.01008 48569	1.00166 96898	0.30899 59997
19	0.33738 55338	19	18	0.01056 12037	1.00185 33392	0.32554 62922
20	0.35514 26672	20	19	0.01102 44188	1.00204 53820	0.34199 74584
21	0.37289 98005	21	20	0.01147 39339	1.00224 55845	0.35834 44886
22	0.39065 69339	22	21	0.01190 91990	1.00245 37025	0.37458 24043
23	0.40841 40672	23	21	0.01232 96827	1.00266 94826	0.39070 62603
24	0.42617 12006	24	22	0.01273 48729	1.00289 26619	0.40671 11462
25	0.44392 83339	25	23	0.01312 42775	1.00312 29684	0.42259 21874
26	0.46168 54673	26	24	0.01349 74251	1.00336 01217	0.43834 45471
27	0.47944 26006	27	25	0.01385 38651	1.00360 38326	0.45396 34276
28	0.49719 97340	28	25	0.01419 31688	1.00385 38044	0.46944 40717
29	0.51495 68674	29	25	0.01451 49297	1.00410 97324	0.48478 17640
30	0.53271 40007	30	26	0.01481 87635	1.00437 13049	0.49997 18327
31	0.55047 11341	31	26	0.01510 43095	1.00463 82031	0.51500 96510
32	0.56822 82674	32	27	0.01537 12298	1.00491 01019	0.52989 06380
33	0.58598 54008	33	27	0.01561 92109	1.00518 66701	0.54461 02607
34	0.60374 25341	34	28	0.01584 79628	1.00546 75706	0.55916 40350
35	0.62149 96675	35	28	0.01605 72204	1.00575 24612	0.57354 75273
36	0.63925 68009	36	28	0.01624 67429	1.00604 09949	0.58775 63556
37	0.65701 39342	37	29	0.01641 63146	1.00633 28201	0.60178 61912
38	0.67477 10676	38	29	0.01656 57446	1.00662 75813	0.61563 27596
39	0.69252 82009	39	29	0.01669 48676	1.00692 49193	0.62929 18421
40	0.71028 53343	40	29	0.01680 35433	1.00722 44718	0.64275 92769
41	0.72804 24676	41	30	0.01689 16569	1.00752 58740	0.65603 09607
42	0.74579 96010	42	30	0.01695 91191	1.00782 87587	0.66910 28494
43	0.76355 67344	43	30	0.01700 58662	1.00813 27567	0.68197 09600
44	0.78131 38677	44	30	0.01703 18597	1.00843 74977	0.69463 13711
45	0.79907 10011	45	30	0.01703 70869	1.00874 26104	0.70708 02248
90−r	$F\psi$	ψ		G(r)	C(r)	B(r)

$q = 0.004333420509983$, $\Theta 0 = 0.9913331597$, $HK = 0.5131518035$

B(r)	C(r)	G(r)	ψ	Fψ	90–r
1.00000 00000	1.01748 52237	0.00000 00000	90° 0′	1.59814 20021	90
0.99984 76723	1.01747 98979	0.00058 94801	89 1	1.58038 48688	89
0.99939 07356	1.01746 39271	0.00117 82606	88 2	1.56262 77354	88
0.99862 93293	1.01743 73307	0.00176 56424	87 3	1.54487 06021	87
0.99756 36857	1.01740 01412	0.00235 09281	86 4	1.52711 34687	86
0.99619 41297	1.01735 24037	0.00293 34228	85 5	1.50935 63353	85
0.99452 10792	1.01729 41766	0.00351 24342	84 6	1.49159 92020	84
0.99254 50444	1.01722 55307	0.00408 72741	83 7	1.47384 20686	83
0.99026 66280	1.01714 65496	0.00465 72589	82 8	1.45608 49353	82
0.98768 65251	1.01705 73297	0.00522 17102	81 9	1.43832 78019	81
0.98480 55225	1.01695 79795	0.00577 99557	80 10	1.42057 06685	80
0.98162 44990	1.01684 86202	0.00633 13300	79 11	1.40281 35352	79
0.97814 44248	1.01672 93849	0.00687 51750	78 12	1.38505 64019	78
0.97436 63613	1.01660 04190	0.00741 08412	77 13	1.36729 92685	77
0.97029 14608	1.01646 18796	0.00793 76880	76 14	1.34954 21352	76
0.96592 09661	1.01631 39354	0.00845 50845	75 15	1.33178 50018	75
0.96125 62102	1.01615 67668	0.00896 24102	74 16	1.31402 78684	74
0.95629 86158	1.01599 05651	0.00945 90560	73 17	1.29627 07351	73
0.95104 96947	1.01581 55329	0.00994 44245	72 18	1.27851 36017	72
0.94551 10478	1.01563 18834	0.01041 79308	71 18	1.26075 64684	71
0.93968 43642	1.01543 98405	0.01087 90033	70 19	1.24299 93350	70
0.93357 14207	1.01523 96380	0.01132 70844	69 20	1.22524 22016	69
0.92717 40815	1.01503 15198	0.01176 16310	68 20	1.20748 50683	68
0.92049 42975	1.01481 57396	0.01218 21151	67 21	1.18972 79349	67
0.91353 41057	1.01459 25602	0.01258 80246	66 22	1.17197 08016	66
0.90629 56284	1.01436 22536	0.01297 88640	65 23	1.15421 36682	65
0.89878 10728	1.01412 51003	0.01335 41547	64 23	1.13645 65348	64
0.89099 27303	1.01388 13892	0.01371 34359	63 24	1.11869 94015	63
0.88293 29756	1.01363 14174	0.01405 62649	62 25	1.10094 22681	62
0.87460 42661	1.01337 54893	0.01438 22180	61 25	1.08318 51348	61
0.86600 91414	1.01311 39167	0.01469 08906	60 26	1.06542 80014	60
0.85715 02219	1.01284 70184	0.01498 18982	59 26	1.04767 08681	59
0.84803 02085	1.01257 51195	0.01525 48767	58 27	1.02991 37347	58
0.83865 18817	1.01229 85512	0.01550 94825	57 27	1.01215 66014	57
0.82901 81005	1.01201 76507	0.01574 53939	56 28	0.99439 94680	56
0.81913 18020	1.01173 27599	0.01596 23105	55 28	0.97664 23346	55
0.80899 59997	1.01144 42262	0.01615 99545	54 28	0.95888 52013	54
0.79861 37836	1.01115 24009	0.01633 80704	53 29	0.94112 80679	53
0.78798 83184	1.01085 76397	0.01649 64258	52 29	0.92337 09346	52
0.77712 28430	1.01056 03017	0.01663 48119	51 29	0.90561 38012	51
0.76602 06691	1.01026 07491	0.01675 30432	50 29	0.88785 66678	50
0.75468 51808	1.00995 93468	0.01685 09584	49 29	0.87009 95345	49
0.74311 98330	1.00965 64622	0.01692 84205	48 30	0.85234 24011	48
0.73132 81506	1.00935 24642	0.01698 53170	47 30	0.83458 52678	47
0.71931 37274	1.00904 77232	0.01702 15600	46 30	0.81682 81344	46
0.70708 02248	1.00874 26104	0.01703 70869	45 30	0.79907 10011	45
A(r)	D(r)	E(r)	φ	Fφ	r

K = 1.6200258991, K′ = 2.5045500790, E = 1.5237992053, E′ = 1.118377738

r	Fφ	φ		E(r)	D(r)	A(r)
0	0.00000 00000	0°	0′	0.00000 00000	1.00000 00000	0.00000 00000
1	0.01800 02878	1	2	0.00106 89581	1.00000 96218	0.01744 81883
2	0.03600 05755	2	4	0.00213 65522	1.00003 84757	0.03489 10694
3	0.05400 08633	3	6	0.00320 14202	1.00008 65263	0.05232 33377
4	0.07200 11511	4	7	0.00426 22042	1.00015 37152	0.06973 96909
5	0.09000 14388	5	9	0.00531 75519	1.00023 99605	0.08713 48313
6	0.10800 17266	6	11	0.00636 61189	1.00034 51572	0.10450 34678
7	0.12600 20144	7	13	0.00740 65708	1.00046 91770	0.12184 03169
8	0.14400 23021	8	15	0.00843 75848	1.00061 18689	0.13914 01051
9	0.16200 25899	9	17	0.00945 78515	1.00077 30591	0.15639 75697
10	0.18000 28777	10	19	0.01046 60772	1.00095 25510	0.17360 74610
11	0.19800 31655	11	20	0.01146 09855	1.00115 01262	0.19076 45434
12	0.21600 34532	12	22	0.01244 13188	1.00136 55438	0.20786 35973
13	0.23400 37410	13	24	0.01340 58406	1.00159 85414	0.22489 94205
14	0.25200 40288	14	25	0.01435 33370	1.00184 88351	0.24186 68298
15	0.27000 43165	15	27	0.01528 26180	1.00211 61200	0.25876 06626
16	0.28800 46043	16	28	0.01619 25197	1.00240 00704	0.27557 57786
17	0.30600 48921	17	30	0.01708 19057	1.00270 03405	0.29230 70609
18	0.32400 51799	18	32	0.01794 96683	1.00301 65642	0.30894 94182
19	0.34200 54676	19	33	0.01879 47304	1.00334 83565	0.32549 77855
20	0.36000 57554	20	35	0.01961 60466	1.00369 53131	0.34194 71266
21	0.37800 60431	21	36	0.02041 26046	1.00405 70112	0.35829 24349
22	0.39600 63309	22	37	0.02118 34268	1.00443 30101	0.37452 87349
23	0.41400 66187	23	39	0.02192 75711	1.00482 28518	0.39065 10844
24	0.43200 69064	24	40	0.02264 41321	1.00522 60614	0.40665 45753
25	0.45000 71942	25	41	0.02333 22426	1.00564 21475	0.42253 43354
26	0.46800 74820	26	42	0.02399 10740	1.00607 06033	0.43828 55296
27	0.48600 77697	27	44	0.02461 98378	1.00651 09067	0.45390 33618
28	0.50400 80575	28	45	0.02521 77862	1.00696 25213	0.46938 30761
29	0.52200 83453	29	46	0.02578 42130	1.00742 48968	0.48471 99582
30	0.54000 86330	30	46	0.02631 84541	1.00789 74700	0.49990 93370
31	0.55800 89208	31	47	0.02681 98888	1.00837 96651	0.51494 65858
32	0.57600 92086	32	48	0.02728 79396	1.00887 08946	0.52982 71240
33	0.59400 94963	33	49	0.02772 20732	1.00937 05600	0.54454 64181
34	0.61200 97841	34	50	0.02812 18009	1.00987 80525	0.55909 99835
35	0.63001 00719	35	50	0.02848 66791	1.01039 27539	0.57348 33858
36	0.64801 03597	36	51	0.02881 63091	1.01091 40371	0.58769 22416
37	0.66601 06474	37	51	0.02911 03382	1.01144 12669	0.60172 22208
38	0.68401 09352	38	52	0.02936 84591	1.01197 38011	0.61556 90470
39	0.70201 12230	39	52	0.02959 04103	1.01251 09908	0.62922 84994
40	0.72001 15107	40	53	0.02977 59763	1.01305 21815	0.64269 64140
41	0.73801 17985	41	53	0.02992 49874	1.01359 67138	0.65596 86845
42	0.75601 20863	42	53	0.03003 73198	1.01414 39245	0.66904 12642
43	0.77401 23740	43	53	0.03011 28953	1.01469 31466	0.68191 01665
44	0.79201 26618	44	53	0.03015 16811	1.01524 37112	0.69457 14668
45	0.81001 29496	45	53	0.03015 36896	1.01579 49474	0.70702 13033
90−r	Fψ	ψ		G(r)	C(r)	B(r)

$q = 0.007774680416442$, $\Theta 0 = 0.9844506465$, $HK = 0.5939185400$

B(r)	C(r)	G(r)	ψ	Fψ	90−r
1.00000 00000	1.03158 99246	0.00000 00000	90° 0′	1.62002 58991	90
0.99984 76215	1.03158 03027	0.00103 62474	89 2	1.60202 56113	89
0.99939 05327	1.03155 14488	0.00207 12902	88 4	1.58402 53236	88
0.99862 88734	1.03150 33980	0.00310 39250	87 6	1.56602 50358	87
0.99756 28767	1.03143 62088	0.00413 29509	86 7	1.54802 47480	86
0.99619 28686	1.03134 99632	0.00515 71704	85 9	1.53002 44603	85
0.99451 92682	1.03124 47661	0.00617 53910	84 11	1.51202 41725	84
0.99254 25876	1.03112 07458	0.00718 64259	83 13	1.49402 38847	83
0.99026 34315	1.03097 80534	0.00818 90957	82 15	1.47602 35970	82
0.98768 24970	1.03081 68627	0.00918 22293	81 16	1.45802 33092	81
0.98480 05736	1.03063 73701	0.01016 46651	80 18	1.44002 30214	80
0.98161 85429	1.03043 97942	0.01113 52523	79 20	1.42202 27337	79
0.97813 73781	1.03022 43759	0.01209 28519	78 22	1.40402 24459	78
0.97435 81442	1.02999 13775	0.01303 63381	77 23	1.38602 21581	77
0.97028 19968	1.02974 10829	0.01396 45994	76 25	1.36802 18704	76
0.96591 01827	1.02947 37972	0.01487 65396	75 27	1.35002 15826	75
0.96124 40390	1.02918 98458	0.01577 10793	74 28	1.33202 12948	74
0.95628 49924	1.02888 95748	0.01664 71568	73 30	1.31402 10070	73
0.95103 45595	1.02857 33501	0.01750 37292	72 31	1.29602 07193	72
0.94549 43456	1.02824 15568	0.01833 97739	71 33	1.27802 04315	71
0.93966 60449	1.02789 45992	0.01915 42895	70 34	1.26002 01437	70
0.93355 14391	1.02753 28994	0.01994 62967	69 36	1.24201 98560	69
0.92715 23977	1.02715 69001	0.02071 48399	68 37	1.22401 95682	68
0.92047 08768	1.02676 70574	0.02145 89881	67 38	1.20601 92804	67
0.91350 89187	1.02636 38468	0.02217 78360	66 40	1.18801 89927	66
0.90626 86515	1.02594 77596	0.02287 05049	65 41	1.17001 87049	65
0.89875 22880	1.02551 93029	0.02353 61442	64 42	1.15201 84171	64
0.89096 21252	1.02507 89985	0.02417 39320	63 43	1.13401 81294	63
0.88290 05436	1.02462 73829	0.02478 30767	62 44	1.11601 78416	62
0.87457 00067	1.02416 50064	0.02536 28172	61 45	1.09801 75538	61
0.86597 30595	1.02369 24323	0.02591 24248	60 46	1.08001 72661	60
0.85711 23285	1.02321 02363	0.02643 12037	59 47	1.06201 69783	59
0.84799 05205	1.02271 90060	0.02691 84920	58 48	1.04401 66905	58
0.83861 04218	1.02221 93398	0.02737 36626	57 49	1.02601 64028	57
0.82897 48973	1.02171 18465	0.02779 61243	56 49	1.00801 61150	56
0.81908 68896	1.02119 71444	0.02818 53227	55 50	0.99001 58272	55
0.80894 94182	1.02067 58606	0.02854 07409	54 51	0.97201 55395	54
0.79856 55784	1.02014 86302	0.02886 19001	53 51	0.95401 52517	53
0.78793 85407	1.01961 60955	0.02914 83611	52 52	0.93601 49639	52
0.77707 15491	1.01907 89054	0.02939 97245	51 52	0.91801 46761	51
0.76596 79209	1.01853 77143	0.02961 56313	50 53	0.90001 43884	50
0.75463 10450	1.01799 31816	0.02979 57642	49 53	0.88201 41006	49
0.74306 43814	1.01744 59707	0.02993 98477	48 53	0.86401 38129	48
0.73127 14598	1.01689 67484	0.03004 76489	47 53	0.84601 35251	47
0.71925 58784	1.01634 61837	0.03011 89783	46 53	0.82801 32373	46
0.70702 13033	1.01579 49474	0.03015 36896	45 53	0.81001 29496	45
A(r)	D(r)	E(r)	φ	Fφ	r

K = 1.6489952185, K′ = 2.3087867982, E = 1.4981149284, E′ = 1.1638279645,

r	Fφ	φ	E(r)	D(r)	A(r)
0	0.00000 00000	0° 0′	0.00000 00000	1.00000 00000	0.00000 00000
1	0.01832 21691	1 3	0.00167 60815	1.00001 53565	0.01744 18591
2	0.03664 43382	2 6	0.00334 99667	1.00006 14074	0.03487 84245
3	0.05496 65073	3 9	0.00501 94629	1.00013 80964	0.05230 44041
4	0.07328 86764	4 12	0.00668 23842	1.00024 53303	0.06971 45088
5	0.09161 08455	5 15	0.00833 65551	1.00038 29783	0.08710 34544
6	0.10993 30145	6 18	0.00997 98139	1.00055 08728	0.10446 59627
7	0.12825 51836	7 21	0.01161 00163	1.00074 88092	0.12179 67635
8	0.14657 73527	8 24	0.01322 50382	1.00097 65463	0.13909 05958
9	0.16489 95218	9 26	0.01482 27797	1.00123 38067	0.15634 22095
10	0.18322 16909	10 29	0.01640 11677	1.00152 02770	0.17354 63669
11	0.20154 38600	11 32	0.01795 81596	1.00183 56081	0.19069 78446
12	0.21986 60291	12 35	0.01949 17458	1.00217 94159	0.20779 14345
13	0.23818 81982	13 37	0.02099 99533	1.00255 12815	0.22482 19454
14	0.25651 03673	14 40	0.02248 08485	1.00295 07519	0.24178 42052
15	0.27483 25364	15 43	0.02393 25396	1.00337 73404	0.25867 30615
16	0.29315 47055	16 45	0.02535 31798	1.00383 05272	0.27548 33838
17	0.31147 68746	17 48	0.02674 09700	1.00430 97603	0.29221 00649
18	0.32979 90437	18 50	0.02809 41609	1.00481 44557	0.30884 80221
19	0.34812 12128	19 53	0.02941 10555	1.00534 39986	0.32539 21991
20	0.36644 33819	20 56	0.03069 00118	1.00589 77438	0.34183 75673
21	0.38476 55510	21 57	0.03192 94445	1.00647 50167	0.35817 91274
22	0.40308 77201	22 59	0.03312 78272	1.00707 51140	0.37441 19107
23	0.42140 98892	24 1	0.03428 36945	1.00769 73046	0.39053 09808
24	0.43973 28582	25 3	0.03539 56434	1.00834 08304	0.40653 14352
25	0.45805 42273	26 5	0.03646 23352	1.00900 49074	0.42240 84064
26	0.47637 63964	27 7	0.03748 24970	1.00968 87266	0.43815 70635
27	0.49469 85655	28 9	0.03845 49232	1.01039 14548	0.45377 26140
28	0.51302 07346	29 11	0.03937 84764	1.01111 22358	0.46925 03045
29	0.53134 29037	30 12	0.04025 20886	1.01185 01916	0.48458 54231
30	0.54966 50728	31 14	0.04107 47627	1.01260 44231	0.49977 32999
31	0.56798 72419	32 15	0.04184 55726	1.01337 40113	0.51480 93092
32	0.58630 94110	33 16	0.04256 36643	1.01415 80186	0.52968 88703
33	0.60463 15801	34 18	0.04322 82564	1.01495 54899	0.54440 74492
34	0.62295 37492	35 19	0.04383 86406	1.01576 54535	0.55896 05600
35	0.64127 59183	36 20	0.04439 41821	1.01658 69227	0.57334 37662
36	0.65959 80874	37 21	0.04489 43196	1.01741 88967	0.58755 26819
37	0.67792 02565	38 22	0.04533 85655	1.01826 03617	0.60158 29737
38	0.69624 24256	39 23	0.04572 65058	1.01911 02927	0.61543 03611
39	0.71456 45947	40 23	0.04605 78000	1.01996 76540	0.62909 06189
40	0.73288 67638	41 23	0.04633 21809	1.02083 14013	0.64255 95777
41	0.75120 89328	42 24	0.04654 94543	1.02170 04820	0.65583 31255
42	0.76953 11019	43 24	0.04670 94981	1.02257 38374	0.66890 72089
43	0.78785 32710	44 24	0.04681 22622	1.02345 04035	0.68177 78347
44	0.80617 54401	45 24	0.04685 77678	1.02432 91122	0.69444 10704
45	0.82449 76092	46 24	0.04684 61065	1.02520 88930	0.70689 30463
90−r	Fψ	ψ	G(r)	C(r)	B(r)

$q = 0.012294560527181$, $\Theta 0 = 0.975410924642$, $HK = 0.666076159327$

B(r)	C(r)	G(r)	ψ	Fψ	90–r
1.00000 00000	1.05041 79735	0.00000 00000	90° 0′	1.64899 52185	90
0.99984 75111	1.05040 26167	0.00159 57045	89 3	1.63067 30494	89
0.99939 00912	1.05035 65652	0.00318 96046	88 6	1.61235 08803	88
0.99862 78812	1.05027 98750	0.00477 98977	87 9	1.59402 87112	87
0.99756 11158	1.05017 26395	0.00636 47840	86 12	1.57570 65421	86
0.99619 01235	1.05003 49895	0.00794 24686	85 15	1.55738 43730	85
0.99451 53263	1.04986 70926	0.00951 11627	84 17	1.53906 22039	84
0.99253 72400	1.04966 91533	0.01106 90855	83 20	1.52074 00348	83
0.99025 64734	1.04944 14129	0.01261 44653	82 23	1.50241 78657	82
0.98767 37287	1.04918 41489	0.01414 55416	81 26	1.48409 56966	81
0.98478 98010	1.04889 76746	0.01566 05663	80 29	1.46577 35275	80
0.98160 55779	1.04858 23391	0.01715 78054	79 31	1.44745 13584	79
0.97812 20395	1.04823 85265	0.01863 55407	78 34	1.42912 91893	78
0.97434 02576	1.04786 66559	0.02009 20712	77 37	1.41080 70202	77
0.97026 13962	1.04746 71802	0.02152 57149	76 39	1.39248 48511	76
0.96588 67101	1.04704 05862	0.02293 48102	75 42	1.37416 26821	75
0.96121 75452	1.04658 73936	0.02431 77177	74 44	1.35584 05130	74
0.95625 53377	1.04610 81546	0.02567 28218	73 47	1.33751 83439	73
0.95100 16139	1.04560 34530	0.02699 85322	72 49	1.31919 61748	72
0.94545 79893	1.04507 39038	0.02829 32857	71 52	1.30087 40057	71
0.93962 61686	1.04452 01522	0.02955 55477	70 54	1.28255 18366	70
0.93350 79444	1.04394 28728	0.03078 38140	69 56	1.26422 96675	69
0.92710 51976	1.04334 27690	0.03197 66123	68 58	1.24590 74984	68
0.92041 98958	1.04272 05719	0.03313 25038	68 0	1.22758 53293	67
0.91345 40932	1.04207 70396	0.03425 00853	67 2	1.20926 31602	66
0.90620 99299	1.04141 29561	0.03532 79902	66 4	1.19094 09911	65
0.89868 96309	1.04072 91305	0.03636 48907	65 6	1.17261 88220	64
0.89089 55058	1.04002 63960	0.03735 94992	64 8	1.15429 66529	63
0.88282 99477	1.03930 56088	0.03831 05700	63 10	1.13597 44838	62
0.87449 54326	1.03856 76470	0.03921 69009	62 11	1.11765 23147	61
0.86589 45184	1.03781 34098	0.04007 73349	61 13	1.09933 01456	60
0.85702 98444	1.03704 38161	0.04089 07619	60 14	1.08100 79765	59
0.84790 41300	1.03625 98035	0.04165 61200	59 16	1.06268 58075	58
0.83852 01744	1.03546 23272	0.04237 23976	58 17	1.04436 36384	57
0.82888 08549	1.03465 23588	0.04303 86345	57 18	1.02604 14693	56
0.81898 91269	1.03383 08852	0.04365 39236	56 19	1.00771 93002	55
0.80884 80221	1.03299 89073	0.04421 74127	55 20	0.98939 71311	54
0.79846 06482	1.03215 74386	0.04472 83056	54 21	0.97107 49620	53
0.78783 01874	1.03130 75044	0.04518 58637	53 22	0.95275 27929	52
0.77695 98956	1.03045 01401	0.04558 94076	52 22	0.93443 06238	51
0.76585 31015	1.02958 63905	0.04593 83183	51 23	0.91610 84547	50
0.75451 32053	1.02871 73077	0.04623 20386	50 24	0.89778 62856	49
0.74294 36775	1.02784 39507	0.04647 00744	49 24	0.87946 41165	48
0.73114 80583	1.02696 73835	0.04665 19961	48 24	0.86114 19474	47
0.71912 99561	1.02608 86741	0.04677 74393	47 24	0.84281 97783	46
0.70689 30463	1.02520 88930	0.04684 61065	46 24	0.82449 76092	45
A(r)	D(r)	E(r)	φ	Fφ	r

K = 1.6857503548, K′ = 2.1565156475, E = 1.4674622093 E′ = 1.211056028,

r	Fφ	φ		E(r)	D(r)	A(r)
0	0.00000 00000	0°	0′	0.00000 00000	1.00000 00000	0.00000 00000
1	0.01873 05595	1	4	0.00242 48763	1.00002 27125	0.01742 98716
2	0.03746 11190	2	9	0.00484 64683	1.00009 08222	0.03485 44751
3	0.05619 16785	3	13	0.00726 14977	1.00020 42462	0.05226 85438
4	0.07492 22380	4	18	0.00966 66975	1.00036 28463	0.06966 68140
5	0.09365 27975	5	22	0.01205 88178	1.00056 64294	0.08704 40267
6	0.11238 33570	6	26	0.01443 46319	1.00081 47472	0.10439 49285
7	0.13111 39165	7	30	0.01679 09412	1.00110 74975	0.12171 42736
8	0.14984 44760	8	35	0.01912 45813	1.00144 43235	0.13899 68254
9	0.16857 50355	9	39	0.02143 24269	1.00182 48148	0.15623 73574
10	0.18730 55950	10	43	0.02371 13976	1.00224 85079	0.17343 06551
11	0.20603 61545	11	47	0.02595 84626	1.00271 48868	0.19057 15175
12	0.22476 67140	12	51	0.02817 06459	1.00322 33830	0.20765 47584
13	0.24349 72734	13	55	0.03034 50312	1.00377 33773	0.22467 52081
14	0.26222 78329	14	59	0.03247 87664	1.00436 41996	0.24162 77146
15	0.28095 83924	16	3	0.03456 90685	1.00499 51300	0.25850 71454
16	0.29968 89519	17	6	0.03661 32272	1.00566 54000	0.27530 83886
17	0.31841 95114	18	10	0.03860 86097	1.00637 41929	0.29202 63549
18	0.33715 00709	19	14	0.04055 26642	1.00712 06453	0.30865 59785
19	0.35588 06304	20	17	0.04244 29236	1.00790 38477	0.32519 22190
20	0.37461 11899	21	20	0.04427 70092	1.00872 28461	0.34163 00625
21	0.39334 17494	22	23	0.04605 26335	1.00957 66426	0.35796 45236
22	0.41207 23089	23	27	0.04776 76034	1.01046 41971	0.37419 06461
23	0.43080 28684	24	30	0.04941 98229	1.01138 44282	0.39030 35051
24	0.44953 34279	25	33	0.05100 72958	1.01233 62150	0.40629 82084
25	0.46826 39874	26	36	0.05252 81275	1.01331 83978	0.42216 98975
26	0.48699 45469	27	38	0.05398 05273	1.01432 97800	0.43791 37495
27	0.50572 51064	28	41	0.05536 28100	1.01536 91295	0.45352 49782
28	0.52445 56659	29	43	0.05667 33976	1.01643 51800	0.46899 88358
29	0.54318 62254	30	46	0.05791 08204	1.01752 66329	0.48433 06142
30	0.56191 67849	31	48	0.05907 37181	1.01864 21583	0.49951 56464
31	0.58064 73444	32	50	0.06016 08407	1.01978 03972	0.51454 93080
32	0.59937 79039	33	52	0.06117 10486	1.02093 99629	0.52942 70185
33	0.61810 84634	34	54	0.06210 33138	1.02211 94428	0.54414 42428
34	0.63683 90229	35	55	0.06295 67191	1.02331 73997	0.55869 64925
35	0.65556 95824	36	56	0.06373 04587	1.02453 23743	0.57307 93274
36	0.67430 01419	37	58	0.06442 38375	1.02576 28863	0.58728 83566
37	0.69303 07014	38	59	0.06503 62710	1.02700 74365	0.60131 92403
38	0.71176 12609	40	0	0.06556 72843	1.02826 45087	0.61516 76907
39	0.73049 18204	41	1	0.06601 65112	1.02953 25714	0.62882 94738
40	0.74922 23799	42	2	0.06638 36938	1.03081 00797	0.64230 04103
41	0.76795 29394	43	3	0.06666 86806	1.03209 54771	0.65557 63772
42	0.78668 34989	44	3	0.06687 14255	1.03338 71976	0.66865 33089
43	0.80541 40584	45	3	0.06699 19865	1.03468 36674	0.68152 71988
44	0.82414 46179	46	4	0.06703 05237	1.03598 33070	0.69419 41003
45	0.84287 51774	47	3	0.06698 72981	1.03728 45330	0.70665 01282
90–r	Fψ	ψ		G(r)	C(r)	B(r)

$q = 0.017972387008967$, $\Theta 0 = 0.9640554346$, HK = 0.7325237222

B(r)	C(r)	G(r)	ψ	Fψ	90−r
1.00000 00000	1.07456 99318	0.00000 00000	90° 0′	1.68575 03548	90
0.99984 73018	1.07454 72183	0.00225 68053	89 4	1.66701 97953	89
0.99938 92548	1.07447 91054	0.00451 11469	88 8	1.64828 92358	88
0.99862 60018	1.07436 56761	0.00676 05625	87 13	1.62955 86763	87
0.99755 77806	1.07420 70687	0.00900 25936	86 17	1.61082 81168	86
0.99618 49242	1.07400 34764	0.01123 47869	85 21	1.59209 75573	85
0.99450 78603	1.07375 51471	0.01345 46957	84 25	1.57336 69978	84
0.99252 71115	1.07346 23837	0.01565 98823	83 29	1.55463 64383	83
0.99024 32948	1.07312 55426	0.01784 79196	82 33	1.53590 58788	82
0.98765 71218	1.07274 50344	0.02001 63924	81 38	1.51717 53193	81
0.98476 93979	1.07232 13226	0.02216 28998	80 42	1.49844 47598	80
0.98158 10224	1.07185 49236	0.02428 50568	79 46	1.47971 42003	79
0.97809 29880	1.07134 64055	0.02638 04961	78 49	1.46098 36408	78
0.97430 63806	1.07079 63881	0.02844 68702	77 53	1.44225 30813	77
0.97022 23787	1.07020 55414	0.03048 18529	76 57	1.42352 25218	76
0.96584 22530	1.06957 45853	0.03248 31417	76 1	1.40479 19623	75
0.96116 73661	1.06890 42887	0.03444 84594	75 4	1.38606 14028	74
0.95619 91719	1.06819 54682	0.03637 55563	74 8	1.36733 08433	73
0.95093 92151	1.06744 89874	0.03826 22123	73 12	1.34860 02839	72
0.94538 91306	1.06666 57559	0.04010 62389	72 15	1.32986 97244	71
0.93955 06429	1.06584 67280	0.04190 54809	71 18	1.31113 91649	70
0.93342 55657	1.06499 29016	0.04365 78194	70 22	1.29240 86054	69
0.92701 58009	1.06410 53170	0.04536 11731	69 25	1.27367 80459	68
0.92032 33381	1.06318 50556	0.04701 35012	68 28	1.25494 74864	67
0.91335 02539	1.06223 32387	0.04861 28052	67 31	1.23621 69269	66
0.90609 87113	1.06125 10260	0.05015 71313	66 34	1.21748 63674	65
0.89857 09587	1.06023 96142	0.05164 45728	65 36	1.19875 58079	64
0.89076 93291	1.05920 02357	0.05307 32725	64 39	1.18002 52484	63
0.88269 62394	1.05813 41567	0.05444 14248	63 41	1.16129 46889	62
0.87435 41897	1.05704 26763	0.05574 72783	62 44	1.14256 41294	61
0.86574 57620	1.05592 71242	0.05698 91384	61 46	1.12383 35699	60
0.85687 36199	1.05478 88596	0.05816 53694	60 48	1.10510 30104	59
0.84774 05068	1.05362 92695	0.05927 43970	59 50	1.08637 24509	58
0.83834 92461	1.05244 97665	0.06031 47110	58 52	1.06764 18914	57
0.82870 27391	1.05125 17878	0.06128 48679	57 54	1.04891 13319	56
0.81880 39648	1.05003 67930	0.06218 34927	56 55	1.03018 07724	55
0.80865 59785	1.04880 62525	0.06300 92824	55 57	1.01145 02129	54
0.79826 19108	1.04756 16953	0.06376 10074	54 58	0.99271 96534	53
0.78762 49668	1.04630 46080	0.06443 75150	53 59	0.97398 90939	52
0.77674 84245	1.04503 65320	0.06503 77310	53 0	0.95525 85344	51
0.76563 56343	1.04375 90125	0.06556 06627	52 1	0.93652 79749	50
0.75429 00174	1.04247 36057	0.06600 54011	51 2	0.91779 74154	49
0.74271 50649	1.04118 18779	0.06637 11230	50 3	0.89906 68559	48
0.73091 43366	1.03988 54029	0.06665 70938	49 3	0.88033 62964	47
0.71889 14599	1.03858 57601	0.06686 26693	48 3	0.86160 57369	46
0.70665 01282	1.03728 45330	0.06698 72981	47 3	0.84287 51774	45
A(r)	D(r)	E(r)	ϕ	Fϕ	r

K = 1.7312451757, K′ = 2.0347153122, E = 1.4322909693, E′ = 1.2586796248,

r	Fφ	φ	E(r)	D(r)	A(r)
0	0.00000 00000	0° 0′	0.00000 00000	1.00000 00000	0.00000 00000
1	0.01923 60575	1 6	0.00332 09329	1.00003 19451	0.01740 91115
2	0.03847 21150	2 12	0.00663 71847	1.00012 77415	0.03481 29991
3	0.05770 81725	3 18	0.00994 40836	1.00028 72724	0.05220 64403
4	0.07694 42300	4 24	0.01323 69759	1.00051 03436	0.06958 42154
5	0.09618 02875	5 30	0.01651 12357	1.00079 66833	0.08694 11086
6	0.11541 63450	6 36	0.01976 22733	1.00114 59427	0.10427 19100
7	0.13465 24025	7 42	0.02298 55446	1.00155 76965	0.12157 14162
8	0.15388 84600	8 48	0.02617 65594	1.00203 14429	0.13883 44322
9	0.17312 45176	9 54	0.02933 08900	1.00256 66050	0.15605 57726
10	0.19236 05751	11 0	0.03244 41797	1.00316 25308	0.17323 02632
11	0.21159 66326	12 5	0.03551 21508	1.00381 84944	0.19035 27418
12	0.23083 26901	13 11	0.03853 06122	1.00453 36968	0.20741 80603
13	0.25006 87476	14 16	0.04149 54668	1.00530 72668	0.22442 10857
14	0.26930 48051	15 22	0.04440 27192	1.00613 82620	0.24135 67013
15	0.28854 08626	16 27	0.04724 84818	1.00702 56701	0.25821 98088
16	0.30777 69201	17 32	0.05002 89819	1.00796 84103	0.27500 53288
17	0.32701 29776	18 37	0.05274 05671	1.00896 53340	0.29170 82026
18	0.34624 90351	19 42	0.05537 97118	1.01001 52268	0.30832 33939
19	0.36548 50926	20 47	0.05794 30217	1.01111 68099	0.32484 58897
20	0.38472 11501	21 52	0.06042 72392	1.01226 87413	0.34127 07019
21	0.40395 72077	22 56	0.06282 92476	1.01346 96177	0.35759 28687
22	0.42319 32652	24 0	0.06514 60751	1.01471 79763	0.37380 74559
23	0.44242 93227	25 5	0.06737 48988	1.01601 22964	0.38990 95585
24	0.46166 53802	26 9	0.06951 30473	1.01735 10012	0.40589 43019
25	0.48090 14377	27 13	0.07155 80036	1.01873 24599	0.42175 68435
26	0.50013 74952	28 16	0.07350 74079	1.02015 49897	0.43749 23737
27	0.51937 35527	29 20	0.07535 90588	1.02161 68576	0.45309 61179
28	0.53860 96102	30 23	0.07711 09151	1.02311 62828	0.46856 33375
29	0.55784 56677	31 27	0.07876 10969	1.02465 14386	0.48388 93314
30	0.57708 17252	32 30	0.08030 78862	1.02622 04548	0.49906 94371
31	0.59631 77827	33 32	0.08174 97274	1.02782 14201	0.51409 90330
32	0.61555 38402	34 35	0.08308 52267	1.02945 23841	0.52897 35386
33	0.63478 98977	35 37	0.08431 31523	1.03111 13599	0.54368 84170
34	0.65402 59552	36 40	0.08543 24331	1.03279 63263	0.55823 91754
35	0.67326 20128	37 42	0.08644 21580	1.03450 52308	0.57262 13672
36	0.69249 80703	38 43	0.08734 15741	1.03623 59914	0.58683 05928
37	0.71173 41278	39 45	0.08813 00853	1.03798 64996	0.60086 25017
38	0.73097 01853	40 46	0.08880 72502	1.03975 46228	0.61471 27930
39	0.75020 62428	41 48	0.08937 27798	1.04153 82068	0.62837 72177
40	0.76944 23003	42 49	0.08982 65352	1.04333 50787	0.64185 15792
41	0.78867 83578	43 49	0.09016 85246	1.04514 30495	0.65513 17355
42	0.80791 44153	44 50	0.09039 89009	1.04695 99164	0.66821 35999
43	0.82715 04728	45 50	0.09051 79579	1.04878 34660	0.68109 31428
44	0.84638 65303	46 51	0.09052 61280	1.05061 14765	0.69376 63926
45	0.86562 25878	47 51	0.09042 39779	1.05244 17208	0.70622 94378
90–r	Fψ	ψ	G(r)	C(r)	B(r)

$q = 0.024915062523981$, $\Theta 0 = 0.9501706456$, HK $= 0.7950876364$

B(r)	C(r)	G(r)	ψ	Fψ	90−r
1.00000 00000	1.10488 66859	0.00000 00000	90° 0′	1.73124 51757	90
0.99984 69394	1.10485 47369	0.00300 62320	89 6	1.71200 91181	89
0.99938 78065	1.10475 89287	0.00600 93218	88 12	1.69277 30606	88
0.99862 27471	1.10459 93781	0.00900 61288	87 17	1.67353 70031	87
0.99755 20048	1.10437 62795	0.01199 35156	86 23	1.65430 09456	86
0.99617 59200	1.10408 99048	0.01496 83495	85 29	1.63506 48881	85
0.99449 49305	1.10374 06029	0.01792 75043	84 35	1.61582 88306	84
0.99250 95707	1.10332 87996	0.02086 78620	83 40	1.59659 27731	83
0.99022 04719	1.10285 49965	0.02378 63141	82 46	1.57735 67156	82
0.98762 83615	1.10231 97711	0.02667 97640	81 51	1.55812 06581	81
0.98473 40633	1.10172 37756	0.02954 51279	80 57	1.53888 46006	80
0.98153 84966	1.10106 77362	0.03237 93372	80 2	1.51964 85431	79
0.97804 26763	1.10035 24524	0.03517 93404	79 8	1.50041 24856	78
0.97424 77117	1.09957 87957	0.03794 21046	78 13	1.48117 64281	77
0.97015 48073	1.09874 77089	0.04066 46178	77 19	1.46194 03706	76
0.96576 52612	1.09786 02047	0.04334 38907	76 24	1.44270 43130	75
0.96108 04649	1.09691 73646	0.04597 69592	75 29	1.42346 82555	74
0.95610 19028	1.09592 03375	0.04856 08861	74 34	1.40423 21980	73
0.95083 11516	1.09487 03382	0.05109 27637	73 38	1.38499 61405	72
0.94526 98796	1.09376 86463	0.05356 97161	72 43	1.36576 00830	71
0.93941 98461	1.09261 66042	0.05598 89014	71 48	1.34652 40255	70
0.93328 29005	1.09141 56156	0.05834 75147	70 52	1.32728 79680	69
0.92686 09817	1.09016 71440	0.06064 27902	69 56	1.30805 19105	68
0.92015 61173	1.08887 27107	0.06287 20041	69 1	1.28881 58530	67
0.91317 04228	1.08753 38930	0.06503 24775	68 5	1.26957 97955	66
0.90590 61007	1.08615 23221	0.06712 15792	67 9	1.25034 37380	65
0.89836 54396	1.08472 96815	0.06913 67285	66 12	1.23110 76805	64
0.89055 08135	1.08326 77048	0.07107 53988	65 16	1.21187 16230	63
0.88246 46805	1.08176 81732	0.07293 51200	64 19	1.19263 55655	62
0.87410 95823	1.08023 29140	0.07471 34824	63 23	1.17339 95080	61
0.86548 81427	1.07866 37978	0.07640 81398	62 26	1.15416 34504	60
0.85660 30670	1.07706 27365	0.07801 68127	61 29	1.13492 73929	59
0.84745 71408	1.07543 16809	0.07953 72924	60 31	1.11569 13354	58
0.83805 32290	1.07377 26184	0.08096 74440	59 34	1.09645 52779	57
0.82839 42745	1.07208 75705	0.08230 52102	58 36	1.07721 92204	56
0.81848 32973	1.07037 85902	0.08354 86152	57 39	1.05798 31629	55
0.80832 33933	1.06864 77599	0.08469 57684	56 41	1.03874 71054	54
0.79791 77333	1.06689 71884	0.08574 48680	55 43	1.01951 10479	53
0.78726 95615	1.06512 90086	0.08669 42053	54 44	1.00027 49904	52
0.77638 21945	1.06334 53750	0.08754 21680	53 46	0.98103 89329	51
0.76525 90201	1.06154 84606	0.08828 72448	52 48	0.96180 28754	50
0.75390 34961	1.05974 04548	0.08892 80287	51 49	0.94256 68179	49
0.74231 91490	1.05792 35605	0.08946 32214	50 49	0.92333 07604	48
0.73050 95727	1.05609 99913	0.08989 16370	49 50	0.90409 47028	47
0.71847 84273	1.05427 19690	0.09021 22056	48 50	0.88485 86453	46
0.70622 94378	1.05244 17208	0.09042 39779	47 51	0.85562 25878	45
A(r)	D(r)	E(r)	φ	Fφ	r

K = 1.7867691349, K′ = 1.9355810960, E = 1.3931402485, E′ = 1.3055390943,

r	Fφ	φ	E(r)	D(r)	A(r)
0	0.00000 00000	0° 0′	0.00000 00000	1.00000 00000	0.00000 00000
1	0.01985 29904	1 8	0.00437 25767	1.00004 34107	0.01737 52657
2	0.03970 59807	2 16	0.00873 86910	1.00017 35897	0.03474 53796
3	0.05955 89712	3 24	0.01309 18945	1.00039 03787	0.05210 51913
4	0.07941 19615	4 32	0.01742 57681	1.00069 35136	0.06944 95525
5	0.09926 49519	5 41	0.02173 39351	1.00108 26253	0.08677 33185
6	0.11911 79423	6 49	0.02601 00761	1.00155 72398	0.10407 13496
7	0.13897 09327	7 57	0.03024 79420	1.00211 67791	0.12133 85117
8	0.15882 39231	9 5	0.03444 13683	1.00276 05620	0.13856 96780
9	0.17867 69135	10 13	0.03858 42875	1.00348 78042	0.15575 97300
10	0.19852 99039	11 21	0.04267 07422	1.00429 76203	0.17290 35587
11	0.21838 28943	12 28	0.04669 48973	1.00518 90239	0.18999 60657
12	0.23823 58847	13 36	0.05065 10519	1.00616 09295	0.20703 21648
13	0.25808 88751	14 43	0.05453 36499	1.00721 21534	0.22400 67828
14	0.27794 18655	15 51	0.05833 72913	1.00834 14154	0.24091 48609
15	0.29779 48558	16 58	0.06205 67422	1.00954 73402	0.25775 13559
16	0.31764 78462	18 5	0.06568 69435	1.01082 84592	0.27451 12417
17	0.33750 08366	19 12	0.06922 30203	1.01218 32120	0.29118 95099
18	0.35735 38270	20 18	0.07266 02895	1.01360 99487	0.30778 11718
19	0.37720 68174	21 25	0.07599 42673	1.01510 69318	0.32428 12593
20	0.39705 98078	22 31	0.07922 06754	1.01667 23379	0.34068 48260
21	0.41691 27981	23 37	0.08233 54475	1.01830 42606	0.35698 69491
22	0.43676 57885	24 42	0.08533 47336	1.02000 07123	0.37318 27300
23	0.45661 87789	25 48	0.08821 49046	1.02175 96267	0.38926 72959
24	0.47647 17693	26 53	0.09097 25564	1.02357 88616	0.40523 58014
25	0.49632 47597	27 59	0.09360 45123	1.02545 62012	0.42108 34293
26	0.51617 77501	29 4	0.09610 78252	1.02738 93589	0.43680 53924
27	0.53603 07405	30 8	0.09847 97792	1.02937 59801	0.45239 69344
28	0.55588 37309	31 13	0.10071 78905	1.03141 36450	0.46785 33318
29	0.57573 67212	32 17	0.10281 99075	1.03349 98717	0.48316 98948
30	0.59558 97116	33 22	0.10478 38101	1.03563 21191	0.49834 19688
31	0.61544 27020	34 25	0.10660 78092	1.03780 77899	0.51336 49360
32	0.63529 56924	35 28	0.10829 03444	1.04002 42340	0.52823 42166
33	0.65514 86828	36 31	0.10983 00821	1.04227 87515	0.54294 52702
34	0.67500 16732	37 34	0.11122 59132	1.04456 85961	0.55749 35973
35	0.69485 46636	38 37	0.11247 69491	1.04689 09786	0.57187 47405
36	0.71470 76540	39 39	0.11358 25187	1.04924 30699	0.58608 42864
37	0.73456 06443	40 41	0.11454 21645	1.05162 20047	0.60011 78665
38	0.75441 36347	41 42	0.11535 56375	1.05402 48851	0.61397 11590
39	0.77426 66251	42 44	0.11602 28932	1.05644 87839	0.62763 98902
40	0.79411 96155	43 46	0.11654 40861	1.05889 07481	0.64111 98356
41	0.81397 26059	44 46	0.11691 95649	1.06134 78029	0.65440 68220
42	0.83382 55963	45 47	0.11714 98662	1.06381 69550	0.66749 67282
43	0.85367 85867	46 47	0.11723 57096	1.06629 51962	0.68038 54871
44	0.87353 15771	47 48	0.11717 79914	1.06877 95074	0.69306 90869
45	0.89338 45674	48 48	0.11697 77784	1.07126 68617	0.70554 35725
90−r	Fψ	ψ	G(r)	C(r)	B(r)

$q = 0.033265256695577$, $\Theta 0 = 0.9334719356$, HK $= 0.8550825245$

B(r)	C(r)	G(r)	ψ	Fψ	90−r
1.00000 00000	1.14254 42177	0.00000 00000	90° 0′	1.78676 91349	90
0.99984 63487	1.14250 07942	0.00382 84907	89 8	1.76691 61445	89
0.99938 54451	1.14237 05769	0.00765 31872	88 15	1.74706 31541	88
0.99861 74408	1.14215 37243	0.01147 02963	87 23	1.72721 01637	87
0.99754 25881	1.14185 05008	0.01527 60269	86 30	1.70735 71733	86
0.99616 12401	1.14146 12760	0.01906 65913	85 38	1.68750 41829	85
0.99447 38506	1.14098 65243	0.02283 82057	84 46	1.66765 11926	84
0.99248 09734	1.14042 68243	0.02658 70918	83 53	1.64779 82022	83
0.99018 32628	1.13978 28584	0.03030 94781	83 1	1.62794 52118	82
0.98758 14726	1.13905 54113	0.03400 16009	82 8	1.60809 22214	81
0.98467 64560	1.13824 53698	0.03765 97054	81 16	1.58823 92310	80
0.98146 91652	1.13735 37211	0.04128 00477	80 23	1.56838 62406	79
0.97796 06509	1.13638 15521	0.04485 88958	79 30	1.54853 32502	78
0.97415 20616	1.13533 00476	0.04839 25314	78 37	1.52868 02598	77
0.97004 46432	1.13420 04893	0.05187 72514	77 44	1.50882 72694	76
0.96563 97386	1.13299 42539	0.05530 93702	76 51	1.48897 42791	75
0.96093 87866	1.13171 28116	0.05868 52206	75 57	1.46912 12887	74
0.95594 33213	1.13035 77242	0.06200 11573	75 4	1.44926 82983	73
0.95065 49716	1.12893 06433	0.06525 35577	74 10	1.42941 53079	72
0.94507 54604	1.12743 33082	0.06843 88251	73 17	1.40956 23175	71
0.93920 66032	1.12586 75438	0.07155 33910	72 23	1.38970 93271	70
0.93305 03082	1.12423 52584	0.07459 37177	71 29	1.36985 63367	69
0.92660 85744	1.12253 84414	0.07755 63011	70 34	1.35000 33463	68
0.91988 34913	1.12077 91607	0.08043 76736	69 40	1.33015 03560	67
0.91287 72377	1.11895 95604	0.08323 44077	68 45	1.31029 73656	66
0.90559 20807	1.11708 18582	0.08594 31188	67 51	1.29044 43752	65
0.89803 03745	1.11514 83422	0.08856 04692	66 56	1.27059 13848	64
0.89019 45598	1.11316 13690	0.09108 31714	66 0	1.25073 83944	63
0.88208 71618	1.11112 33599	0.09350 79923	65 5	1.23088 54040	62
0.87371 07901	1.10903 67986	0.09583 17573	64 9	1.21103 24136	61
0.86506 81367	1.10690 42279	0.09805 13545	63 14	1.19117 94233	60
0.85616 19751	1.10472 82465	0.10016 37391	62 18	1.17132 64329	59
0.84699 51593	1.10251 15061	0.10216 59383	61 21	1.15147 34425	58
0.83757 06220	1.10025 67080	0.10405 50557	60 25	1.13162 04521	57
0.82789 13739	1.09796 65999	0.10582 82770	59 28	1.11176 74617	56
0.81796 05020	1.09564 39724	0.10748 28746	58 32	1.09191 44713	55
0.80778 11684	1.09329 16556	0.10901 62132	57 34	1.07206 14809	54
0.79735 66091	1.09091 25160	0.11042 57553	56 37	1.05220 84905	53
0.78669 01322	1.08850 94525	0.11170 90668	55 39	1.03235 55001	52
0.77578 51173	1.08608 53932	0.11286 38228	54 42	1.01250 25098	51
0.76464 50133	1.08364 32917	0.11388 78137	53 44	0.99264 95194	50
0.75327 33376	1.08118 61237	0.11477 89511	52 45	0.97279 65290	49
0.74167 36742	1.07871 68830	0.11553 52736	51 46	0.95294 35386	48
0.72984 96728	1.07623 85782	0.11615 49535	50 46	0.93309 05482	47
0.71780 50468	1.07375 42288	0.11663 63025	49 47	0.91323 75578	46
0.70554 35725	1.07126 68617	0.11697 77784	48 48	0.89338 45674	45
A(r)	D(r)	E(r)	φ	Fφ	r

K = K′ = 1.8540746773, E = E′ = 1.3506438810,

r	Fφ	φ	E(r)	D(r)	A(r)
0	0.00000 00000	0° 0′	0.00000 00000	1.00000 00000	0.00000 00000
1	0.02060 08297	1 11	0.00559 22185	1.00005 76114	0.01732 23240
2	0.04120 16595	2 22	0.01117 56998	1.00023 03752	0.03463 96092
3	0.06180 24892	3 32	0.01674 17286	1.00051 80814	0.05194 68175
4	0.08240 33190	4 43	0 02228 16343	1.00092 03796	0.06923 89126
5	0.10300 41487	5 54	0.02778 68124	1.00143 67802	0.08651 08611
6	0.12360 49785	7 4	0.03324 87460	1.00206 66547	0.10375 76329
7	0.14420 58082	8 15	0.03865 90273	1.00280 92364	0.12097 42023
8	0.16480 66380	9 25	0.04400 93780	1.00366 36213	0.13815 55494
9	0.18540 74677	10 36	0.04929 16689	1.00462 87696	0.15529 66598
10	0.20600 82975	11 46	0.05449 79400	1.00570 35065	0.17239 25270
11	0.22660 91272	12 56	0.05962 04166	1.00688 65237	0.18943 81524
12	0.24720 99570	14 6	0.06465 15306	1.00817 63813	0.20642 85463
13	0.26781 07867	15 15	0.06958 39334	1.00957 15091	0.22335 87294
14	0.28841 16165	16 25	0.07441 05129	1.01107 02088	0.24022 37330
15	0.30901 24462	17 34	0.07912 44078	1.01267 06562	0.25701 86008
16	0.32961 32760	18 43	0.08371 90207	1.01437 09030	0.27373 83893
17	0.35021 41057	19 52	0.08818 80301	1.01616 88793	0.29037 81691
18	0.37081 49355	21 1	0.09252 54012	1.01806 23965	0.30693 30262
19	0.39141 57652	22 9	0.09672 53955	1.02004 91494	0.32339 80622
20	0.41201 65950	23 17	0.10078 25794	1.02212 67193	0.33976 83967
21	0.43261 74247	24 25	0.10469 18308	1.02429 25769	0.35603 91671
22	0.45321 82545	25 33	0.10844 83455	1.02654 40853	0.37220 55308
23	0.47381 90842	26 40	0.11204 76417	1.02887 85035	0.38826 26656
24	0.49441 99139	27 47	0.11548 55630	1.03129 29893	0.40420 57714
25	0.51502 07437	28 54	0.11875 82813	1.03378 46028	0.42003 00711
26	0.53562 15734	30 0	0.12186 22978	1.03635 03103	0.43573 08120
27	0.55622 24032	31 6	0.12479 44425	1.03898 69880	0.45130 32670
28	0.57682 32329	32 12	0.12755 18736	1.04169 14251	0.46674 27359
29	0.59742 40627	33 17	0.13013 20757	1.04446 03288	0.48204 45468
30	0.61802 48924	34 22	0.13253 28561	1.04729 03271	0.49720 40572
31	0.63862 57222	35 27	0.13475 23413	1.05017 79739	0.51221 66556
32	0.65922 65519	36 32	0.13678 89725	1.05311 97528	0.52707 77628
33	0.67982 73817	37 36	0.13864 14993	1.05611 20812	0.54178 28334
34	0.70042 82114	38 39	0.14030 89744	1.05915 13149	0.55632 73569
35	0.72102 90412	39 43	0.14179 07457	1.06223 37524	0.57070 68597
36	0.74162 98709	40 46	0.14308 64509	1.06535 56397	0.58491 69061
37	0.76223 07007	41 48	0.14419 60059	1.06851 31742	0.59895 31001
38	0.78283 15304	42 51	0.14511 96000	1.07170 25103	0.61281 10868
39	0.80343 23602	43 54	0.14585 76849	1.07491 97630	0.62648 65539
40	0.82403 31899	44 54	0.14641 09671	1.07816 10137	0.63997 52334
41	0.84463 40197	45 55	0.14678 03964	1.08142 23139	0.65327 29030
42	0.86523 48494	46 56	0.14696 71583	1.08469 96910	0.66637 53880
43	0.88583 56792	47 57	0.14697 26631	1.08798 91523	0.67927 85625
44	0.90643 65089	48 57	0.14679 85365	1.09128 66907	0.69197 83514
45	0.92703 73387	49 57	0.14644 66094	1.09458 82886	0.70447 07318
90–r	Fψ	ψ	G(r)	C(r)	B(r)

$q = e^{-\pi} = 0.04321391826377$, $\Theta 0 = 0.9135791382$, $HK = 0.9135791382$

B(r)	C(r)	G(r)	ψ	Fψ	90–r
1.00000 00000	1.18920 71150	0.00000 00000	90° 0′	1.85407 46773	90
0.99984 54246	1.18914 94665	0.00470 60108	89 10	1.83347 38476	89
0.99938 17514	1.18897 65912	0.00940 76502	88 20	1.81287 30178	88
0.99860 91406	1.18868 87000	0.01410 05467	87 30	1.79227 21881	87
0.99752 78584	1.18828 61440	0.01878 03289	86 40	1.77167 13583	86
0.99613 82775	1.18776 94140	0.02344 26255	85 49	1.75107 05286	85
0.99444 08767	1.18713 91403	0.02808 30653	84 59	1.73046 96988	84
0.99243 62407	1.18639 60914	0.03269 72774	84 9	1.70986 88691	83
0.99012 50593	1.18554 11736	0.03728 08916	83 18	1.68926 80393	82
0.98750 81276	1.18457 54293	0.04182 95382	82 28	1.66866 72096	81
0.98458 63450	1.18350 00363	0.04633 88487	81 37	1.64806 63798	80
0.98136 07151	1.18231 63059	0.05080 44575	80 47	1.62746 55501	79
0.97783 23446	1.18102 56817	0.05522 19994	79 56	1.60686 47203	78
0.97400 24430	1.17962 97376	0.05958 71139	79 5	1.58626 38906	77
0.96987 23216	1.17813 01756	0.06389 54439	78 14	1.56566 30608	76
0.96544 33929	1.17652 88244	0.06814 26379	77 23	1.54506 22311	75
0.96071 71696	1.17482 76366	0.07232 43506	76 32	1.52446 14013	74
0.95569 52639	1.17302 86866	0.07643 62449	75 40	1.50386 05716	73
0.95037 93863	1.17113 41680	0.08047 39933	74 48	1.48325 97418	72
0.94477 13447	1.16914 63907	0.08443 32799	73 57	1.46265 89121	71
0.93887 30433	1.16706 77783	0.08830 98027	73 5	1.44205 80823	70
0.93268 64814	1.16490 08653	0.09209 92756	72 13	1.42145 72526	69
0.92621 37526	1.16264 82937	0.09579 74315	71 20	1.40085 64228	68
0.91945 70430	1.16031 28097	0.09940 00252	70 27	1.38025 55931	67
0.91241 86305	1.15789 72608	0.10290 28362	69 34	1.35965 47634	66
0.90510 08831	1.15540 45920	0.10630 16727	68 41	1.33905 39336	65
0.89750 62579	1.15283 78419	0.10959 23752	67 48	1.31845 31039	64
0.88963 72995	1.15020 01398	0.11277 08206	66 54	1.29785 22741	63
0.88149 66386	1.14749 47011	0.11583 29266	66 0	1.27725 14444	62
0.87308 69906	1.14472 48239	0.11877 46567	65 6	1.25665 06146	61
0.86441 11542	1.14189 38846	0.12159 20252	64 11	1.23604 97849	60
0.85547 20099	1.13900 53339	0.12428 11025	63 16	1.21544 89551	59
0.84627 25182	1.13606 26928	0.12683 80211	62 21	1.19484 81254	58
0.83681 57184	1.13306 95480	0.12925 89815	61 26	1.17424 72956	57
0.82710 47269	1.13002 95477	0.13154 02588	60 30	1.15364 64659	56
0.81714 27355	1.12694 63970	0.13367 82099	59 34	1.13304 56361	55
0.80693 30099	1.12382 38537	0.13566 92789	58 38	1.11244 48064	54
0.79647 88881	1.12066 57231	0.13751 00077	57 42	1.09184 39766	53
0.78578 37785	1.11747 58542	0.13919 70407	56 45	1.07124 31469	52
0.77485 11587	1.11425 81342	0.14072 71344	55 47	1.05064 23171	51
0.76368 45735	1.11101 64844	0.14209 71663	54 50	1.03004 14874	50
0.75228 76332	1.10775 48548	0.14330 41415	53 52	1.00944 06576	49
0.74066 40121	1.10447 72199	0.14434 52037	52 53	0.98883 98279	48
0.72881 74469	1.10118 75735	0.14521 76436	51 55	0.96823 89981	47
0.71675 17348	1.09788 99237	0.14591 89078	50 56	0.94763 81684	46
0.70447 07318	1.09458 82886	0.14644 66094	49 57	0.92703 73387	45
A(r)	D(r)	E(r)	φ	Fφ	r

K = 1.9355810960, K′ = 1.7867691349, E = 1.3055390943, E′ = 1.3931402485,

r	Fφ	φ	E(r)	D(r)	A(r)
0	0.00000 00000	0° 0′	0.00000 00000	1.00000 00000	0.00000 00000
1	0.02150 64566	1 14	0.00699 85212	1.00007 52700	0.01724 17831
2	0.04301 29132	2 28	0.01398 53763	1.00030 09884	0.03447 86990
3	0.06451 93699	3 41	0.02094 89334	1.00067 68809	0.05170 58810
4	0.08602 58265	4 55	0.02787 76288	1.00120 24903	0.06891 84630
5	0.10753 22831	6 9	0.03476 00006	1.00187 71775	0.08611 15805
6	0.12903 87397	7 22	0.04158 42717	1.00270 01222	0.10328 03705
7	0.15054 51963	8 36	0.04834 06320	1.00367 03237	0.12041 99725
8	0.17205 16530	9 49	0.05501 67694	1.00478 66023	0.13752 55283
9	0.19355 81096	11 3	0.06160 24003	1.00604 76005	0.15459 21831
10	0.21506 45662	12 16	0.06808 70479	1.00745 17850	0.17161 50856
11	0.23657 10228	13 28	0.07446 05194	1.00899 74482	0.18858 93888
12	0.25807 74795	14 41	0.08071 29320	1.01068 27105	0.20551 02505
13	0.27958 39361	15 53	0.08683 47367	1.01250 55225	0.22237 28335
14	0.30109 03927	17 6	0.09281 67403	1.01446 36673	0.23917 23067
15	0.32259 68493	18 18	0.09865 01256	1.01655 47635	0.25590 38457
16	0.34410 33059	19 29	0.10432 64694	1.01877 62678	0.27256 26330
17	0.36560 97626	20 40	0.10983 77593	1.02112 54784	0.28914 38591
18	0.38711 62192	21 51	0.11517 64068	1.02359 95379	0.30564 27234
19	0.40862 26758	23 2	0.12033 52604	1.02619 54370	0.32205 44344
20	0.43012 91324	24 13	0.12530 76146	1.02891 00179	0.33837 42110
21	0.45163 55891	25 22	0.13008 72182	1.03173 99787	0.35459 72832
22	0.47314 20457	26 31	0.13466 82799	1.03468 18764	0.37071 88930
23	0.49464 85023	27 41	0.13904 54724	1.03773 21323	0.38673 42953
24	0.51615 49589	28 50	0.14321 39340	1.04088 70352	0.40263 87589
25	0.53766 14155	29 59	0.14716 92687	1.04414 27466	0.41842 75678
26	0.55916 78722	31 6	0.15090 75443	1.04749 53052	0.43409 60218
27	0.58067 43288	32 14	0.15442 52892	1.05094 06315	0.44963 94381
28	0.60218 07854	33 21	0.15771 94871	1.05447 45329	0.46505 31522
29	0.62368 72420	34 29	0.16078 75703	1.05809 27090	0.48033 25191
30	0.64519 36987	35 36	0.16362 74123	1.06179 07561	0.49547 29148
31	0.66670 01553	36 41	0.16623 73178	1.06556 41737	0.51046 97376
32	0.68820 66119	37 46	0.16861 60131	1.06940 83686	0.52531 84091
33	0.70971 30685	38 51	0.17076 26341	1.07331 86617	0.54001 43761
34	0.73121 95251	39 56	0.17267 67142	1.07729 02929	0.55455 31119
35	0.75272 59818	41 1	0.17435 81713	1.08131 84270	0.56893 01177
36	0.77423 24384	42 4	0.17580 72936	1.08539 81601	0.58314 09242
37	0.79573 88950	43 7	0.17702 47258	1.08952 45247	0.59718 10935
38	0.81724 53516	44 9	0.17801 14536	1.09369 24965	0.61104 62201
39	0.83875 18083	45 12	0.17876 87890	1.09789 70001	0.62473 19335
40	0.86025 82649	46 15	0.17929 83544	1.10213 29153	0.63823 38991
41	0.88176 47215	47 15	0.17960 20675	1.10639 50831	0.65154 78204
42	0.90327 11781	48 16	0.17968 21252	1.11067 83124	0.66466 94406
43	0.92477 76347	49 16	0.17954 09878	1.11497 73861	0.67759 45449
44	0.94628 40914	50 17	0.17918 13641	1.11928 70673	0.69031 89618
45	0.96779 05480	51 17	0.17860 61952	1.12360 21058	0.70283 85652
90−r	Fψ	ψ	G(r)	C(r)	B(r)

$q = 0.055019933698829$, $\Theta 0 = 0.8899784604$, HK $= 0.9715669451$

B(r)	C(r)	G(r)	ψ	Fψ	90-r
1.00000 00000	1.24728 65857	0.00000 00000	90° 0′	1.93558 10960	90
0.99984 40186	1.24721 12154	0.00561 92362	89 12	1.91407 46394	89
0.99937 61319	1.24698 51964	0.01123 36482	88 25	1.89256 81828	88
0.99859 65127	1.24660 88048	0.01683 84106	87 37	1.87106 17261	87
0.99750 54487	1.24608 24999	0.02242 89646	86 50	1.84955 52695	86
0.99610 33424	1.24540 69243	0.02799 96670	86 2	1.82804 88129	85
0.99439 07108	1.24458 29027	0.03354 64884	85 14	1.80654 23563	84
0.99236 81849	1.24361 14410	0.03906 43123	84 26	1.78503 58997	83
0.99003 65093	1.24249 37250	0.04454 82835	83 39	1.76352 94430	82
0.98739 65416	1.24123 11192	0.04999 35367	82 51	1.74202 29864	81
0.98444 92517	1.23982 51648	0.05539 51961	82 3	1.72051 65298	80
0.98119 57210	1.23827 75779	0.06074 83740	81 14	1.69901 00732	79
0.97763 71417	1.23659 02476	0.06604 81700	80 26	1.67750 36165	78
0.97377 48160	1.23476 52334	0.07128 96708	79 37	1.65599 71599	77
0.96961 01546	1.23280 47629	0.07646 79497	78 49	1.63449 07033	76
0.96514 46762	1.23071 12287	0.08157 80662	78 0	1.61298 42467	75
0.96038 00059	1.22848 71860	0.08661 50665	77 10	1.59147 77901	74
0.95531 78745	1.22613 53491	0.09157 39836	76 21	1.56997 13334	73
0.94996 01167	1.22365 85882	0.09644 98379	75 31	1.54846 48768	72
0.94430 86698	1.22105 99257	0.10123 76383	74 42	1.52695 84202	71
0.93836 55727	1.21834 25328	0.10593 23833	73 52	1.50545 19636	70
0.93213 29639	1.21550 97252	0.11052 90627	73 1	1.48394 55069	69
0.92561 30802	1.21256 49596	0.11502 26595	72 11	1.46243 90503	68
0.91880 82552	1.20951 18289	0.11940 81521	71 20	1.44093 25937	67
0.91172 09173	1.20635 40582	0.12368 05174	70 30	1.41942 61371	66
0.90435 35883	1.20309 54999	0.12783 47335	69 39	1.39791 96805	65
0.89670 88815	1.19974 01294	0.13186 57834	68 47	1.37641 32238	64
0.88878 94998	1.19629 20396	0.13576 86595	67 55	1.35490 67672	63
0.88059 82341	1.19275 54368	0.13953 83674	67 2	1.33340 03106	62
0.87213 79612	1.18913 46345	0.14316 99314	66 10	1.31189 38540	61
0.86341 16420	1.18543 40490	0.14665 83999	65 18	1.29038 73973	60
0.85442 23195	1.18165 81935	0.14999 88516	64 24	1.26888 09407	59
0.84517 31166	1.17781 16727	0.15318 64017	63 30	1.24737 44841	58
0.83566 72345	1.17389 91774	0.15621 62095	62 36	1.22586 80275	57
0.82590 79506	1.16992 54783	0.15908 34859	61 42	1.20436 15709	56
0.81589 86161	1.16589 54205	0.16178 35017	60 48	1.18285 51142	55
0.80564 26543	1.16181 39175	0.16431 15964	59 52	1.16134 86576	54
0.79514 35583	1.15768 59453	0.16666 31878	58 56	1.13984 22010	53
0.78440 48891	1.15351 65361	0.16883 37818	58 0	1.11833 57444	52
0.77343 02735	1.14931 07723	0.17081 89832	57 4	1.09682 92877	51
0.76222 34019	1.14507 37802	0.17261 45069	56 8	1.07532 28311	50
0.75078 80264	1.14081 07240	0.17421 61892	55 10	1.05381 63745	49
0.73912 79584	1.13652 67992	0.17562 00006	54 12	1.03230 99179	48
0.72724 70671	1.13222 72263	0.17682 20583	53 13	1.01080 34613	47
0.71514 92767	1.12791 72446	0.17781 86395	52 15	0.98929 70046	46
0.70283 85652	1.12360 21058	0.17860 61952	51 17	0.96779 05480	45
A(r)	D(r)	E(r)	φ	Fφ	r

$K = 2.0347153122$, $K' = 1.7312451757$, $E = 1.2586796248$, $E' = 1.4322909693$,

r	Fφ	φ	E(r)	D(r)	A(r)
0	0.00000 00000	0° 0′	0.00000 00000	1.00000 00000	0.00000 00000
1	0.02260 79479	1 18	0.00862 00346	1.00009 74600	0.01712 13223
2	0.04521 58958	2 35	0.01722 45749	1.00038 97217	0.03423 80342
3	0.06782 38437	3 53	0.02579 81795	1.00087 64305	0.05134 55249
4	0.09043 17916	5 10	0.03432 55123	1.00155 69957	0.06843 91832
5	0.11303 97395	6 28	0.04279 13942	1.00243 05914	0.08551 43971
6	0.13564 76875	7 45	0.05118 08539	1.00349 61575	0.10256 65538
7	0.15825 56354	9 2	0.05947 91769	1.00475 24006	0.11959 10390
8	0.18086 35833	10 19	0.06767 19530	1.00619 77962	0.13658 32373
9	0.20347 15312	11 36	0.07574 51216	1.00783 05901	0.15353 85318
10	0.22607 94791	12 52	0.08368 50144	1.00964 88003	0.17045 23039
11	0.24868 74270	14 9	0.09147 83960	1.01165 02201	0.18731 99332
12	0.27129 53749	15 25	0.09911 25013	1.01383 24199	0.20413 67975
13	0.29390 33229	16 40	0.10657 50694	1.01619 27508	0.22089 82730
14	0.31651 12708	17 56	0.11385 43755	1.01872 83473	0.23759 97340
15	0.33911 92187	19 11	0.12093 92580	1.02143 61311	0.25423 65532
16	0.36172 71666	20 25	0.12781 91435	1.02431 28147	0.27080 41017
17	0.38433 51145	21 40	0.13448 40670	1.02735 49050	0.28729 77496
18	0.40694 30624	22 54	0.14092 46901	1.03055 87080	0.30371 28656
19	0.42955 10103	24 7	0.14713 23140	1.03392 03331	0.32004 48178
20	0.45215 89583	25 20	0.15309 88906	1.03743 56974	0.33628 89743
21	0.47476 69062	26 33	0.15881 70288	1.04110 05314	0.35244 07031
22	0.49737 48541	27 45	0.16427 99989	1.04491 03831	0.36849 53729
23	0.51998 28020	28 56	0.16948 17327	1.04886 06244	0.38444 83538
24	0.54259 07499	30 8	0.17441 68208	1.05294 64558	0.40029 50181
25	0.56519 86978	31 18	0.17908 05075	1.05716 29130	0.41603 07408
26	0.58780 66457	32 28	0.18346 86827	1.06150 48720	0.43165 09003
27	0.61041 45937	33 38	0.18757 78710	1.06596 70560	0.44715 08801
28	0.63302 25418	34 46	0.19140 52188	1.07054 40415	0.46253 60691
29	0.65563 04895	35 55	0.19494 84794	1.07523 02647	0.47777 18627
30	0.67823 84374	37 3	0.19820 59959	1.08002 00285	0.49288 36645
31	0.70084 63853	38 10	0.20117 66827	1.08490 75092	0.50785 68872
32	0.72345 43332	39 16	0.20386 00053	1.08988 67634	0.52268 69541
33	0.74606 22811	40 23	0.20625 59591	1.09495 17358	0.53736 93004
34	0.76867 02290	41 28	0.20836 50468	1.10009 62656	0.55189 93747
35	0.79127 81769	42 33	0.21018 82554	1.10531 40947	0.56627 26408
36	0.81388 61249	43 38	0.21172 70324	1.11059 88749	0.58048 45794
37	0.83649 40728	44 41	0.21298 32611	1.11594 41760	0.59453 06894
38	0.85910 20207	45 45	0.21395 92364	1.12134 34929	0.60840 64905
39	0.88170 99686	46 48	0.21465 76400	1.12679 02542	0.62210 75244
40	0.90431 79165	47 50	0.21508 15155	1.13227 78297	0.63562 93571
41	0.92692 58644	48 51	0.21523 42440	1.13779 95386	0.64896 75812
42	0.94953 38123	49 53	0.21511 95200	1.14334 86579	0.66211 78175
43	0.97214 17602	50 53	0.21474 13276	1.14891 84299	0.67507 57177
44	0.99474 97081	51 53	0.21410 39170	1.15450 20711	0.68783 69663
45	1.01735 76561	52 52	0.21321 17818	1.16009 27802	0.70039 72833
90-r	Fψ	ψ	G(r)	C(r)	B(r)

$q = 0.069042299609032$, $\Theta 0 = 0.8619608462$, HK = 1.0300875730

B(r)	C(r)	G(r)	ψ	Fψ	90-r
1.00000 00000	1.32039 64540	0.00000 00000	90° 0′	2.03471 53122	90
0.99984 19155	1.32029 87371	0.00654 66917	89 15	2.01210 73643	89
0.99936 77261	1.32000 57060	0.01308 82806	88 31	1.98949 94164	88
0.99857 76238	1.31951 77192	0.01961 96606	87 46	1.96689 14685	87
0.99747 19280	1.31883 53734	0.02613 57182	87 1	1.94428 35205	86
0.99605 10861	1.31795 95033	0.03263 13295	86 17	1.92167 55726	85
0.99431 56720	1.31689 11801	0.03910 13564	85 32	1.89906 76247	84
0.99226 63864	1.31563 17106	0.04554 06434	84 47	1.87645 96768	83
0.98990 40553	1.31418 26349	0.05194 40144	84 2	1.85385 17289	82
0.98722 96302	1.31254 57253	0.05830 62693	83 17	1.83124 37810	81
0.98424 41861	1.31072 29838	0.06462 21812	82 32	1.80863 58331	80
0.98094 89213	1.30871 66392	0.07088 64934	81 46	1.78602 78851	79
0.97734 51558	1.30652 91449	0.07709 39167	81 1	1.76341 99372	78
0.97343 43300	1.30416 31759	0.08323 91270	80 15	1.74081 19893	77
0.96921 80039	1.30162 16250	0.08931 67629	79 29	1.71820 40414	76
0.96469 78546	1.29890 75994	0.09532 14240	78 43	1.69559 60935	75
0.95987 56758	1.29602 44173	0.10124 76688	77 56	1.67298 81456	74
0.95475 33753	1.29297 56032	0.10709 00133	77 10	1.65038 01977	73
0.94933 29736	1.28976 48840	0.11284 29301	76 23	1.62777 22497	72
0.94361 66021	1.28639 61840	0.11850 08473	75 35	1.60516 43018	71
0.93760 65006	1.28287 36204	0.12405 81487	74 48	1.58255 63539	70
0.93130 50161	1.27920 14980	0.12950 91731	74 0	1.55994 84060	69
0.92471 45998	1.27538 43041	0.13484 82153	73 12	1.53734 04581	68
0.91783 78055	1.27142 67027	0.14006 95267	72 23	1.51473 25102	67
0.91067 72870	1.26733 35291	0.14516 73172	71 35	1.49212 45623	66
0.90323 57961	1.26310 97835	0.15013 57566	70 46	1.46951 66144	65
0.89551 61797	1.25876 06253	0.15496 89777	69 56	1.44690 86665	64
0.88752 13778	1.25429 13663	0.15966 10790	69 7	1.42430 07185	63
0.87925 44206	1.24970 74646	0.16420 61290	68 16	1.40169 27706	62
0.87071 84265	1.24501 45176	0.16859 81701	67 26	1.37908 48227	61
0.86191 65988	1.24021 82552	0.17283 12244	66 35	1.35647 68748	60
0.85285 22237	1.23532 45329	0.17689 92991	65 43	1.33386 89269	59
0.84352 86672	1.23033 93242	0.18079 63935	64 51	1.31126 09790	58
0.83394 93726	1.22526 87137	0.18451 65064	63 59	1.28865 30311	57
0.82411 78578	1.22011 88895	0.18805 36444	63 6	1.26604 50832	56
0.81403 77126	1.21489 61356	0.19140 18312	62 12	1.24343 71353	55
0.80371 25960	1.20960 68240	0.19455 51177	61 19	1.22082 91873	54
0.79314 62334	1.20425 74072	0.19750 75927	60 24	1.19822 12394	53
0.78234 24136	1.19885 44102	0.20025 33955	59 30	1.17561 32915	52
0.77130 49868	1.19340 44225	0.20278 67279	58 35	1.15300 53436	51
0.76003 78612	1.18791 40899	0.20510 18688	57 39	1.13039 73957	50
0.74854 50007	1.18239 01066	0.20719 31885	56 42	1.10778 94478	49
0.73683 04220	1.17683 92068	0.20905 51650	55 46	1.08518 14999	48
0.72489 81922	1.17126 81567	0.21068 24001	54 48	1.06257 35519	47
0.71275 24260	1.16568 37461	0.21206 96376	53 50	1.03996 56041	46
0.70039 72833	1.16009 27802	0.21321 17818	52 52	1.01735 76561	45
A(r)	D(r)	E(r)	φ	Fφ	r

K = 2.1565156475, K′ = 1.6857503548, E = 1.211056028, E′ = 1.4674622093,

r	Fφ	φ	E(r)	D(r)	A(r)
0	0.00000 00000	0° 0′	0.00000 00000	1.00000 00000	0.00000 00000
1	0.02396 12850	1 22	0.01050 21636	1.00012 58452	0.01694 24822
2	0.04792 25699	2 45	0.02098 36904	1.00050 32288	0.03388 07351
3	0.07188 38549	4 7	0.03142 40274	1.00113 16945	0.05081 05279
4	0.09584 51399	5 29	0.04180 27880	1.00201 04822	0.06772 76275
5	0.11980 64248	6 51	0.05209 98337	1.00313 85295	0.08462 77970
6	0.14376 77098	8 13	0.06229 53533	1.00451 44723	0.10150 67944
7	0.16772 89948	9 35	0.07236 99392	1.00613 66468	0.11836 03717
8	0.19169 02798	10 56	0.08230 46606	1.00800 30911	0.13518 42734
9	0.21565 15647	12 17	0.09208 11326	1.01011 15480	0.15197 42358
10	0.23961 28497	13 38	0.10168 15801	1.01245 94672	0.16872 59855
11	0.26357 41347	14 58	0.11108 88976	1.01504 40088	0.18543 52386
12	0.28753 54197	16 18	0.12028 67034	1.01786 20463	0.20209 76999
13	0.31149 67046	17 38	0.12925 93879	1.02091 01701	0.21870 90619
14	0.33545 79896	18 57	0.13799 21563	1.02418 46923	0.23526 50037
15	0.35941 92746	20 16	0.14647 10652	1.02768 16504	0.25176 11911
16	0.38338 05595	21 35	0.15468 30530	1.03139 68120	0.26819 32750
17	0.40734 18445	22 53	0.16261 59647	1.03532 56803	0.28455 68916
18	0.43130 31295	24 10	0.17025 85702	1.03946 34991	0.30084 76617
19	0.45526 44145	25 26	0.17760 05773	1.04380 52583	0.31706 11903
20	0.47922 56994	26 42	0.18463 26382	1.04834 57003	0.33319 30665
21	0.50318 69844	27 58	0.19134 63517	1.05307 93260	0.34923 88634
22	0.52714 82694	29 13	0.19773 42593	1.05800 04010	0.36519 41381
23	0.55110 95544	30 27	0.20378 98371	1.06310 29632	0.38105 44318
24	0.57507 08393	31 41	0.20950 74827	1.06838 08291	0.39681 52701
25	0.59903 21243	32 54	0.21488 24988	1.07382 76019	0.41247 21633
26	0.62299 34093	34 7	0.21991 10718	1.07943 66784	0.42802 06069
27	0.64695 46942	35 18	0.22459 02484	1.08520 12575	0.44345 60826
28	0.67091 59792	36 29	0.22891 79082	1.09111 43480	0.45877 40585
29	0.69487 72642	37 39	0.23289 27342	1.09716 87771	0.47396 99905
30	0.71883 85492	38 49	0.23651 41807	1.10335 71989	0.48903 93230
31	0.74279 98341	39 58	0.23978 24399	1.10967 21031	0.50397 74905
32	0.76676 11191	41 6	0.24269 84060	1.11610 58243	0.51877 99184
33	0.79072 24041	42 13	0.24526 36394	1.12265 05510	0.53344 20249
34	0.81468 36890	43 20	0.24748 03283	1.12929 83350	0.54795 92224
35	0.83864 49740	44 26	0.24935 12513	1.13604 11010	0.56232 69191
36	0.86260 62590	45 31	0.25087 97387	1.14287 06563	0.57654 05212
37	0.88656 75440	46 35	0.25206 96336	1.14977 87007	0.59059 54347
38	0.91052 88289	47 39	0.25292 52540	1.15675 68364	0.60448 70673
39	0.93449 01139	48 42	0.25345 13545	1.16379 65783	0.61821 08313
40	0.95845 13989	49 44	0.25365 30884	1.17088 93642	0.63176 21451
41	0.98241 26838	50 45	0.25353 59713	1.17802 65652	0.64513 64364
42	1.00637 39688	51 46	0.25310 58450	1.18519 94959	0.65832 91446
43	1.03033 52538	52 46	0.25236 88429	1.19239 94253	0.67133 57232
44	1.05429 65388	53 45	0.25133 13558	1.19961 75873	0.68415 16433
45	1.07825 78237	54 44	0.25000 00000	1.20684 51910	0.69677 23959
90-r	Fψ	ψ	G(r)	C(r)	B(r)

$q = 0.085795733702195$, $\Theta 0 = 0.8285168980$, HK = 1.0903895588

B(r)	C(r)	G(r)	ψ	Fψ	90-r
1.00000 00000	1.41421 35624	0.00000 00000	90° 0′	2.15651 56475	90
0.99983 87925	1.41408 70799	0.00746 45017	89 19	2.13255 43625	89
0.99935 52434	1.41370 77878	0.01492 38646	88 38	2.10859 30775	88
0.99854 95732	1.41307 61515	0.02237 29430	87 57	2.08463 17926	87
0.99742 21491	1.41219 29466	0.02980 65777	87 16	2.06067 05076	86
0.99597 34843	1.41105 92570	0.03721 95889	86 35	2.03670 92226	85
0.99420 42378	1.40967 64744	0.04460 67701	85 53	2.01274 79377	84
0.99211 52135	1.40804 62958	0.05196 28815	85 11	1.98878 66527	83
0.98970 73588	1.40617 07222	0.05928 26440	84 29	1.96482 53677	82
0.98698 17641	1.40405 20551	0.06656 07336	83 47	1.94086 40827	81
0.98393 96610	1.40169 28947	0.07379 17757	83 5	1.91690 27978	80
0.98058 24210	1.39909 61356	0.08097 03401	82 23	1.89294 15128	79
0.97691 15541	1.39626 49639	0.08809 09364	81 41	1.86898 02278	78
0.97292 87065	1.39320 28531	0.09514 80095	80 58	1.84501 89429	77
0.96863 56591	1.38991 35592	0.10213 59353	80 15	1.82105 76579	76
0.96403 43250	1.38640 11169	0.10904 90175	79 32	1.79709 63729	75
0.95912 67478	1.38266 98339	0.11588 14840	78 49	1.77313 50879	74
0.95391 50985	1.37872 42853	0.12262 74837	78 5	1.74917 38030	73
0.94840 16738	1.37456 93090	0.12928 10844	77 21	1.72521 25180	72
0.94258 88926	1.37020 99983	0.13583 62697	76 37	1.70125 12330	71
0.93647 92941	1.36565 16965	0.14228 69378	75 53	1.67728 99480	70
0.93007 55342	1.36089 99899	0.14862 68991	75 8	1.65332 86631	69
0.92338 03829	1.35596 07006	0.15484 98749	74 23	1.62936 73781	68
0.91639 67210	1.35083 98797	0.16094 94967	73 37	1.60540 60931	67
0.90912 75372	1.34554 37995	0.16691 93054	72 51	1.58144 48082	66
0.90157 59245	1.34007 89457	0.17275 27505	72 5	1.55748 35232	65
0.89374 50771	1.33445 20094	0.17844 31913	71 18	1.53352 22382	64
0.88563 82868	1.32866 98789	0.18398 38964	70 30	1.50956 09532	63
0.87725 89396	1.32273 96308	0.18936 80462	69 42	1.48559 96683	62
0.86861 05122	1.31666 85215	0.19458 87340	68 54	1.46163 83833	61
0.85969 65682	1.31046 39783	0.19963 89691	68 5	1.43767 70983	60
0.85052 07549	1.30413 35898	0.20451 16802	67 16	1.41371 58134	59
0.84108 67990	1.29768 50969	0.20919 97204	66 26	1.38975 45284	58
0.83139 85036	1.29112 63832	0.21369 58722	65 36	1.36579 32434	57
0.82145 97438	1.28446 54650	0.21799 28546	64 45	1.34183 19584	56
0.81127 44636	1.27771 04815	0.22208 33313	63 53	1.31787 06735	55
0.80084 66719	1.27086 96850	0.22595 99196	63 1	1.29390 93885	54
0.79018 04386	1.26395 14305	0.22961 52018	62 9	1.26994 81035	53
0.77927 98915	1.25696 41655	0.23304 17372	61 15	1.24598 68185	52
0.76814 92120	1.24991 64194	0.23623 20761	60 21	1.22202 55336	51
0.75679 26317	1.24281 67937	0.23917 87758	59 27	1.19806 42486	50
0.74521 44290	1.23567 39504	0.24187 44177	58 32	1.17410 29636	49
0.73341 89253	1.22849 66025	0.24431 16265	57 36	1.15014 16787	48
0.72141 04816	1.22129 35025	0.24648 30908	56 39	1.12618 03937	47
0.70919 34952	1.21407 34320	0.24838 15864	55 42	1.10221 91087	46
0.69677 23959	1.20684 51910	0.25000 00000	54 44	1.07825 78237	45
A(r)	D(r)	E(r)	φ	Fφ	r

K = 2.3087867982, K′ = 1.6489952185, E = 1.1638279645, E′ = 1.4981149284,

r	Fφ	φ	E(r)	D(r)	A(r)
0	0.00000 00000	0° 0′	0.00000 00000	1.00000 00000	0.00000 00000
1	0.02565 31866	1 28	0.01271 71437	1.00016 31607	0.01667 62945
2	0.05130 63733	2 56	0.02540 65870	1.00065 24464	0.03334 89266
3	0.07695 95599	4 24	0.03804 07622	1.00146 72698	0.05001 42309
4	0.10261 27466	5 52	0.05059 23651	1.00260 66524	0.06666 85367
5	0.12826 59332	7 20	0.06303 44839	1.00406 92257	0.08330 81651
6	0.15391 91199	8 47	0.07534 07235	1.00585 32333	0.09992 94260
7	0.17957 23085	10 14	0.08748 53252	1.00795 65320	0.11652 86159
8	0.20522 54932	11 41	0.09944 32800	1.01037 65954	0.13310 20150
9	0.23087 86798	13 8	0.11119 04341	1.01311 05159	0.14964 58850
10	0.25653 18665	14 34	0.12270 35875	1.01615 50083	0.16615 64662
11	0.28218 50531	16 0	0.13396 05824	1.01950 64139	0.18262 99754
12	0.30783 82398	17 25	0.14494 03827	1.02316 07042	0.19906 26038
13	0.33349 14264	18 50	0.15562 31436	1.02711 34860	0.21545 05144
14	0.35914 46131	20 14	0.16599 02705	1.03136 00060	0.23178 98405
15	0.38479 77997	21 38	0.17602 44678	1.03589 51569	0.24807 66833
16	0.41045 09864	23 1	0.18570 97766	1.04071 34825	0.26430 71105
17	0.43610 41730	24 23	0.19503 16024	1.04580 91848	0.28047 71545
18	0.46175 73596	25 44	0.20397 67323	1.05117 61304	0.29658 28110
19	0.48741 05463	27 4	0.21253 33427	1.05680 78572	0.31260 00376
20	0.51306 37329	28 24	0.22069 09968	1.06269 75825	0.32858 47528
21	0.53871 69196	29 43	0.22844 06338	1.06883 82109	0.34447 28350
22	0.56437 01062	31 1	0.23577 45496	1.07522 23418	0.36028 01217
23	0.59002 32929	32 19	0.24268 63696	1.08184 22789	0.37600 24088
24	0.61567 64795	33 36	0.24917 10151	1.08869 00386	0.39163 54503
25	0.64132 96662	34 52	0.25522 46626	1.09575 73598	0.40717 49584
26	0.66698 28528	36 7	0.26084 46988	1.10303 57129	0.42261 66028
27	0.69263 60395	37 21	0.26602 96698	1.11051 63106	0.43795 60117
28	0.71828 92261	38 34	0.27077 92271	1.11819 01175	0.45318 87717
29	0.74394 24127	39 46	0.27509 40704	1.12604 78613	0.46831 04285
30	0.76959 55994	40 58	0.27897 58872	1.13408 00433	0.48331 64880
31	0.79524 87860	42 9	0.28242 72920	1.14227 69496	0.49820 24170
32	0.82090 19727	43 18	0.28545 17629	1.15062 86634	0.51296 36449
33	0.84655 51593	44 26	0.28805 35786	1.15912 50752	0.52759 55647
34	0.87220 83460	45 34	0.29023 77551	1.16775 58964	0.54209 35352
35	0.89786 15326	46 41	0.29200 99830	1.17651 06705	0.55645 28823
36	0.92351 47193	47 47	0.29337 65659	1.18537 87860	0.57066 89018
37	0.94916 79059	48 52	0.29434 43597	1.19434 94887	0.58473 68614
38	0.97482 10926	49 56	0.29492 07141	1.20341 18951	0.59865 20033
39	1.00047 42792	50 59	0.29511 34159	1.21255 50050	0.61240 95465
40	1.02612 74659	52 1	0.29493 06347	1.22176 77148	0.62600 46907
41	1.05178 06525	53 2	0.29438 08705	1.23103 88308	0.63943 26185
42	1.07743 38392	54 2	0.29347 29047	1.24035 70830	0.65268 84992
43	1.10308 70258	55 1	0.29221 57532	1.24971 11383	0.66576 74922
44	1.12874 02125	56 0	0.29061 86227	1.25908 96145	0.67866 47507
45	1.15439 33991	56 58	0.28869 08691	1.26848 10938	0.69137 54254
90–r	Fψ	ψ	G(r)	C(r)	B(r)

$q = 0.106054020185994$, $\Theta 0 = 0.7881449667$, $HK = 1.1541701350$

B(r)	C(r)	G(r)	ψ	Fψ	90−r
1.00000 00000	1.53824 62687	0.00000 00000	90° 0′	2.30878 67982	90
0.99983 41412	1.53808 15440	0.00834 87781	88 23	2.28313 36115	89
0.99933 66526	1.53758 75740	0.01669 26008	88 46	2.25748 04249	88
0.99850 77970	1.53676 49688	0.02502 65041	88 9	2.23182 72382	87
0.99734 80125	1.53561 47447	0.03334 55075	87 32	2.20617 40516	86
0.99585 79109	1.53413 83232	0.04164 46052	86 54	2.18052 08649	85
0.99403 82778	1.53233 75281	0.04991 87582	86 16	2.15486 76783	84
0.99189 00707	1.53021 45843	0.05816 28855	85 38	2.12921 44916	83
0.98941 44182	1.52777 21140	0.06637 18564	85 0	2.10356 13050	82
0.98661 26176	1.52501 31340	0.07454 04819	84 22	2.07790 81184	81
0.98348 61339	1.52194 10514	0.08266 35068	83 44	2.05225 49317	80
0.98003 65970	1.51855 96596	0.09073 56016	83 6	2.02660 17451	79
0.97626 57996	1.51487 31329	0.09875 13547	82 27	2.00094 85584	78
0.97217 56947	1.51088 60218	0.10670 52642	81 48	1.97529 53718	77
0.96776 83924	1.50660 32466	0.11459 17308	81 9	1.94964 21851	76
0.96304 61576	1.50203 00916	0.12240 50500	80 30	1.92398 89985	75
0.95801 14060	1.49717 21977	0.13013 94047	79 50	1.89833 58118	74
0.95266 67013	1.49203 55559	0.13778 88583	79 10	1.87268 26251	73
0.94701 47511	1.48662 64993	0.14534 73477	78 30	1.84702 94385	72
0.94105 84035	1.48095 16947	0.15280 86769	77 49	1.82137 62519	71
0.93480 06429	1.47501 81348	0.16016 65105	77 8	1.79572 30652	70
0.92824 45859	1.46883 31288	0.16741 43683	76 26	1.77006 98786	69
0.92139 34772	1.46240 42933	0.17454 56190	75 44	1.74441 66919	68
0.91425 06851	1.45573 95424	0.18155 34763	75 2	1.71876 35053	67
0.90681 96968	1.44884 70781	0.18843 09933	74 19	1.69311 03186	66
0.89910 41140	1.44173 53793	0.19517 10594	73 36	1.66745 71320	65
0.89110 76479	1.43441 31916	0.20176 63966	72 52	1.64180 39453	64
0.88283 41144	1.42688 95162	0.20820 95570	72 8	1.61615 07587	63
0.87428 74294	1.41917 35981	0.21449 29211	71 23	1.59049 75721	62
0.86547 16034	1.41127 49149	0.22060 86968	70 37	1.56484 43854	61
0.85639 07366	1.40320 31647	0.22654 89197	69 51	1.53919 11988	60
0.84704 90138	1.39496 82541	0.23230 54536	69 4	1.51353 80121	59
0.83745 06991	1.38658 02852	0.23786 99932	68 17	1.48788 48255	58
0.82760 01310	1.37804 95440	0.24323 40676	67 29	1.46223 16388	57
0.81750 17168	1.36938 64865	0.24838 90447	66 41	1.43657 84522	56
0.80715 99276	1.36060 17261	0.25332 61379	65 52	1.41092 52655	55
0.79657 92934	1.35170 60205	0.25803 64133	65 2	1.38527 20789	54
0.78576 43973	1.34271 02582	0.26251 08001	64 11	1.35961 88922	53
0.77471 98708	1.33362 54449	0.26674 01012	63 20	1.33396 57055	52
0.76345 03889	1.32446 26900	0.27071 50065	62 28	1.30831 25189	51
0.75196 06646	1.31523 31927	0.27442 61086	61 35	1.28265 93322	50
0.74025 54443	1.30594 82284	0.27786 39198	60 41	1.25700 61456	49
0.72833 95027	1.29661 91348	0.28101 88920	59 46	1.23135 29589	48
0.71621 76383	1.28725 72976	0.28388 14388	58 51	1.20569 97723	47
0.70389 46686	1.27787 41372	0.28644 19600	57 55	1.18004 65856	46
0.69137 54254	1.26848 10938	0.28869 08691	56 58	1.15439 33991	45
A(r)	D(r)	E(r)	φ	Fφ	r

K = 2.5045500790, K′ = 1.6200258991, E = 1.1183777380, E′ = 1.5237992053,

r	Fφ	φ	E(r)	D(r)	A(r)
0	0.00000 00000	0° 0′	0.00000 00000	1.00000 00000	0.00000 00000
1	0.02782 83342	1 36	0.01539 55735	1.00021 42837	0.01627 42346
2	0.05565 66684	3 11	0.03075 31429	1.00085 68806	0.03254 56619
3	0.08348 50026	4 47	0.04603 49252	1.00192 70294	0.04881 14698
4	0.11131 33368	6 22	0.06120 35769	1.00342 34614	0.06506 88358
5	0.13914 16710	7 57	0.07622 24069	1.00534 44028	0.08131 49227
6	0.16697 00053	9 32	0.09105 55815	1.00768 75763	0.09754 68734
7	0.19479 83395	11 6	0.10566 83193	1.01045 02032	0.11376 18057
8	0.22262 66737	12 40	0.12002 70732	1.01362 90072	0.12995 68083
9	0.25045 50079	14 13	0.13409 96984	1.01722 02172	0.14612 89355
10	0.27828 33421	15 46	0.14785 56040	1.02121 95717	0.16227 52029
11	0.30611 16763	17 18	0.16126 58874	1.02562 23237	0.17839 25828
12	0.33394 00105	18 50	0.17430 34501	1.03042 32454	0.19447 80006
13	0.36176 83447	20 20	0.18694 30948	1.03561 66341	0.21052 83297
14	0.38959 66790	21 50	0.19916 16028	1.04119 63185	0.22654 03885
15	0.41742 50132	23 20	0.21093 77918	1.04715 56657	0.24251 09363
16	0.44525 33474	24 48	0.22225 25549	1.05348 75877	0.25843 66697
17	0.47308 16816	26 16	0.23308 88806	1.06018 45500	0.27431 42196
18	0.50091 00158	27 42	0.24343 18557	1.06723 85795	0.29014 01480
19	0.52873 83500	29 8	0.25326 86498	1.07464 12734	0.30591 09453
20	0.55656 66842	30 32	0.26258 84862	1.08238 38086	0.32162 30277
21	0.58439 50184	31 56	0.27138 25968	1.09045 69513	0.33727 27349
22	0.61222 33526	33 18	0.27964 41653	1.09885 10673	0.35285 63285
23	0.64005 16869	34 40	0.28736 82581	1.10755 61330	0.36836 99898
24	0.66788 00211	36 0	0.29455 17462	1.11656 17464	0.38380 98186
25	0.69570 83553	37 19	0.30119 32185	1.12585 71388	0.39917 18323
26	0.72353 66895	38 37	0.30729 28884	1.13543 11869	0.41445 19649
27	0.75136 50237	39 54	0.31285 24953	1.14527 24256	0.42964 60668
28	0.77919 33579	41 10	0.31787 52022	1.15536 90607	0.44474 99043
29	0.80702 16921	42 24	0.32236 54911	1.16570 89825	0.45975 91601
30	0.83485 00263	43 38	0.32632 90569	1.17627 97795	0.47466 94339
31	0.86267 83605	44 50	0.32977 27014	1.18706 87529	0.48947 62428
32	0.89050 66948	46 1	0.33270 42283	1.19806 29307	0.50417 50229
33	0.91833 50290	47 11	0.33513 23398	1.20924 90830	0.51876 11309
34	0.94616 33632	48 20	0.33706 65364	1.22061 37375	0.53322 98456
35	0.97399 16974	49 27	0.33851 70194	1.23214 31946	0.54757 63701
36	1.00182 00316	50 34	0.33949 45975	1.24382 35438	0.56179 58348
37	1.02964 83658	51 39	0.34001 05978	1.25564 06798	0.57588 32996
38	1.05747 67000	52 43	0.34007 67814	1.26758 03194	0.58983 37576
39	1.08530 50342	53 46	0.33970 52640	1.27962 80178	0.60364 21381
40	1.11313 33684	54 48	0.33890 84414	1.29176 91861	0.61730 33109
41	1.14096 17027	55 49	0.33769 89203	1.30398 91085	0.63081 20897
42	1.16879 00369	56 48	0.33608 94543	1.31627 29599	0.64416 32373
43	1.19661 83711	57 47	0.33409 28851	1.32860 58237	0.65735 14695
44	1.22444 67053	58 44	0.33172 20892	1.34097 27096	0.67037 14605
45	1.25227 50395	59 41	0.32898 99283	1.35335 85717	0.68321 78479
90-r	Fψ	ψ	G(r)	C(r)	B(r)

$q = 0.131061824499858, \quad \Theta 0 = 0.7384664407, \quad HK = 1.2240462555$

B(r)	C(r)	G(r)	ψ	Fψ	90−r
1.00000 00000	1.70991 35651	0.00000 00000	90° 0′	2.50455 00790	90
0.99982 71058	1.70969 53883	0.00917 03805	89 27	2.47672 17448	89
0.99930 85325	1.70904 11308	0.01833 63062	88 55	2.44889 34106	88
0.99844 46074	1.70795 16110	0.02749 33119	88 22	2.42106 50764	87
0.99723 58755	1.70642 81917	0.03663 69110	87 49	2.39323 67422	86
0.99568 30984	1.70447 27784	0.04576 25853	87 16	2.36540 84079	85
0.99378 72533	1.70208 78163	0.05486 57745	86 43	2.33758 00737	84
0.99154 95309	1.69927 62875	0.06394 18650	86 10	2.30975 17395	83
0.98897 13334	1.69604 17067	0.07298 61798	85 36	2.28192 34053	82
0.98605 42725	1.69238 81168	0.08199 39678	85 3	2.25409 50711	81
0.98280 01661	1.68832 00831	0.09096 03928	84 29	2.22626 67369	80
0.97921 10356	1.68384 26872	0.09988 05231	83 55	2.19843 84027	79
0.97528 91023	1.67896 15207	0.10874 93206	83 21	2.17061 00685	78
0.97103 67835	1.67368 26771	0.11756 16303	82 46	2.14278 17343	77
0.96645 66885	1.66801 27439	0.12631 21691	82 12	2.11495 34000	76
0.96155 16144	1.66195 87940	0.13499 55158	81 37	2.08712 50658	75
0.95632 45409	1.65552 83761	0.14360 60995	81 1	2.05929 67316	74
0.95077 86259	1.64872 95046	0.15213 81898	80 25	2.03146 83974	73
0.94491 71996	1.64157 06491	0.16058 58855	79 49	2.00364 00632	72
0.93874 37597	1.63406 07230	0.16894 31044	79 13	1.97581 17290	71
0.93226 19647	1.62620 90720	0.17720 35729	78 36	1.94798 33948	70
0.92547 56289	1.61802 54615	0.18536 08158	77 58	1.92015 50606	69
0.91838 87155	1.60952 00637	0.19340 81461	77 20	1.89232 67264	68
0.91100 53304	1.60070 34445	0.20133 86551	76 42	1.86449 83921	67
0.90332 97156	1.59158 65494	0.20914 52034	76 3	1.83667 00579	66
0.89536 62423	1.58218 06891	0.21682 04110	75 23	1.80884 17237	65
0.88711 94043	1.57249 75252	0.22435 66494	74 43	1.78101 33895	64
0.87859 38106	1.56254 90544	0.23174 60328	74 2	1.75318 50553	63
0.86979 41783	1.55234 75933	0.23898 04111	73 21	1.72535 67211	62
0.86072 53257	1.54190 57623	0.24605 13624	72 39	1.69752 83869	61
0.85139 21644	1.53123 64694	0.25295 01875	71 56	1.66970 00527	60
0.84179 96923	1.52035 28933	0.25966 79043	71 13	1.64187 17185	59
0.83195 29861	1.50926 84668	0.26619 52443	70 29	1.61404 33842	58
0.82185 71938	1.49799 68595	0.27252 26492	69 44	1.58621 50500	57
0.81151 75269	1.48655 19601	0.27864 02697	68 59	1.55838 67158	56
0.80093 92537	1.47494 78592	0.28453 79654	68 12	1.53055 83816	55
0.79012 76914	1.46319 88308	0.29020 53069	67 25	1.50273 00474	54
0.77908 81986	1.45131 93148	0.29563 15786	66 37	1.47490 17132	53
0.76782 61683	1.43932 38985	0.30080 57852	65 48	1.44707 33790	52
0.75634 70207	1.42722 72983	0.30571 66593	64 59	1.41924 50448	51
0.74465 61957	1.41504 43413	0.31035 26720	64 8	1.39141 67106	50
0.73275 91466	1.40278 99470	0.31470 20462	63 17	1.36358 83763	49
0.72066 13327	1.39047 91083	0.31875 27727	62 24	1.33576 00421	48
0.70836 82126	1.37812 68735	0.32249 26298	61 31	1.30793 17079	47
0.69588 52382	1.36574 83271	0.32590 92064	60 36	1.28010 33737	46
0.68321 78479	1.35335 85717	0.32898 99283	59 41	1.25227 50395	45
A(r)	D(r)	E(r)	φ	Fφ	r

$K = 2.7680631454 = K'\sqrt{3}$, $K' = 1.5981420021$, $E = 1.076405113$, $E' = 1.5441504969$,

r	Fφ	φ	E(r)	D(r)	A(r)
0	0.00000 00000	0° 0′	0.00000 00000	1.00000 00000	0.00000 00000
1	0.03075 62572	1 46	0.01878 71553	1.00028 90226	0.01564 67728
2	0.06151 25143	3 37	0.03752 01201	1.00115 57568	0.03129 20711
3	0.09226 87715	5 17	0.05614 50985	1.00259 92025	0.04693 44040
4	0.12302 50287	7 2	0.07460 90790	1.00461 76935	0.06257 22754
5	0.15378 12859	8 47	0.09286 02109	1.00720 88997	0.07820 41558
6	0.18453 75430	10 31	0.11084 81632	1.01036 98288	0.09382 84843
7	0.21529 38002	12 15	0.12852 44620	1.01409 68295	0.10944 36574
8	0.24605 00574	13 58	0.14584 27986	1.01838 55946	0.12504 80220
9	0.27680 63145	15 40	0.16275 93073	1.02323 11658	0.14063 98665
10	0.30756 25717	17 22	0.17923 28093	1.02862 79374	0.15621 74137
11	0.33831 88289	19 3	0.19522 50184	1.03456 96626	0.17177 88130
12	0.36907 50860	20 43	0.21070 07095	1.04104 94593	0.18732 21327
13	0.39983 13432	22 22	0.22562 78479	1.04805 98163	0.20284 53538
14	0.43058 76004	23 59	0.23997 76797	1.05559 26010	0.21834 63622
15	0.46134 38576	25 36	0.25372 47838	1.06363 90673	0.23382 29430
16	0.49210 01147	27 12	0.26684 70884	1.07218 98642	0.24927 27739
17	0.52285 63719	28 46	0.27932 58519	1.08123 50446	0.26469 34194
18	0.55361 26291	30 19	0.29114 56129	1.09076 40755	0.28008 23255
19	0.58436 88862	31 50	0.30229 41110	1.10076 58484	0.29543 68145
20	0.61512 51434	33 21	0.31276 21816	1.11122 86903	0.31075 40803
21	0.64588 14006	34 50	0.32254 36297	1.12214 03756	0.32603 11842
22	0.67663 76577	36 17	0.33163 50828	1.13348 81382	0.34126 50509
23	0.70739 39149	37 43	0.34003 58309	1.14525 86847	0.35645 24653
24	0.73815 01721	39 8	0.34774 76532	1.15743 82078	0.37159 00694
25	0.76890 64293	40 31	0.35477 46364	1.17001 24008	0.38667 43599
26	0.79966 26864	41 52	0.36112 29881	1.18296 64722	0.40170 16862
27	0.83041 89436	43 12	0.36680 08467	1.19628 51612	0.41666 82489
28	0.86117 52008	44 31	0.37181 80918	1.20995 27538	0.43157 00988
29	0.89193 14579	45 48	0.37618 61563	1.22395 30995	0.44640 31361
30	0.92268 77151	47 3	0.37991 78428	1.23826 96285	0.46116 31110
31	0.95344 39723	48 18	0.38302 71460	1.25288 53692	0.47584 56238
32	0.98420 02294	49 30	0.38552 90817	1.26778 29672	0.49044 61259
33	1.01495 64866	50 41	0.38743 95246	1.28294 47038	0.50495 99214
34	1.04571 27438	51 51	0.38877 50552	1.29835 25154	0.51938 21695
35	1.07646 90010	52 59	0.38955 28159	1.31398 80140	0.53370 78866
36	1.10722 52581	54 5	0.38979 03785	1.32983 25072	0.54793 19494
37	1.13798 15153	55 10	0.38950 56204	1.34586 70195	0.56204 90989
38	1.16873 77725	56 14	0.38871 66125	1.36207 23140	0.57605 39442
39	1.19949 40296	57 16	0.38744 15171	1.37842 89138	0.58994 09669
40	1.23025 02868	58 17	0.38569 84955	1.39491 71251	0.60370 45267
41	1.26100 65440	59 17	0.38350 56260	1.41151 70596	0.61733 88663
42	1.29176 28011	60 15	0.38088 08305	1.42820 86579	0.63083 81179
43	1.32251 90583	61 12	0.37784 18107	1.44497 17132	0.64419 63092
44	1.35327 53155	62 8	0.37440 59923	1.46178 58952	0.65740 73705
45	1.38403 15727	63 2	0.37059 04774	1.47863 07744	0.67046 51423
90−r	Fψ	ψ	G(r)	C(r)	B(r)

$q = 0.163033534821580$, $\Theta 0 = 0.6753457533$, $HK = 1.3046678096$

B(r)	C(r)	G(r)	ψ	Fψ	90−r
1.00000 00000	1.96563 05108	0.00000 00000	90° 0′	2.76806 31454	90
0.99981 60886	1.96533 12951	0.00989 91720	89 33	2.73730 68882	89
0.99926 44975	1.96443 40309	0.01979 47043	89 5	2.70655 06310	88
0.99834 56552	1.96293 98674	0.02968 29453	88 38	2.67579 43738	87
0.99706 02753	1.96085 07176	0.03956 02195	88 10	2.64503 81167	86
0.99540 93546	1.95816 92561	0.04942 28154	87 43	2.61428 18595	85
0.99339 41714	1.95489 89147	0.05926 69738	87 15	2.58352 56023	84
0.99101 62829	1.95104 38778	0.06908 88752	86 47	2.55276 93451	83
0.98827 75221	1.94660 90763	0.07888 46278	86 19	2.52201 30880	82
0.98517 99940	1.94160 01803	0.08865 02550	85 51	2.49125 68308	81
0.98172 60720	1.93602 35909	0.09838 16828	85 22	2.46050 05736	80
0.97791 83923	1.92988 64309	0.10807 47268	84 54	2.42974 43165	79
0.97375 98498	1.92319 65349	0.11772 50798	84 25	2.39898 80593	78
0.96925 35914	1.91596 24373	0.12732 82981	83 55	2.36823 18021	77
0.96440 30106	1.90819 33609	0.13687 97883	83 26	2.33747 55450	76
0.95921 17405	1.89989 92030	0.14637 47936	82 56	2.30671 92878	75
0.95368 36468	1.89109 05214	0.15580 83802	82 25	2.27596 30306	74
0.94782 28200	1.88177 85195	0.16517 54225	81 55	2.24520 67734	73
0.94163 35686	1.87197 50301	0.17447 05894	81 24	2.21445 05163	72
0.93512 04092	1.86169 24991	0.18368 83293	80 52	2.18369 42591	71
0.92828 80593	1.8[illegible]94 39670	0.19282 28550	80 20	2.15293 80019	70
0.92114 14274	1.8[illegible]974 30516	0.20186 81293	79 48	2.12218 17448	69
0.91368 56040	1.82810 39279	0.21081 78488	79 15	2.09142 54876	68
0.90592 58521	1.81604 13089	0.21966 54291	78 41	2.06066 92304	67
0.89786 75972	1.80357 04247	0.22840 39887	78 7	2.02991 29733	66
0.88951 64174	1.79070 70015	0.23702 63334	77 32	1.99915 67161	65
0.88087 80328	1.77746 72401	0.24552 49406	76 56	1.96840 04589	64
0.87195 82952	1.76386 77929	0.25389 19433	76 20	1.93764 42017	63
0.86276 31773	1.74992 57419	0.26211 91147	75 43	1.90688 79446	62
0.85329 87622	1.73565 85746	0.27019 78524	75 6	1.87613 16874	61
0.84357 12322	1.72108 41609	0.27811 91636	74 27	1.84537 54302	60
0.83358 68580	1.70622 07286	0.28587 36500	73 48	1.81461 91731	59
0.82335 19876	1.69108 68389	0.29345 14936	73 8	1.78386 29159	58
0.81287 30353	1.67570 13618	0.30084 24433	72 28	1.75310 66587	57
0.80215 64710	1.66008 34507	0.30803 58026	71 46	1.72235 04016	56
0.79120 88085	1.64425 25175	0.31502 04176	71 4	1.69159 41444	55
0.78003 65955	1.62822 82065	0.32178 46673	70 20	1.66083 78872	54
0.76864 64021	1.61203 03692	0.32831 64547	69 36	1.63008 16300	53
0.75704 48103	1.59567 90385	0.33460 32006	68 50	1.59932 53729	52
0.74523 84036	1.57919 44025	0.34063 18384	68 4	1.56856 91157	51
0.73323 37566	1.56259 67789	0.34638 88130	67 16	1.53781 28585	50
0.72103 74248	1.54590 65890	0.35186 00808	66 28	1.50705 66014	49
0.70865 59347	1.52914 43320	0.35703 11148	65 38	1.47630 03442	48
0.69609 57739	1.51233 05588	0.36188 69115	64 47	1.44554 40870	47
0.68336 33823	1.49548 58469	0.36641 20039	63 55	1.41478 78299	46
0.67046 51423	1.47863 07744	0.37059 04774	63 2	1.38403 15727	45
A(r)	D(r)	E(r)	φ	Fφ	r

K = 3.1533852519, K′ = 1.5828428043, E = 1.0401143957, E′ = 1.5588871966,

r	Fφ	φ		E(r)	D(r)	A(r)
0	0.00000 00000	0°	0′	0.00000 00000	1.00000 00000	0.00000 00000
1	0.03503 76139	2	0	0.02346 68886	1.00041 13182	0.01460 06854
2	0.07007 52278	4	1	0.04685 05457	1.00164 48264	0.02920 20956
3	0.10511 28417	6	1	0.07006 85417	1.00369 91860	0.04380 49412
4	0.14015 04556	8	0	0.09304 00333	1.00657 21668	0.05840 99043
5	0.17518 80695	9	59	0.11568 65173	1.01026 06485	0.07301 76251
6	0.21022 56835	11	58	0.13793 25365	1.01476 06225	0.08762 86871
7	0.24526 32974	13	55	0.15970 63263	1.02006 71948	0.10224 36040
8	0.28030 09113	15	52	0.18094 03901	1.02617 45886	0.11686 28061
9	0.31533 85252	17	47	0.20157 19949	1.03307 61484	0.13148 66263
10	0.35037 61391	19	41	0.22154 35813	1.04076 43440	0.14611 52882
11	0.38541 37530	21	34	0.24080 30831	1.04923 07759	0.16074 88922
12	0.42045 13669	23	26	0.25930 41559	1.05846 61800	0.17538 74040
13	0.45548 89808	25	16	0.27700 63163	1.06846 04345	0.19003 06422
14	0.49052 65947	27	4	0.29387 49943	1.07920 25667	0.20467 82669
15	0.52556 42086	28	51	0.30988 15035	1.09068 07598	0.21932 97686
16	0.56060 18226	30	36	0.32500 29380	1.10288 23622	0.23398 44577
17	0.59563 94365	32	20	0.33922 20017	1.11579 38955	0.24864 14540
18	0.63067 70504	34	1	0.35252 67798	1.12940 10647	0.26329 96779
19	0.66571 46643	35	41	0.36491 04618	1.14368 87684	0.27795 78408
20	0.70075 22782	37	18	0.37637 10249	1.15864 11101	0.29261 44375
21	0.73578 98921	38	54	0.38691 08879	1.17424 14105	0.30726 77376
22	0.77082 75060	40	28	0.39653 65430	1.19047 22196	0.32191 57797
23	0.80586 51199	41	59	0.40525 81757	1.20731 53312	0.33655 63638
24	0.84090 27338	43	29	0.41308 92784	1.22475 17970	0.35118 70467
25	0.87594 03477	44	56	0.42004 62655	1.24276 19421	0.36580 51367
26	0.91097 79617	46	22	0.42614 80965	1.26132 53814	0.38040 76896
27	0.94601 55756	47	45	0.43141 59095	1.28042 10369	0.39499 15050
28	0.98105 31895	49	7	0.43587 26721	1.30002 71557	0.40955 31244
29	1.01609 08034	50	26	0.43954 28505	1.32012 13294	0.42408 88287
30	1.05112 84173	51	44	0.44245 21005	1.34068 05139	0.43859 46375
31	1.08616 60312	52	59	0.44462 69813	1.36168 10508	0.45306 63090
32	1.12120 36451	54	12	0.44609 46931	1.38309 86893	0.46749 93405
33	1.15624 12590	55	24	0.44688 28394	1.40490 86089	0.48188 89699
34	1.19127 88729	56	33	0.44701 92128	1.42708 54443	0.49623 01775
35	1.22631 64868	57	41	0.44653 16053	1.44960 33094	0.51051 76900
36	1.26135 41008	58	47	0.44544 76404	1.47243 58241	0.52474 59832
37	1.29639 17147	59	51	0.44379 46284	1.49555 61410	0.53890 92878
38	1.33142 93286	60	53	0.44159 94403	1.51893 69731	0.55300 15938
39	1.36646 69425	61	54	0.43888 84024	1.54255 06233	0.56701 66575
40	1.40150 45564	62	53	0.43568 72080	1.56636 90138	0.58094 80084
41	1.43654 21703	63	50	0.43202 08450	1.59036 37173	0.59478 89567
42	1.47157 97842	64	45	0.42791 35381	1.61450 59885	0.60853 26019
43	1.50661 73981	65	39	0.42338 87053	1.63876 67967	0.62217 18423
44	1.54165 50120	66	32	0.41846 89243	1.66311 68595	0.63569 93846
45	1.57669 26259	67	23	0.41317 59112	1.68752 66770	0.64910 77548
90−r	Fψ	ψ		G(r)	C(r)	B(r)

$q = 0.206609755200965$, $\Theta 0 = 0.590423578356$, $HK = 1.406061468420$

B(r)	C(r)	G(r)	ψ	Fψ	90−r
1.00000 00000	2.39974 38370	0.00000 00000	90° 0′	3.15338 52519	90
0.99979 75549	2.39930 24464	0.01049 98939	89 39	3.11834 76380	89
0.99919 04200	2.39797 88675	0.02099 72691	89 18	3.08331 00241	88
0.99817 91961	2.39577 48778	0.03148 95952	88 57	3.04827 24102	87
0.99676 48832	2.39269 34364	0.04197 43187	88 36	3.01323 47963	86
0.99494 88778	2.38873 86793	0.05244 88508	88 15	2.97819 71823	85
0.99273 29703	2.38391 59122	0.06291 05559	87 54	2.94315 95684	84
0.99011 93406	2.37823 16019	0.07335 67394	87 32	2.90812 19545	83
0.98711 05534	2.37169 33654	0.08378 46353	87 11	2.87308 43406	82
0.98370 95524	2.36430 99572	0.09419 13935	86 49	2.83804 67267	81
0.97991 96536	2.35609 12550	0.10457 40674	86 27	2.80300 91128	80
0.97574 45380	2.34704 82431	0.11492 96001	86 4	2.76797 14989	79
0.97118 82434	2.33719 29943	0.12525 48110	85 42	2.73293 38850	78
0.96625 51552	2.32653 86504	0.13554 63814	85 19	2.69789 62711	77
0.96094 99971	2.31509 94002	0.14580 08404	84 56	2.66285 86572	76
0.95527 78200	2.30289 04563	0.15601 45490	84 32	2.62782 10432	75
0.94924 39913	2.28992 80308	0.16618 36848	84 8	2.59278 34293	74
0.94285 41832	2.27622 93087	0.17630 42256	83 44	2.55774 58154	73
0.93611 43595	2.26181 24201	0.18637 19320	83 19	2.52270 82015	72
0.92903 07633	2.24669 64112	0.19638 23298	82 54	2.48767 05876	71
0.92160 99031	2.23090 12139	0.20633 06915	82 28	2.45263 29137	70
0.91385 85385	2.21444 76139	0.21621 20167	82 1	2.41759 53578	69
0.90578 36660	2.19735 72184	0.22602 10124	81 35	2.38255 77459	68
0.89739 25035	2.17965 24214	0.23575 20713	81 7	2.34752 01320	67
0.88869 24749	2.16135 63692	0.24539 92508	80 39	2.31248 25181	66
0.87969 11946	2.14249 29245	0.25495 62494	80 10	2.27744 49041	65
0.87039 64511	2.12308 66296	0.26441 63838	79 41	2.24240 72902	64
0.86081 61906	2.10316 26690	0.27377 25638	79 11	2.20736 96763	63
0.85095 85006	2.08274 68307	0.28301 72673	78 40	2.17233 20624	62
0.84083 15928	2.06186 54682	0.29214 25142	78 8	2.13729 44485	61
0.83044 37863	2.04054 54606	0.30113 98388	77 35	2.10225 68346	60
0.81980 34906	2.01881 41730	0.31000 02630	77 2	2.06721 92207	59
0.80891 91886	1.99669 94165	0.31871 42670	76 28	2.03218 16068	58
0.79779 94194	1.97422 94075	0.32727 17611	75 52	1.99714 39929	57
0.78645 27612	1.95143 27275	0.33566 20561	75 16	1.96210 63790	56
0.77488 78149	1.92833 82823	0.34387 38337	74 39	1.92706 87650	55
0.76311 31867	1.90497 52611	0.35189 51171	74 1	1.89203 11511	54
0.75113 74717	1.88137 30959	0.35971 32414	73 21	1.85699 35372	53
0.73896 92379	1.85756 14210	0.36731 48250	72 41	1.82195 59233	52
0.72661 70097	1.83357 00328	0.37468 57413	71 59	1.78691 83094	51
0.71408 92524	1.80942 88493	0.38181 10919	71 16	1.75188 06955	50
0.70139 43563	1.78516 78703	0.38867 51812	70 32	1.71684 30816	49
0.68854 06225	1.76081 71386	0.39526 14938	69 47	1.68180 54677	48
0.67553 62475	1.73640 67003	0.40155 26735	69 0	1.64676 78538	47
0.66238 93095	1.71196 65668	0.40753 05071	68 12	1.61173 02399	46
0.64910 77548	1.68752 66770	0.41317 59112	67 23	1.57669 26259	45
A(r)	D(r)	E(r)	φ	Fφ	r

K = 3.2553029421, K′ = 1.5805409339, E = 1.033789462, E′ = 1.5611417453,

r	Fφ	φ		E(r)	D(r)	A(r)
0	0.00000 00000	0°	0′	0.00000 00000	1.00000 00000	0.00000 00000
1	0.03617 00327	2	4	0.02466 81037	1.00044 63617	0.01430 61216
2	0.07234 00654	4	8	0.04924 41210	1.00178 49728	0.02861 35824
3	0.10851 00981	6	12	0.07363 69132	1.00401 44114	0.04292 37056
4	0.14468 01308	8	16	0.09775 72158	1.00713 23089	0.05723 77835
5	0.18085 01635	10	18	0.12151 85252	1.01113 53504	0.07155 70609
6	0.21702 01961	12	20	0.14483 79258	1.01601 92772	0.08588 27206
7	0.25319 02288	14	21	0.16763 68426	1.02177 88885	0.10021 58677
8	0.28936 02615	16	21	0.18984 17049	1.02840 80440	0.11455 75144
9	0.32553 02942	18	20	0.21138 45101	1.03589 96677	0.12890 85656
10	0.36170 03269	20	18	0.23220 32821	1.04424 57511	0.14326 98042
11	0.39787 03596	22	14	0.25224 24183	1.05343 73577	0.15764 18767
12	0.43404 03923	24	8	0.27145 29257	1.06346 46282	0.17202 52803
13	0.47021 04250	26	1	0.28979 25485	1.07431 67854	0.18642 03484
14	0.50638 04577	27	53	0.30722 57913	1.08598 21410	0.20082 72392
15	0.54255 04904	29	42	0.32372 38467	1.09844 81017	0.21524 59210
16	0.57872 05230	31	29	0.33926 44357	1.11170 11775	0.22967 61638
17	0.61489 05557	33	15	0.35383 15704	1.12572 69891	0.24411 75248
18	0.65106 05884	34	58	0.36741 52534	1.14051 02773	0.25856 93397
19	0.68723 06211	36	40	0.38001 11223	1.15603 49127	0.27303 07120
20	0.72340 06538	38	19	0.39162 00536	1.17228 39058	0.28750 05037
21	0.75957 06865	39	56	0.40224 77358	1.18923 94189	0.30197 73269
22	0.79574 07192	41	32	0.41190 42239	1.20688 27779	0.31645 95358
23	0.83191 07519	43	4	0.42060 34838	1.22519 44855	0.33094 52195
24	0.86808 07846	44	35	0.42836 29362	1.24415 42355	0.34543 21958
25	0.90425 08173	46	4	0.43520 30077	1.26374 09274	0.35991 80053
26	0.94042 08500	47	30	0.44114 66947	1.28393 26825	0.37439 99070
27	0.97659 08826	48	54	0.44621 91466	1.30470 68611	0.38887 48743
28	1.01276 09153	50	16	0.45044 72717	1.32604 00803	0.40333 95918
29	1.04893 09480	51	36	0.45385 93683	1.34790 82334	0.41779 04532
30	1.08510 09807	52	54	0.45648 47848	1.37028 65097	0.43222 35599
31	1.12127 10134	54	9	0.45835 36084	1.39314 94160	0.44663 47209
32	1.15744 10461	55	23	0.45949 63831	1.41647 07992	0.46101 94525
33	1.19361 10788	56	34	0.45994 38581	1.44022 38696	0.47537 29805
34	1.22978 11115	57	43	0.45972 67648	1.46438 12257	0.48969 02419
35	1.26595 11442	58	51	0.45887 56209	1.48891 48802	0.50396 58883
36	1.30212 11769	59	56	0.45742 05619	1.51379 62870	0.51819 42896
37	1.33829 12095	61	0	0.45539 11968	1.53899 63693	0.53236 95393
38	1.37446 12422	62	2	0.45281 64872	1.56448 55491	0.54648 54602
39	1.41063 12749	63	1	0.44972 46468	1.59023 37776	0.56053 56107
40	1.44680 13076	64	0	0.44614 30615	1.61621 05676	0.57451 32929
41	1.48297 13403	64	56	0.44209 82256	1.64238 50248	0.58841 15607
42	1.51914 13730	65	51	0.43761 56944	1.66872 58833	0.60222 32286
43	1.55531 14057	66	44	0.43272 00503	1.69520 15399	0.61594 08825
44	1.59148 14384	67	35	0.42743 48807	1.72178 00903	0.62955 68896
45	1.62765 14711	68	25	0.42178 27675	1.74842 93662	0.64306 34108
90-r	Fψ	ψ		G(r)	C(r)	B(r)

TABLE $\theta = 81°$

$q = 0.217548949699726$, $\Theta 0 = 0.5693797108$, HK = 1.4306906219

B(r)	C(r)	G(r)	ψ	Fψ	90-r
1.00000 00000	2.52833 01251	0.00000 00000	90° 0′	3.25530 29421	90
0.99979 22836	2.52784 54320	0.01060 10292	89 41	3.21913 29095	89
0.99916 93515	2.52639 20136	0.02119 97963	89 21	3.18296 28768	88
0.99813 18540	2.52397 18509	0.03179 40278	89 2	3.14679 28441	87
0.99668 08734	2.52058 82420	0.04238 14278	88 42	3.11062 28114	86
0.99481 79213	2.51624 57960	0.05295 96662	88 22	3.07445 27787	85
0.99254 49353	2.51095 04254	0.06352 63677	88 2	3.03828 27460	84
0.98986 42745	2.50470 93354	0.07407 90993	87 42	3.00211 27133	83
0.98677 87139	2.49753 10120	0.08461 53590	87 22	2.96594 26806	82
0.98329 14382	2.48942 52067	0.09513 25631	87 2	2.92977 26479	81
0.97940 60344	2.48040 29203	0.10562 80337	86 41	2.89360 26152	80
0.97512 64836	2.47047 63835	0.11609 89854	86 20	2.85743 25825	79
0.97045 71520	2.45965 90364	0.12654 25123	85 59	2.82126 25499	78
0.96540 27806	2.44796 55051	0.13695 55734	85 38	2.78509 25172	77
0.95996 84748	2.43541 15773	0.14733 49785	85 16	2.74892 24845	76
0.95415 96925	2.42201 41749	0.15767 73727	84 54	2.71275 24518	75
0.94798 22318	2.40779 13262	0.16797 92208	84 32	2.67658 24191	74
0.94144 22181	2.39276 21349	0.17823 67907	84 9	2.64041 23864	73
0.93454 60898	2.37694 67487	0.18844 61360	83 45	2.60424 23537	72
0.92730 05843	2.36036 63252	0.19860 30778	83 21	2.56807 23210	71
0.91971 27230	2.34304 29976	0.20870 31860	82 57	2.53190 22883	70
0.91178 97950	2.32499 98377	0.21874 17592	82 32	2.49573 22556	69
0.90353 93417	2.30626 08184	0.22871 38038	82 7	2.45956 22230	68
0.89496 91397	2.28685 07750	0.23861 40125	81 41	2.42339 21903	67
0.88608 71836	2.26679 53647	0.24843 67407	81 14	2.38722 21576	66
0.87690 16690	2.24612 10260	0.25817 59833	80 47	2.35105 21249	65
0.86742 09743	2.22485 49364	0.26782 53494	80 19	2.31488 20922	64
0.85765 36425	2.20302 49697	0.27737 80358	79 50	2.27871 20595	63
0.84760 83633	2.18065 96524	0.28682 68004	79 20	2.24254 20268	62
0.83729 39541	2.15778 81197	0.29616 39332	78 50	2.20637 19941	61
0.82671 93416	2.13444 00706	0.30538 12272	78 19	2.17020 19614	60
0.81589 35429	2.11064 57227	0.31446 99478	77 47	2.13403 19287	59
0.80482 56467	2.08643 57672	0.32342 08014	77 14	2.09786 18960	58
0.79352 47945	2.06184 13229	0.33222 39026	76 40	2.06169 18634	57
0.78200 01623	2.03689 38902	0.34086 87415	76 5	2.02552 18307	56
0.77026 09411	2.01162 53056	0.34934 41494	75 29	1.98935 17980	55
0.75831 63194	1.98606 76958	0.35763 82644	74 53	1.95318 17653	54
0.74617 54642	1.96025 34320	0.36573 84971	74 14	1.91701 17326	53
0.73384 75039	1.93421 50843	0.37363 14953	73 35	1.88084 16999	52
0.72134 15096	1.90798 53771	0.38130 31100	72 55	1.84467 16672	51
0.70866 64787	1.88159 71433	0.38873 83616	72 13	1.80850 16345	50
0.69583 13178	1.85508 32817	0.39592 14068	71 30	1.77233 16018	49
0.68284 48256	1.82847 67117	0.40283 55079	70 46	1.73616 15691	48
0.66971 56781	1.80181 03311	0.40946 30040	70 1	1.69999 15365	47
0.65645 24120	1.77511 69734	0.41578 52846	69 14	1.66382 15038	46
0.64306 34108	1.74842 93662	0.42178 27675	68 25	1.62765 14711	45
A(r)	D(r)	E(r)	φ	Fφ	r

K = 3.3698680267, K′ = 1.5784865777, E = 1.027843620, E′ = 1.5629622295,

r	Fφ	φ	E(r)	D(r)	A(r)
0	0.00000 00000	0° 0′	0.00000 00000	1.00000 00000	0.00000 00000
1	0.03744 29781	2 9	0.02600 53438	1.00048 71379	0.01396 87846
2	0.07488 59561	4 17	0.05190 80180	1.00194 80481	0.02793 96081
3	0.11232 89342	6 26	0.07760 64875	1.00438 12208	0.04191 44920
4	0.14977 19123	8 35	0.10300 14601	1.00778 41400	0.05589 54231
5	0.18721 48904	10 40	0.12799 69416	1.01215 32844	0.06988 43359
6	0.22465 78684	12 46	0.15250 12188	1.01748 41292	0.08388 30956
7	0.26210 08465	14 51	0.17642 77402	1.02377 11470	0.09789 34813
8	0.29954 38246	16 55	0.19969 58914	1.03100 78103	0.11191 71690
9	0.33698 68027	18 58	0.22223 16400	1.03918 65941	0.12595 57152
10	0.37442 97807	20 59	0.24396 80481	1.04829 89781	0.14001 05412
11	0.41187 27588	22 58	0.26484 56468	1.05833 54510	0.15408 29167
12	0.44931 57369	24 56	0.28481 26740	1.06928 55135	0.16817 39451
13	0.48675 87150	26 52	0.30382 51779	1.08113 76835	0.18228 45483
14	0.52420 16930	28 46	0.32184 69961	1.09387 95005	0.19641 54524
15	0.56164 46711	30 38	0.33884 96193	1.10749 75312	0.21056 71740
16	0.59908 76492	32 28	0.35481 19530	1.12197 73762	0.22474 00071
17	0.63653 06273	34 16	0.36971 99918	1.13730 36763	0.23893 40100
18	0.67397 36053	36 2	0.38356 64197	1.15346 01207	0.25314 89941
19	0.71141 65834	37 46	0.39635 01539	1.17042 94549	0.26738 45123
20	0.74885 95615	39 27	0.40807 58450	1.18819 34902	0.28163 98484
21	0.78630 25396	41 6	0.41875 33497	1.20673 31139	0.29591 40077
22	0.82374 55176	42 42	0.42839 71871	1.22602 82998	0.31020 57076
23	0.86118 84957	44 16	0.43702 59916	1.24605 81209	0.32451 33701
24	0.89863 14738	45 48	0.44466 19725	1.26680 07616	0.33883 51142
25	0.93607 44519	47 18	0.45133 03888	1.28823 35321	0.35316 87494
26	0.97351 74299	48 45	0.45705 90462	1.31033 28836	0.36751 17704
27	1.01096 04080	50 10	0.46187 78212	1.33307 44242	0.38186 13526
28	1.04840 33861	51 32	0.46581 82181	1.35643 29365	0.39621 43484
29	1.08584 63641	52 52	0.46891 29597	1.38038 23962	0.41056 72843
30	1.12328 93422	54 10	0.47119 56148	1.40489 59917	0.42491 63594
31	1.16073 23203	55 26	0.47270 02620	1.42994 61457	0.43925 74448
32	1.19817 52984	56 39	0.47346 11908	1.45550 45373	0.45358 60835
33	1.23561 82764	57 50	0.47351 26377	1.48154 21259	0.46789 74917
34	1.27306 12545	59 0	0.47288 85574	1.50802 91764	0.48218 65611
35	1.31050 42326	60 7	0.47162 24256	1.53493 52855	0.49644 78621
36	1.34794 72107	61 12	0.46974 70729	1.56222 94100	0.51067 56480
37	1.38539 01887	62 15	0.46729 45464	1.58987 98960	0.52486 38600
38	1.42283 31668	63 16	0.46429 59969	1.61785 45092	0.53900 61335
39	1.46027 61449	64 15	0.46078 15892	1.64612 04680	0.55309 58052
40	1.49771 91230	65 12	0.45678 04338	1.67464 44762	0.56712 59210
41	1.53516 21010	66 7	0.45232 05363	1.70339 27583	0.58108 92454
42	1.57260 50791	67 1	0.44742 87637	1.73233 10960	0.59497 82708
43	1.61004 80572	67 53	0.44213 08242	1.76142 48657	0.60878 52287
44	1.64749 10353	68 44	0.43645 12599	1.79063 90777	0.62250 21016
45	1.68493 40133	69 32	0.43041 34495	1.81993 84164	0.63612 06349
90−r	Fψ	ψ	G(r)	C(r)	B(r)

$q = 0.229567159881194$, $\Theta 0 = 0.5464169465$, $HK = 1.4575481002$

B(r)	C(r)	G(r)	ψ	Fψ	90−r
1.00000 00000	2.68054 03437	0.00000 00000	90° 0′	3.36986 80267	90
0.99978 62112	2.68000 36787	0.01069 49135	89 42	3.33242 50486	89
0.99914 50809	2.67839 44283	0.02138 78301	89 24	3.29498 20705	88
0.99807 73170	2.67571 48255	0.03207 67423	89 6	3.25753 90925	87
0.99658 40972	2.67196 85860	0.04275 96209	88 48	3.22009 61144	86
0.99466 70666	2.66716 09043	0.05343 44040	88 30	3.18265 31363	85
0.99232 83334	2.66129 84418	0.06409 89867	88 12	3.14521 01582	84
0.98957 04645	2.65438 93156	0.07475 12085	87 53	3.10776 71802	83
0.98639 64786	2.64644 30842	0.08538 88428	87 35	3.07032 42021	82
0.98280 98400	2.63747 07296	0.09600 95847	87 16	3.03288 12240	81
0.97881 44497	2.62748 46381	0.10661 10385	86 57	2.99543 82459	80
0.97441 46367	2.61649 85778	0.11719 07054	86 37	2.95799 52679	79
0.96961 51474	2.60452 76741	0.12774 59701	86 18	2.92055 22898	78
0.96442 11348	2.59158 83828	0.13827 40870	85 58	2.88310 93117	77
0.95883 81466	2.57769 84606	0.14877 21662	85 38	2.84566 63336	76
0.95287 21117	2.56287 69342	0.15923 71580	85 17	2.80822 33556	75
0.94652 93269	2.54714 40664	0.16966 58376	84 56	2.77078 03775	74
0.93981 64421	2.53052 13208	0.18005 47885	84 35	2.73333 73994	73
0.93274 04449	2.51303 13248	0.19040 03849	84 13	2.69589 44213	72
0.92530 86446	2.49469 78294	0.20069 87739	83 51	2.65845 14433	71
0.91752 86553	2.47554 56695	0.21094 58556	83 28	2.62100 84652	70
0.90940 83786	2.45560 07207	0.22113 72633	83 5	2.58356 54871	69
0.90095 59853	2.43488 98556	0.23126 83422	82 41	2.54612 25090	68
0.89217 98975	2.41344 08985	0.24133 41265	82 16	2.50867 95310	67
0.88308 87690	2.39128 25787	0.25132 93157	81 51	2.47123 65529	66
0.87369 14660	2.36844 44831	0.26124 82501	81 25	2.43379 35748	65
0.86399 70475	2.34495 70070	0.27108 48837	80 59	2.39635 05967	64
0.85401 47452	2.32085 13053	0.28083 27574	80 32	2.35890 76187	63
0.84375 39427	2.29615 92414	0.29048 49692	80 4	2.32146 46406	62
0.83322 41555	2.27091 33365	0.30003 41444	79 35	2.28402 16625	61
0.82243 50100	2.24514 67182	0.30947 24031	79 5	2.24657 86844	60
0.81139 62227	2.21889 30687	0.31879 13276	78 35	2.20913 57064	59
0.80011 75795	2.19218 65719	0.32798 19272	78 4	2.17169 27283	58
0.78860 89149	2.16506 18621	0.33703 46027	77 31	2.13424 97502	57
0.77688 00911	2.13755 39706	0.34593 91087	76 58	2.09680 67721	56
0.76494 09778	2.10969 82742	0.35468 45152	76 23	2.05936 37941	55
0.75280 14315	2.08153 04423	0.36325 91686	75 48	2.02192 08160	54
0.74047 12755	2.05308 63856	0.37165 06505	75 11	1.98447 78379	53
0.72796 02805	2.02440 22044	0.37984 57377	74 34	1.94703 48599	52
0.71527 81443	1.99551 41373	0.38783 03601	73 55	1.90959 18818	51
0.70243 44736	1.96645 85115	0.39558 95596	73 14	1.87214 89037	50
0.68943 87648	1.93727 16923	0.40310 74491	72 33	1.83470 59256	49
0.67630 03866	1.90799 00345	0.41036 71725	71 50	1.79726 29476	48
0.66302 85617	1.87864 98345	0.41735 08655	71 6	1.75981 99695	47
0.64963 23506	1.84928 72824	0.42403 96200	70 20	1.72237 69914	46
0.63612 06349	1.81993 84164	0.43041 34495	69 32	1.68493 40133	45
A(r)	D(r)	E(r)	φ	Fφ	r

K = 3.5004224992, K′ = 1.5766779816, E = 1.022312588, E′ = 1.5649475630,

r	$F\phi$	ϕ	E(r)	D(r)	A(r)
0	0.00000 00000	0° 0′	0.00000 00000	1.00000 00000	0.00000 00000
1	0.03889 35833	2 14	0.02751 52459	1.00053 54142	0.01357 81428
2	0.07778 71666	4 27	0.05491 49171	1.00214 11230	0.02715 91294
3	0.11668 07500	6 40	0.08208 48196	1.00481 55243	0.04074 57840
4	0.15557 43333	8 53	0.10891 34862	1.00855 59486	0.05434 08922
5	0.19446 79166	11 4	0.13529 34531	1.01335 86590	0.06794 71815
6	0.23336 14999	13 15	0.16112 24388	1.01921 88518	0.08156 73027
7	0.27225 50833	15 25	0.18630 43989	1.02613 06577	0.09520 38101
8	0.31114 86666	17 33	0.21075 04315	1.03408 71422	0.10885 91438
9	0.35004 22499	19 40	0.23437 95237	1.04308 03072	0.12253 56111
10	0.38893 58332	21 45	0.25711 91248	1.05310 10924	0.13623 53681
11	0.42782 94166	23 48	0.27890 55463	1.06413 93774	0.14996 04030
12	0.46672 29999	25 50	0.29968 41874	1.07618 39836	0.16371 25182
13	0.50561 65832	27 50	0.31940 95974	1.08922 26769	0.17749 33141
14	0.54451 01665	29 47	0.33804 53836	1.10324 21710	0.19130 41733
15	0.58340 37499	31 42	0.35556 39822	1.11822 81308	0.20514 62446
16	0.62229 73332	33 35	0.37194 63079	1.13416 51764	0.21902 04287
17	0.66119 09165	35 26	0.38718 13038	1.15103 68883	0.23292 73637
18	0.70008 44998	37 14	0.40126 54102	1.16882 58124	0.24686 74120
19	0.73897 80832	38 59	0.41420 19722	1.18751 34668	0.26084 06476
20	0.77787 16665	40 42	0.42600 06064	1.20708 03483	0.27484 68440
21	0.81676 52498	42 23	0.43667 65427	1.22750 59404	0.28888 54637
22	0.85565 88331	44 1	0.44624 99581	1.24876 87226	0.30295 56475
23	0.89455 24165	45 37	0.45474 53170	1.27084 61798	0.31705 62057
24	0.93344 59998	47 10	0.46219 07281	1.29371 48135	0.33118 56095
25	0.97233 95831	48 40	0.46861 73287	1.31735 01537	0.34534 19839
26	1.01123 31664	50 8	0.47405 87042	1.34172 67728	0.35952 31012
27	1.05012 67498	51 33	0.47855 03463	1.36681 82994	0.37372 63757
28	1.08902 03331	52 56	0.48212 91569	1.39259 74348	0.38794 88593
29	1.12791 39164	54 17	0.48483 29959	1.41903 59703	0.40218 72381
30	1.16680 74997	55 35	0.48670 02770	1.44610 48057	0.41643 78306
31	1.20570 10830	56 50	0.48776 96093	1.47377 39701	0.43069 65861
32	1.24459 46664	58 4	0.48807 94838	1.50201 26433	0.44495 90849
33	1.28348 82497	59 14	0.48766 80032	1.53078 91792	0.45922 05390
34	1.32238 18330	60 23	0.48657 26520	1.56007 11317	0.47347 57948
35	1.36127 54163	61 30	0.48483 01039	1.58982 52804	0.48771 93356
36	1.40016 89997	62 34	0.48247 60647	1.62001 76598	0.50194 52865
37	1.43906 25830	63 36	0.47954 51456	1.65061 35895	0.51614 74196
38	1.47795 61663	64 36	0.47607 07644	1.68157 77058	0.53031 91603
39	1.51684 97496	65 35	0.47208 50753	1.71287 39955	0.54445 35952
40	1.55574 33330	66 31	0.46761 89121	1.74446 58318	0.55854 34803
41	1.59463 69163	67 25	0.46270 17621	1.77631 60110	0.57258 12511
42	1.63353 04996	68 18	0.45736 17475	1.80838 67918	0.58655 90333
43	1.67242 40829	69 9	0.45162 56249	1.84063 99362	0.60046 86540
44	1.71131 76663	69 58	0.44551 87962	1.87303 67513	0.61430 16549
45	1.75021 12496	70 45	0.43906 53283	1.90553 81344	0.62804 93057
90−r	$F\psi$	ψ	G(r)	C(r)	B(r)

$q = 0.242912974306665$, $\Theta 0 = 0.5211317465$, $HK = 1.4872214813$

B(r)	C(r)	G(r)	ψ	Fψ	90−r
1.00000 00000	2.86452 59727	0.00000 00000	90° 0′	3.50042 24992	90
0.99977 91249	2.86392 54580	0.01078 10889	89 44	3.46152 89158	89
0.99911 67583	2.86212 47652	0.02156 04536	89 27	3.42263 53325	88
0.99801 36755	2.85912 64461	0.03233 63597	89 11	3.38374 17492	87
0.99647 11670	2.85493 47485	0.04310 70526	88 55	3.34484 81659	86
0.99449 10345	2.84955 56077	0.05387 07471	88 38	3.30595 45826	85
0.99207 55874	2.84299 66356	0.06462 56168	88 21	3.26706 09992	84
0.98922 76367	2.83526 71062	0.07536 97836	88 5	3.22816 74159	83
0.98595 04884	2.82637 79377	0.08610 13069	87 48	3.18927 38326	82
0.98224 79350	2.81634 16722	0.09681 81718	87 30	3.15038 02493	81
0.97812 42473	2.80517 24517	0.10751 82779	87 13	3.11148 66659	80
0.97358 41628	2.79288 59919	0.11819 94268	86 55	3.07259 30826	79
0.96863 28755	2.77949 95523	0.12885 93097	86 37	3.03369 94993	78
0.96327 60226	2.76503 19042	0.13949 54938	86 19	2.99480 59160	77
0.95751 96711	2.74950 32957	0.15010 54088	86 1	2.95591 23326	76
0.95137 03036	2.73293 54142	0.16068 63318	85 42	2.91701 87493	75
0.94483 48022	2.71535 13465	0.17123 53724	85 23	2.87812 51660	74
0.93792 04329	2.69677 55363	0.18174 94560	85 3	2.83923 15827	73
0.93063 48276	2.67723 37397	0.19222 53067	84 43	2.80033 79993	72
0.92298 59663	2.65675 29786	0.20265 94294	84 22	2.76144 44160	71
0.91498 21585	2.63536 14921	0.21304 80901	84 1	2.72255 08327	70
0.90663 20234	2.61308 86858	0.22338 72956	83 39	2.68365 72494	69
0.89794 44698	2.58996 50797	0.23367 27719	83 17	2.64476 36660	68
0.88892 86753	2.56602 22548	0.24389 99414	82 54	2.60587 00827	67
0.87959 40653	2.54129 27973	0.25406 38981	82 31	2.56697 64994	66
0.86995 02909	2.51581 02430	0.26415 93822	82 7	2.52808 29161	65
0.86000 72069	2.48960 90190	0.27418 07525	81 42	2.48918 93327	64
0.84977 48495	2.46272 43859	0.28412 19576	81 16	2.45029 57494	63
0.83926 34134	2.43519 23782	0.29397 65053	80 50	2.41140 21661	62
0.82848 32287	2.40704 97447	0.30373 74301	80 23	2.37250 85828	61
0.81744 47382	2.37833 38874	0.31339 72593	79 55	2.33361 49994	60
0.80615 84738	2.34908 28015	0.32294 79773	79 26	2.29472 14161	59
0.79463 50337	2.31933 50143	0.33238 09873	78 56	2.25582 78328	58
0.78288 50590	2.28912 95239	0.34168 70724	78 26	2.21693 42495	57
0.77091 92109	2.25850 57383	0.35085 63539	77 54	2.17804 06662	56
0.75874 81476	2.22750 34151	0.35987 82486	77 21	2.13914 70828	55
0.74638 25018	2.19616 26008	0.36874 14237	76 47	2.10025 34995	54
0.73383 28587	2.16452 35708	0.37743 37507	76 12	2.06135 99162	53
0.72110 97334	2.13262 67708	0.38594 22578	75 36	2.02246 63329	52
0.70822 35503	2.10051 27578	0.39425 30813	74 58	1.98357 27495	51
0.69518 46210	2.06822 21426	0.40235 14155	74 20	1.94467 91662	50
0.68200 31247	2.03579 55331	0.41022 14630	73 40	1.90578 55829	49
0.66868 90878	2.00327 34790	0.41784 63843	72 58	1.86689 19996	48
0.65525 23646	1.97069 64170	0.42520 82479	72 16	1.82799 84162	47
0.64170 26188	1.93810 46179	0.43228 79822	71 31	1.78910 48329	46
0.62804 93057	1.90553 81344	0.43906 53283	70 45	1.75021 12496	45
A(r)	D(r)	E(r)	φ	Fφ	r

K = 3.6518559695, K′ = 1.5751136078, E = 1.017236918, E′ = 1.5664967878,

r	Fφ	φ	E(r)	D(r)	A(r)
0	0.00000 00000	0° 0′	0.00000 00000	1.00000 00000	0.00000 00000
1	0.04057 61774	2 1	0.02925 15342	1.00059 38572	0.01311 92586
2	0.08115 23549	4 29	0.05837 13484	1.00237 48641	0.02624 22974
3	0.12172 85323	6 55	0.08722 94380	1.00534 13262	0.03937 28749
4	0.16230 47098	9 16	0.11569 91812	1.00949 04192	0.05251 47063
5	0.20288 08872	11 33	0.14365 89152	1.01481 81886	0.06567 14426
6	0.24345 70646	13 49	0.17099 33783	1.02131 95491	0.07884 66485
7	0.28403 32421	16 4	0.19759 49853	1.02898 82841	0.09204 37819
8	0.32460 94195	18 17	0.22336 49075	1.03781 70450	0.10526 61731
9	0.36518 55969	20 29	0.24821 39381	1.04779 73504	0.11851 70041
10	0.40576 17744	22 39	0.27206 31341	1.05891 95857	0.13179 92889
11	0.44633 79518	24 46	0.29484 42309	1.07117 30024	0.14511 58534
12	0.48691 41293	26 52	0.31649 98365	1.08454 57174	0.15846 93168
13	0.52749 03067	28 56	0.33698 34175	1.09902 47131	0.17186 20726
14	0.56806 64841	30 58	0.35625 90959	1.11459 58374	0.18529 62711
15	0.60864 26616	32 55	0.37430 12782	1.13124 38038	0.19877 38016
16	0.64921 88390	34 51	0.39109 41430	1.14895 21925	0.21229 62758
17	0.68979 50165	36 44	0.40663 10147	1.16770 34514	0.22586 50123
18	0.73037 11939	38 36	0.42091 36481	1.18747 88983	0.23948 10211
19	0.77094 73713	40 24	0.43395 14533	1.20825 87235	0.25314 49894
20	0.81152 35488	42 9	0.44576 06829	1.23002 19929	0.26685 72683
21	0.85209 97262	43 51	0.45636 36044	1.25274 66524	0.28061 78600
22	0.89267 59037	45 31	0.46578 76783	1.27640 95335	0.29442 64067
23	0.93325 20811	47 8	0.47406 47564	1.30098 63590	0.30828 21794
24	0.97382 82585	48 42	0.48123 03147	1.32645 17509	0.32218 40690
25	1.01440 44360	50 13	0.48732 27312	1.35277 92393	0.33613 05773
26	1.05498 06134	51 42	0.49238 26159	1.37994 12721	0.35011 98097
27	1.09555 67908	53 8	0.49645 21966	1.40790 92268	0.36414 94689
28	1.13613 29683	54 31	0.49957 47663	1.43665 34239	0.37821 68497
29	1.17670 91457	55 51	0.50179 41897	1.46614 31412	0.39231 88350
30	1.21728 53232	57 9	0.50315 44701	1.49634 66307	0.40645 18927
31	1.25786 15006	58 25	0.50369 93739	1.52723 11369	0.42061 20743
32	1.29843 76780	59 38	0.50347 21104	1.55876 29167	0.43479 50141
33	1.33901 38555	60 48	0.50251 50624	1.59090 72622	0.44899 59303
34	1.37959 00329	61 56	0.50086 95651	1.62362 85241	0.46320 96265
35	1.42016 62104	63 2	0.49857 57270	1.65689 01387	0.47743 04952
36	1.46074 23878	64 5	0.49567 22903	1.69065 46558	0.49165 25218
37	1.50131 85652	65 7	0.49219 65260	1.72488 37696	0.50586 92908
38	1.54189 47427	66 6	0.48818 41583	1.75953 83514	0.52007 39919
39	1.58247 09201	67 3	0.48366 93168	1.79457 84847	0.53425 94285
40	1.62304 70975	67 58	0.47868 45099	1.82996 35024	0.54841 80268
41	1.66362 32750	68 51	0.47326 06189	1.86565 20265	0.56254 18461
42	1.70419 94524	69 42	0.46742 69071	1.90160 20099	0.57662 25903
43	1.74477 56299	70 31	0.46121 10428	1.93777 07807	0.59065 16209
44	1.78535 18073	71 19	0.45463 91336	1.97411 50881	0.60461 99704
45	1.82592 79847	72 5	0.44773 57684	2.01059 11517	0.61851 83573
90−r	Fψ	ψ	G(r)	C(r)	B(r)

$q = 0.257940195766337$, $\Theta 0 = 0.4929628191$, HK = 1.5205617314

B(r)	C(r)	G(r)	ψ	Fψ	90–r
1.00000 00000	3.09301 99213	0.00000 00000	90° 0′	3.65185 59695	90
0.99977 07150	3.09233 85676	0.01085 90483	89 45	3.61127 97920	89
0.99908 31458	3.09029 54977	0.02171 66503	89 31	3.57070 36146	88
0.99793 81489	3.08689 36827	0.03257 13506	89 16	3.53012 74372	87
0.99633 71496	3.08213 80679	0.04342 16747	89 1	3.48955 12597	86
0.99428 21381	3.07603 55627	0.05426 61204	88 47	3.44897 50823	85
0.99177 56649	3.06859 50269	0.06510 31473	88 32	3.40839 89048	84
0.98882 08340	3.05982 72527	0.07593 11673	88 17	3.36782 27274	83
0.98542 12955	3.04974 49431	0.08674 85345	88 2	3.32724 65500	82
0.98158 12363	3.03836 26866	0.09755 35344	87 46	3.28667 03725	81
0.97730 53698	3.02569 69280	0.10834 43731	87 30	3.24609 41951	80
0.97259 89240	3.01176 59358	0.11911 91660	87 14	3.20551 80177	79
0.96746 76286	2.99658 97659	0.12987 59255	86 58	3.16494 18402	78
0.96191 77007	2.98019 02223	0.14061 25487	86 42	3.12436 56628	77
0.95595 58299	2.96259 08137	0.15132 68040	86 25	3.08378 94853	76
0.94958 91609	2.94381 67083	0.16201 63172	86 8	3.04321 33079	75
0.94282 52769	2.92389 46843	0.17267 85562	85 50	3.00263 71305	74
0.93567 21802	2.90285 30783	0.18331 08161	85 32	2.96206 09530	73
0.92813 82732	2.88072 17308	0.19391 02013	85 14	2.92148 47756	72
0.92023 23376	2.85753 19293	0.20447 36088	84 55	2.88090 85981	71
0.91196 35133	2.83331 63492	0.21499 77081	84 36	2.84033 24207	70
0.90334 12763	2.80810 89917	0.22547 89218	84 16	2.79975 62433	69
0.89437 54154	2.78194 51210	0.23591 34034	83 55	2.75918 00658	68
0.88507 60096	2.75486 11988	0.24629 70143	83 34	2.71860 38884	67
0.87545 34034	2.72689 48173	0.25662 52995	83 13	2.67802 77109	66
0.86551 81826	2.69808 46313	0.26689 34606	82 51	2.63745 15335	65
0.85528 11491	2.66847 02880	0.27709 63287	82 28	2.59687 53561	64
0.84475 32958	2.63809 23575	0.28722 83335	82 4	2.55629 91786	63
0.83394 57809	2.60699 22604	0.29728 34722	81 39	2.51572 30012	62
0.82286 99019	2.57521 21966	0.30725 52753	81 14	2.47514 68238	61
0.81153 70701	2.54279 50725	0.31713 67705	80 48	2.43457 06463	60
0.79995 87840	2.50978 44281	0.32692 04449	80 21	2.39399 44689	59
0.78814 66036	2.47622 43648	0.33659 82039	79 53	2.35341 82914	58
0.77611 21247	2.44215 94723	0.34616 13287	79 24	2.31284 21140	57
0.76386 69524	2.40763 47564	0.35560 04313	78 54	2.27226 59366	56
0.75142 26764	2.37269 55671	0.36490 54063	78 23	2.23168 97591	55
0.73879 08451	2.33738 75276	0.37406 53814	77 51	2.19111 35817	54
0.72598 29409	2.30175 64635	0.38306 86651	77 18	2.15053 74042	53
0.71301 03561	2.26584 83337	0.39190 26919	76 44	2.10996 12268	52
0.69988 43682	2.22970 91619	0.40055 39659	76 8	2.06938 50494	51
0.68661 61172	2.19338 49695	0.40900 80023	75 31	2.02880 88719	50
0.67321 65825	2.15692 17102	0.41724 92673	74 53	1.98823 26945	49
0.65969 65607	2.12036 52053	0.42526 11165	74 13	1.94765 65171	48
0.64606 66446	2.08376 10820	0.43302 57335	73 32	1.90708 03396	47
0.63233 72022	2.04715 47117	0.44052 40667	72 49	1.86650 41622	46
0.61851 83573	2.01059 11517	0.44773 57684	72 5	1.82592 79847	45
A(r)	D(r)	E(r)	φ	Fφ	r

$K = 3.8317419998,\quad K' = 1.5737921309,\quad E = 1.0126635062,\quad E' = 1.5678090740,$

r	Fφ	φ	E(r)	D(r)	A(r)
0	0.00000 00000	0° 0′	0.00000 00000	1.00000 00000	0.00000 00000
1	0.04257 49111	2 26	0.03129 75841	1.00066 67396	0.01256 98450
2	0.08514 98222	4 52	0.06244 25476	1.00266 63652	0.02514 45765
3	0.12772 47333	7 18	0.09328 44601	1.00599 70974	0.03772 90570
4	0.17029 96444	9 43	0.12367 72052	1.01065 59692	0.05032 81006
5	0.21287 45555	12 6	0.15348 09749	1.01663 88247	0.06294 64495
6	0.25544 94667	14 29	0.18256 40780	1.02394 03165	0.07558 87497
7	0.29802 43778	16 50	0.21080 45154	1.03255 39030	0.08825 95281
8	0.34059 92889	19 9	0.23809 12866	1.04247 18453	0.10096 31685
9	0.38317 42000	21 26	0.26432 54039	1.05368 52030	0.11370 38895
10	0.42574 91111	23 42	0.28942 06026	1.06618 38299	0.12648 57214
11	0.46832 40222	25 55	0.31330 37505	1.07995 63700	0.13931 24846
12	0.51089 89333	28 5	0.33591 49667	1.09499 02519	0.15218 77682
13	0.55347 38444	30 13	0.35720 74739	1.11127 16844	0.16511 49087
14	0.59604 87555	32 18	0.37714 72117	1.12878 56513	0.17809 69700
15	0.63862 36666	34 21	0.39571 22464	1.14751 59063	0.19113 67239
16	0.68119 85777	36 20	0.41289 20138	1.16744 49685	0.20423 66315
17	0.72377 34889	38 17	0.42868 64336	1.18855 41178	0.21739 88246
18	0.76634 84000	40 11	0.44310 49337	1.21082 33907	0.23062 50891
19	0.80892 33111	42 1	0.45616 54173	1.23423 15771	0.24391 68485
20	0.85149 82222	43 49	0.46789 32075	1.25875 62174	0.25727 51484
21	0.89407 31333	45 33	0.47831 99952	1.28437 36007	0.27070 06428
22	0.93664 80444	47 15	0.48748 28142	1.31105 87634	0.28419 35800
23	0.97922 29555	48 53	0.49542 30625	1.33878 54900	0.29775 37910
24	1.02179 78666	50 28	0.50218 55842	1.36752 63142	0.31138 06778
25	1.06437 27777	52 0	0.50781 78217	1.39725 25218	0.32507 32040
26	1.10694 76888	53 29	0.51236 90454	1.42793 41552	0.33882 98857
27	1.14952 25999	54 56	0.51588 96635	1.45954 00195	0.35264 87839
28	1.19209 75110	56 19	0.51843 06138	1.49203 76904	0.36652 74982
29	1.23467 24222	57 39	0.52004 28338	1.52539 35243	0.38046 31619
30	1.27724 73333	58 59	0.52077 68087	1.55957 26706	0.39445 24378
31	1.31982 22444	60 12	0.52068 21896	1.59453 90851	0.40849 15164
32	1.36239 71555	61 24	0.51980 74799	1.63025 55479	0.42257 61140
33	1.40497 20666	62 34	0.51819 97811	1.66668 36814	0.43670 14735
34	1.44754 69777	63 41	0.51590 45944	1.70378 39728	0.45086 23658
35	1.49012 18888	64 46	0.51296 56697	1.74151 57980	0.46505 30926
36	1.53269 67999	65 48	0.50942 48984	1.77983 74487	0.47926 74909
37	1.57527 17110	66 48	0.50532 22421	1.81870 61627	0.49349 89386
38	1.61784 66221	67 46	0.50069 56936	1.85807 81564	0.50774 03615
39	1.66042 15332	68 41	0.49558 12646	1.89790 86607	0.52198 42419
40	1.70299 64444	69 35	0.49001 29952	1.93815 19599	0.53622 26281
41	1.74557 13555	70 26	0.48402 29824	1.97876 14331	0.55044 71457
42	1.78814 62666	71 16	0.47764 14227	2.01968 95998	0.56464 90099
43	1.83072 11777	72 3	0.47089 66670	2.06088 81669	0.57881 90394
44	1.87329 60888	72 49	0.46381 52836	2.10230 80805	0.59294 76712
45	1.91587 09999	73 33	0.45642 21286	2.14389 95792	0.60702 49768
90–r	Fψ	ψ	G(r)	C(r)	B(r)

$q = 0.275179804873563$, $\Theta 0 = 0.4610905222$, HK $= 1.5588714533$

B(r)	C(r)	G(r)	ψ	Fψ	90−r
1.00000 00000	3.38728 70037	0.00000 00000	90° 0′	3.83174 19998	90
0.99976 05041	3.38649 90904	0.01092 82185	89 47	3.78916 70887	89
0.99904 23353	3.38413 65337	0.02185 52713	89 34	3.74659 21776	88
0.99784 64504	3.38020 28815	0.03277 99847	89 22	3.70401 72665	87
0.99617 44409	3.37470 40379	0.04370 11679	89 9	3.66144 23554	86
0.99402 85290	3.36764 82512	0.05461 76051	88 56	3.61886 74443	85
0.99141 15622	3.35904 60961	0.06552 80467	88 43	3.57629 25331	84
0.98832 70058	3.34891 04507	0.07643 12000	88 29	3.53371 76220	83
0.98477 89335	3.33725 64694	0.08732 57205	88 16	3.49114 27109	82
0.98077 20177	3.32410 15504	0.09821 02023	88 2	3.44856 77998	81
0.97631 15168	3.30946 52989	0.10908 31677	87 49	3.40599 28887	80
0.97140 32619	3.29336 94854	0.11994 30573	87 35	3.36341 79776	79
0.96605 36420	3.27583 79999	0.13078 82183	87 20	3.32084 30665	78
0.96026 95874	3.25689 68018	0.14161 68937	87 6	3.27826 81554	77
0.95405 85520	3.23657 38654	0.15242 72092	86 51	3.23569 32443	76
0.94742 84947	3.21489 91220	0.16321 71605	86 35	3.19311 83332	75
0.94038 78585	3.19190 43978	0.17398 45990	86 20	3.15054 34221	74
0.93294 55499	3.16762 33486	0.18472 72171	86 4	3.10796 85109	73
0.92511 09158	3.14209 13909	0.19544 25321	85 48	3.06539 35998	72
0.91689 37204	3.11534 56304	0.20612 78689	85 31	3.02281 86887	71
0.90830 41205	3.08742 47870	0.21678 03419	85 13	2.98024 37776	70
0.89935 26403	3.05836 91177	0.22739 68349	84 55	2.93766 88665	69
0.89005 01452	3.02822 03368	0.23797 39802	84 37	2.89509 39554	68
0.88040 78152	2.99702 15345	0.24850 81357	84 18	2.85251 90443	67
0.87043 71170	2.96481 70925	0.25899 53603	83 58	2.80994 41332	66
0.86014 97763	2.93165 25995	0.26943 13876	83 38	2.76736 92221	65
0.84955 77491	2.89757 47641	0.27981 15977	83 17	2.72479 43110	64
0.83867 31932	2.86263 13272	0.29013 09871	82 55	2.68221 93999	63
0.82750 84383	2.82687 09732	0.30038 41353	82 33	2.63964 44888	62
0.81607 59576	2.79034 32412	0.31056 51708	82 10	2.59706 95776	61
0.80438 83372	2.75309 84351	0.32066 77330	81 46	2.55449 46665	60
0.79245 82474	2.71518 75345	0.33068 49323	81 21	2.51191 97554	59
0.78029 84129	2.67666 21047	0.34060 93073	80 55	2.46934 48443	58
0.76792 15834	2.63757 42081	0.35043 27789	80 28	2.42676 99332	57
0.75534 05043	2.59797 63158	0.36014 66018	80 0	2.38419 50221	56
0.74256 78883	2.55792 12198	0.36974 13124	79 31	2.34162 01110	55
0.72961 63864	2.51746 19471	0.37920 66740	79 2	2.29904 51999	54
0.71649 85603	2.47665 16742	0.38853 16185	78 30	2.25647 02888	53
0.70322 68545	2.43554 36438	0.39770 41848	77 58	2.21389 53777	52
0.68981 35699	2.39419 10827	0.40671 14546	77 24	2.17132 04666	51
0.67627 08370	2.35264 71220	0.41553 94843	76 50	2.12874 55554	50
0.66261 05910	2.31096 47190	0.42417 32345	76 13	2.08617 06443	49
0.64884 45467	2.26919 65819	0.43259 64967	75 35	2.04359 57332	48
0.63498 41750	2.22739 50955	0.44079 18172	74 56	2.00102 08221	47
0.62104 06800	2.18561 22515	0.44874 04204	74 16	1.95844 59110	46
0.60702 49768	2.14389 95792	0.45642 21286	73 33	1.91587 09999	45
A(r)	D(r)	E(r)	φ	Fφ	r

K = 4.0527581695, K′ = 1.5727124350, E = 1.0086479569, E′ = 1.5688837196,

r	Fφ	φ	E(r)	D(r)	A(r)
0	0.00000 00000	0° 0′	0.00000 00000	1.00000 00000	0.00000 00000
1	0.04503 06463	2 35	0.03379 31823	1.00076 14948	0.01189 42847
2	0.09006 12927	5 9	0.06740 53633	1.00304 53671	0.02379 47903
3	0.13509 19390	7 43	0.10065 84494	1.00684 97794	0.03570 77106
4	0.18012 25853	10 16	0.13338 00630	1.01217 16668	0.04763 91855
5	0.22515 32316	12 48	0.16540 61602	1.01900 67332	0.05959 52742
6	0.27018 38780	15 18	0.19658 33739	1.02734 94459	0.07158 19286
7	0.31521 45243	17 46	0.22677 10168	1.03719 30291	0.08360 49670
8	0.36024 51706	20 13	0.25584 26948	1.04852 94558	0.09567 00478
9	0.40527 58170	22 37	0.28368 75021	1.06134 94387	0.10778 26441
10	0.45030 64633	24 58	0.31021 07894	1.07564 24197	0.11994 80182
11	0.49533 71096	27 18	0.33533 45137	1.09139 65585	0.13217 11972
12	0.54036 77559	29 34	0.35899 71966	1.10859 87206	0.14445 69485
13	0.58539 84023	31 47	0.38115 35291	1.12723 44637	0.15680 97563
14	0.63042 90486	33 57	0.40177 36714	1.14728 80243	0.16923 37988
15	0.67545 96949	36 4	0.42084 23033	1.16874 23039	0.18173 29260
16	0.72049 03413	38 8	0.43835 74800	1.19157 88539	0.19431 06384
17	0.76552 09876	40 8	0.45432 93515	1.21577 78616	0.20697 00661
18	0.81055 16339	42 5	0.46877 87966	1.24131 81358	0.21971 39498
19	0.85558 22802	43 58	0.48173 60209	1.26817 70925	0.23254 46217
20	0.90061 29266	45 53	0.49323 91602	1.29633 07415	0.24546 39877
21	0.94564 35729	47 35	0.50333 29227	1.32575 36734	0.25847 35115
22	0.99067 42192	49 18	0.51206 72988	1.35641 90478	0.27157 41984
23	1.03570 48656	50 57	0.51949 63591	1.38829 85826	0.28476 65811
24	1.08073 55119	52 33	0.52567 71528	1.42136 25446	0.29805 07071
25	1.12576 61582	54 6	0.53066 87177	1.45557 97413	0.31142 61261
26	1.17079 68045	55 36	0.53453 12033	1.49091 75157	0.32489 18800
27	1.21582 74509	57 2	0.53732 51072	1.52734 17416	0.33844 64932
28	1.26085 80972	58 25	0.53911 06227	1.56481 68225	0.35208 79650
29	1.30588 87435	59 45	0.53994 70893	1.60330 56919	0.36581 37630
30	1.35091 93898	61 2	0.53989 25408	1.64276 98172	0.37962 08180
31	1.39595 00362	62 16	0.53900 33421	1.68316 92055	0.39350 55205
32	1.44098 06825	63 28	0.53733 39051	1.72446 24133	0.40746 37182
33	1.48601 13288	64 36	0.53493 64751	1.76660 65590	0.42149 07161
34	1.53104 19752	65 42	0.53186 09786	1.80955 73388	0.43558 12766
35	1.57607 26215	66 45	0.52815 49246	1.85326 90463	0.44972 96226
36	1.62110 32678	67 46	0.52386 33506	1.89769 45959	0.46392 94409
37	1.66613 39141	68 44	0.51902 88062	1.94278 55494	0.47817 38881
38	1.71116 45605	69 40	0.51369 13678	1.98849 21476	0.49245 55978
39	1.75619 52068	70 33	0.50788 86793	2.03476 33449	0.50676 66888
40	1.80122 58531	71 25	0.50165 60117	2.08154 68491	0.52109 87757
41	1.84625 64995	72 14	0.49502 63387	2.12878 91642	0.53544 29804
42	1.89128 71458	73 2	0.48803 04242	2.17643 56384	0.54978 99455
43	1.93631 77921	73 47	0.48069 69176	2.22443 05163	0.56412 98491
44	1.98134 84385	74 31	0.47305 24550	2.27271 69945	0.57845 24208
45	2.02637 90848	75 12	0.46512 17631	2.32123 72832	0.59274 69597
90–r	Fψ	ψ	G(r)	C(r)	B(r)

$q = 0.295488385558687$, $\Theta 0 = 0.4242361430$, $HK = 1.6043008048$

B(r)	C(r)	G(r)	ψ	Fψ	90−r
1.00000 00000	3.78623 65254	0.00000 00000	90° 0′	4.05275 81695	90
0.99974 76964	3.78529 99318	0.01098 79345	89 49	4.00772 75232	89
0.99899 11477	3.78249 16163	0.02197 49829	89 38	3.96269 68769	88
0.99773 14382	3.77781 59714	0.03296 02520	89 28	3.91766 62306	87
0.99597 03726	3.77128 03065	0.04394 28343	89 17	3.87263 55842	86
0.99371 04703	3.76289 48312	0.05492 18007	89 6	3.82760 49379	85
0.99095 49588	3.75267 26317	0.06589 61931	88 54	3.78257 42916	84
0.98770 77652	3.74062 96405	0.07686 50165	88 43	3.73754 36452	83
0.98397 35058	3.72678 46000	0.08782 72314	88 32	3.69251 29989	82
0.97975 74732	3.71115 90191	0.09878 17452	88 20	3.64748 23526	81
0.97506 56227	3.69377 71248	0.10972 74034	88 8	3.60245 17063	80
0.96990 45558	3.67466 58061	0.12066 29807	87 56	3.55742 10599	79
0.96428 15032	3.65385 45535	0.13158 71709	87 44	3.51239 04136	78
0.95820 43054	3.63137 53926	0.14249 85767	87 32	3.46735 97673	77
0.95168 13914	3.60726 28114	0.15339 56986	87 19	3.42232 91209	76
0.94472 17573	3.58155 36840	0.16427 69227	87 5	3.37729 84746	75
0.93733 49419	3.55428 71880	0.17514 05085	86 52	3.33226 78283	74
0.92953 10017	3.52550 47184	0.18598 45746	86 38	3.28723 71820	73
0.92132 04850	3.49524 97967	0.19680 70842	86 24	3.24220 65356	72
0.91271 44039	3.46356 79762	0.20760 58292	86 9	3.19717 58893	71
0.90372 42062	3.43050 67437	0.21837 84126	85 54	3.15214 52430	70
0.89436 17453	3.39611 54178	0.22912 22300	85 38	3.10711 45967	69
0.88463 92502	3.36044 50445	0.23983 44495	85 22	3.06208 39503	68
0.87456 92937	3.32354 82896	0.25051 19896	85 5	3.01705 33040	67
0.86416 47610	3.28547 93300	0.26115 14957	84 48	2.97202 26577	66
0.85343 88167	3.24629 37417	0.27174 93142	84 30	2.92699 20113	65
0.84240 48716	3.20604 83874	0.28230 14649	84 11	2.88196 13650	64
0.83107 65499	3.16480 13024	0.29280 36106	83 52	2.83693 07187	63
0.81946 76545	3.12261 15798	0.30325 10250	83 32	2.79190 00724	62
0.80759 21336	3.07953 92551	0.31363 85568	83 11	2.74686 94260	61
0.79546 40466	3.03564 51912	0.32396 05923	82 49	2.70183 87797	60
0.78309 75297	2.99099 09630	0.33421 10135	82 26	2.65680 81334	59
0.77050 67624	2.94563 87432	0.34438 31544	82 3	2.61177 74870	58
0.75770 59335	2.89965 11884	0.35446 97527	81 39	2.56674 68407	57
0.74470 92077	2.85309 13269	0.36446 28984	81 13	2.52171 61944	56
0.73153 06927	2.80602 24483	0.37435 39786	80 47	2.47668 55480	55
0.71818 44065	2.75850 79940	0.38413 36176	80 19	2.43165 49017	54
0.70468 42455	2.71061 14508	0.39379 16142	79 50	2.38662 42554	53
0.69104 39537	2.66239 62465	0.40331 68729	79 20	2.34159 36091	52
0.67727 70914	2.61392 56481	0.41269 73321	78 49	2.29656 29627	51
0.66339 70061	2.56526 26633	0.42191 98869	78 17	2.25153 23164	50
0.64941 68038	2.51646 99446	0.43097 03076	77 43	2.20650 16701	49
0.63534 93209	2.46760 96971	0.43983 31542	77 8	2.16147 10238	48
0.62120 70978	2.41874 35896	0.44849 16855	76 31	2.11644 03774	47
0.60700 23531	2.36993 26700	0.45692 77651	75 52	2.07140 97311	46
0.59274 69597	2.32123 72832	0.46512 17631	75 12	2.02637 90848	45
A(r)	D(r)	E(r)	φ	Fφ	r

K = 4.3386539760, K′ = 1.5718736105, E = 1.0052585872, E′ = 1.5697201504,

r	Fφ	φ		E(r)	D(r)	A(r)
0	0.00000 00000	0°	0′	0.00000 00000	1.00000 00000	0.00000 00000
1	0.04820 72664	2	46	0.03700 05198	1.00089 26934	0.01102 97158
2	0.09641 45328	5	31	0.07377 86246	1.00357 01695	0.02206 73089
3	0.14462 17992	8	15	0.11011 59944	1.00803 06141	0.03312 06260
4	0.19282 90656	10	59	0.14580 23384	1.01427 09982	0.04419 74541
5	0.24103 63320	13	41	0.18063 90239	1.02228 70707	0.05530 54893
6	0.28924 35984	16	21	0.21444 22668	1.03207 33471	0.06645 23081
7	0.33745 08648	18	59	0.24704 57854	1.04362 30963	0.07764 53371
8	0.38565 81312	21	34	0.27830 28485	1.05692 83239	0.08889 18239
9	0.43386 53976	24	7	0.30808 76822	1.07197 97531	0.10019 88085
10	0.48207 26640	26	37	0.33629 62369	1.08876 68032	0.11157 30946
11	0.53027 99304	29	3	0.36284 63422	1.10727 75652	0.12302 12218
12	0.57848 71968	31	27	0.38767 73064	1.12749 87762	0.13454 94383
13	0.62669 44632	33	46	0.41074 90335	1.14941 57909	0.14616 36738
14	0.67490 17296	36	2	0.43204 07437	1.17301 25520	0.15786 95139
15	0.72310 89960	38	14	0.45154 93887	1.19827 15591	0.16967 21746
16	0.77131 62624	40	23	0.46928 78534	1.22517 38362	0.18157 64776
17	0.81952 35288	42	27	0.48528 30289	1.25369 88987	0.19358 68272
18	0.86773 07952	44	28	0.49957 38349	1.28382 47193	0.20570 71870
19	0.91593 80616	46	24	0.51220 92565	1.31552 76945	0.21794 10587
20	0.96414 53280	48	16	0.52324 64512	1.34878 26100	0.23029 14612
21	1.01235 25944	50	5	0.53274 89656	1.38356 26077	0.24276 09111
22	1.06055 98608	51	50	0.54078 50933	1.41983 91529	0.25535 14044
23	1.10876 71272	53	30	0.54742 63924	1.45758 20021	0.26806 43994
24	1.15697 43936	55	7	0.55274 63730	1.49675 91734	0.28090 08008
25	1.20518 16600	56	40	0.55681 93566	1.53733 69175	0.29386 09452
26	1.25338 89264	58	10	0.55971 95044	1.57927 96919	0.30694 45879
27	1.30159 61928	59	36	0.56152 00057	1.62255 01370	0.32015 08913
28	1.34980 34592	60	58	0.56229 24153	1.66710 90551	0.33347 84147
29	1.39801 07256	62	17	0.56210 61265	1.71291 53925	0.34692 51057
30	1.44621 79920	63	33	0.56102 79658	1.75992 62260	0.36048 82928
31	1.49442 52584	64	46	0.55912 18929	1.80809 67519	0.37416 46804
32	1.54263 25248	65	55	0.55644 87947	1.85738 02804	0.38795 03444
33	1.59083 97912	67	2	0.55306 63561	1.90772 82336	0.40184 07305
34	1.63904 70676	68	6	0.54902 89975	1.95909 01488	0.41583 06538
35	1.68725 43240	69	7	0.54438 78661	2.01141 36867	0.42991 42995
36	1.73546 15904	70	5	0.53919 08711	2.06464 46451	0.44408 52267
37	1.78366 88568	71	1	0.53348 27539	2.11872 69773	0.45833 63730
38	1.83187 61232	71	54	0.52730 51847	2.17360 28173	0.47266 00609
39	1.88008 33896	72	45	0.52069 68791	2.22921 25107	0.48704 80065
40	1.92829 06560	73	34	0.51369 37297	2.28549 46508	0.50149 13298
41	1.97649 79224	74	20	0.50632 89466	2.34238 61220	0.51598 05665
42	2.02470 51888	75	5	0.49863 32034	2.39982 21493	0.53050 56822
43	2.07291 24552	75	47	0.49063 47860	2.45773 63538	0.54505 60878
44	2.12111 97216	76	58	0.48235 97411	2.51606 08149	0.55962 06569
45	2.16932 69880	77	7	0.47383 20219	2.57472 61393	0.57418 77451
90−r	Fψ	ψ		G(r)	C(r)	B(r)

$q = 0.320400337134867$, $\Theta 0 = 0.3802048484$, $HK = 1.6608093153$

B(r)	C(r)	G(r)	ψ	Fψ	90−r
1.00000 00000	4.37119 23556	0.00000 00000	90° 0′	4.33865 39760	90
0.99973 08085	4.37002 95871	0.01103 73956	89 51	4.29044 67096	89
0.99892 36540	4.36654 32014	0.02207 41777	89 43	4.24223 94432	88
0.99757 97949	4.36073 89539	0.03310 97273	89 34	4.19403 21768	87
0.99570 13248	4.35262 64203	0.04414 34137	89 25	4.14582 49104	86
0.99329 11666	4.34221 89731	0.05517 45893	89 16	4.09761 76440	85
0.99035 30638	4.32953 37471	0.06620 25830	89 7	4.04941 03776	84
0.98689 15704	4.31459 15972	0.07722 66944	88 58	4.00120 31112	83
0.98291 20378	4.29741 70454	0.08824 61873	88 49	3.95299 58448	82
0.97842 05999	4.27803 82196	0.09926 02826	88 39	3.90478 85784	81
0.97342 41557	4.25648 67836	0.11026 81515	88 30	3.85658 13120	80
0.96793 03503	4.23279 78580	0.12126 89076	88 20	3.80837 40456	79
0.96194 75529	4.20700 99336	0.13226 15989	88 10	3.76016 67792	78
0.95548 48341	4.17916 47765	0.14324 51989	88 0	3.71195 95128	77
0.94855 19406	4.14930 73254	0.15421 85972	87 49	3.66375 22464	76
0.94115 92676	4.11748 55826	0.16518 05896	87 38	3.61554 49800	75
0.93331 78308	4.08375 04971	0.17612 98666	87 27	3.56733 77136	74
0.92503 92359	4.04815 58427	0.18706 50017	87 16	3.51913 04472	73
0.91633 56463	4.01075 80891	0.19798 44386	87 4	3.47092 31808	72
0.90721 97509	3.97161 62682	0.20888 64763	86 51	3.42271 59144	71
0.89770 47288	3.93079 18356	0.21976 92546	86 38	3.37450 86480	70
0.88780 42140	3.88834 85274	0.23063 07363	86 25	3.32630 13816	69
0.87753 22590	3.84435 22135	0.24146 86896	86 11	3.27809 41152	68
0.86690 32971	3.79887 07472	0.25228 06673	85 57	3.22988 68488	67
0.85593 21039	3.75197 38123	0.26306 39853	85 42	3.18167 95824	66
0.84463 37589	3.70373 27678	0.27381 56982	85 27	3.13347 23160	65
0.83302 36055	3.65422 04910	0.28453 25731	85 11	3.08526 50496	64
0.82111 72113	3.60351 12193	0.29521 10610	84 54	3.03705 77832	63
0.80893 03281	3.55168 03915	0.30584 72655	84 37	2.98885 05168	62
0.79647 88516	3.49880 44891	0.31643 69081	84 19	2.94064 32504	61
0.78377 87810	3.44496 08773	0.32697 52911	84 0	2.89243 59840	60
0.77084 61787	3.39022 76481	0.33745 72566	83 40	2.84422 87176	59
0.75769 71307	3.33468 34641	0.34787 71421	83 19	2.79602 14512	58
0.74434 77069	3.27840 74042	0.35822 87319	82 57	2.74781 41848	57
0.73081 39218	3.22147 88118	0.36850 52042	82 35	2.69960 69184	56
0.71711 16962	3.16397 71463	0.37869 90740	82 11	2.65139 96520	55
0.70325 68193	3.10598 18371	0.38880 21304	81 47	2.60319 23856	54
0.68926 49116	3.04757 21420	0.39880 53693	81 21	2.55498 51192	53
0.67515 13887	2.98882 70090	0.40869 89202	80 54	2.50677 78528	52
0.66093 14267	2.92982 49435	0.41847 19672	80 26	2.45857 05864	51
0.64661 99275	2.87064 38790	0.42811 26638	79 56	2.41036 33200	50
0.63223 14865	2.81136 10542	0.43760 80415	79 25	2.36215 60536	49
0.61778 03606	2.75205 28945	0.44694 39111	78 53	2.31394 87872	48
0.60328 04384	2.69279 48995	0.45610 47583	78 19	2.26574 15208	47
0.58874 52110	2.63366 15364	0.46507 36311	77 44	2.21753 42544	46
0.57418 77451	2.57472 61393	0.47383 20219	77 7	2.16932 69880	45
A(r)	D(r)	E(r)	ϕ	Fϕ	r

K = 4.7427172653, K′ = 1.5712749524, E = 1.0025840855, E′ = 1.5703179199,

r	Fφ	φ		E(r)	D(r)	A(r)
0	0.00000 00000	0°	0′	0.00000 00000	1.00000 00000	0.00000 00000
1	0.05269 68585	3	1	0.04150 83698	1.00109 49202	0.00984 61866
2	0.10539 37170	6	2	0.08272 60369	1.00437 91719	0.01970 23988
3	0.15809 05755	9	1	0.12336 86879	1.00985 12249	0.02957 86287
4	0.21078 74340	11	59	0.16316 44916	1.01750 85180	0.03948 48012
5	0.26348 42925	14	56	0.20185 96235	1.02734 74434	0.04943 07415
6	0.31618 11510	17	49	0.23922 29917	1.03936 33238	0.05942 61408
7	0.36887 80095	20	40	0.27504 99964	1.05355 03843	0.06948 05245
8	0.42157 48680	23	28	0.30916 52198	1.06990 17180	0.07960 32187
9	0.47427 17265	26	13	0.34142 40166	1.08840 92458	0.08980 33181
10	0.52696 85850	28	53	0.37171 30376	1.10906 36709	0.10008 96542
11	0.57966 54435	31	30	0.39994 97772	1.13185 44282	0.11047 07636
12	0.63236 23020	34	2	0.42608 12751	1.15676 96284	0.12095 48573
13	0.68505 91605	36	30	0.45008 21300	1.18379 59985	0.13154 97896
14	0.73775 60190	38	53	0.47195 19964	1.21291 88175	0.14226 30292
15	0.79045 28775	41	12	0.49171 27333	1.24412 18489	0.15310 16293
16	0.84314 97360	43	26	0.50940 53625	1.27738 72698	0.16407 21997
17	0.89584 65946	45	35	0.52508 69758	1.31269 55975	0.17518 08788
18	0.94854 34531	47	40	0.53882 77072	1.35002 56142	0.18643 33074
19	1.00124 03116	49	40	0.55070 78595	1.38935 42896	0.19783 46027
20	1.05393 71701	51	34	0.56081 52531	1.43065 67027	0.20938 93338
21	1.10663 40286	53	25	0.56924 28378	1.47390 59633	0.22110 14976
22	1.15933 08871	55	11	0.57608 65921	1.51907 31337	0.23297 44971
23	1.21202 77456	56	52	0.58144 37172	1.56612 71505	0.24501 11193
24	1.26472 46041	58	29	0.58541 11188	1.61503 47485	0.25721 35159
25	1.31742 14626	60	2	0.58808 41618	1.66576 03865	0.26958 31846
26	1.37011 83211	61	31	0.58955 56773	1.71826 61750	0.28212 09517
27	1.42281 51796	62	55	0.58991 51945	1.77251 18082	0.29482 69565
28	1.47551 20381	64	16	0.58924 83721	1.82845 44989	0.30770 06377
29	1.52820 88966	65	33	0.58763 66017	1.88604 89185	0.32074 07202
30	1.58090 57551	66	46	0.58515 67551	1.94524 71416	0.33394 52050
31	1.63360 26136	67	56	0.58188 10541	2.00599 85969	0.34731 13599
32	1.68629 94721	69	3	0.57787 70364	2.06825 00238	0.36083 57125
33	1.73899 63306	70	6	0.57320 76019	2.13194 54360	0.37451 40449
34	1.79169 31891	71	7	0.56793 11188	2.19702 60925	0.38834 13902
35	1.84439 00476	72	4	0.56210 15757	2.26343 04764	0.40231 20314
36	1.89708 69061	72	59	0.55576 87678	2.33109 42822	0.41641 95021
37	1.94978 37646	73	51	0.54897 85058	2.39995 04116	0.43065 65890
38	2.00248 06231	74	41	0.54177 28388	2.46992 89791	0.44501 53371
39	2.05517 74816	75	28	0.53419 02851	2.54095 73266	0.45948 70563
40	2.10787 43401	76	12	0.52626 60647	2.61296 00482	0.47406 23311
41	2.16057 11986	76	55	0.51803 23296	2.68585 90255	0.48873 10316
42	2.21326 80571	77	35	0.50951 83887	2.75957 34731	0.50348 23272
43	2.26596 49156	78	14	0.50075 09241	2.83401 99954	0.51830 47025
44	2.31866 17741	78	50	0.49175 41985	2.90911 26530	0.53318 59750
45	2.37135 86326	79	25	0.48255 02516	2.98476 30422	0.54811 33155
90−r	Fψ	ψ		G(r)	C(r)	B(r)

$q = 0.353165648296037$, $\Theta\,0 = 0.3246110213$, $HK = 1.7370861537$

B(r)	C(r)	G(r)	ψ	Fψ	90−r
1.00000 00000	5.35291 58734	0.00000 00000	90° 0′	4.74271 72653	90
0.99970 65254	5.35135 39870	0.01107 55804	89 54	4.69002 04068	89
0.99882 66090	5.34667 11120	0.02215 08037	89 47	4.63732 35483	88
0.99736 17711	5.33887 55928	0.03322 53090	89 41	4.58462 66898	87
0.99531 45401	5.32798 13106	0.04429 87274	89 35	4.53192 98313	86
0.99268 84456	5.31400 76445	0.05537 06778	89 28	4.47923 29728	85
0.98948 80069	5.29697 94165	0.06644 07630	89 21	4.42653 61143	84
0.98571 87199	5.27692 68222	0.07750 85650	89 15	4.37383 92558	83
0.98138 70401	5.25388 53459	0.08857 36405	89 8	4.32114 23973	82
0.97650 03636	5.22789 56618	0.09963 55161	89 1	4.26844 55388	81
0.97106 70046	5.19900 35203	0.11069 36828	88 54	4.21574 86803	80
0.96509 61704	5.16725 96214	0.12174 75905	88 46	4.16305 18218	79
0.95859 79343	5.13271 94744	0.13279 66420	88 39	4.11035 49633	78
0.95158 32050	5.09544 32457	0.14384 01862	88 31	4.05765 81048	77
0.94406 36948	5.05549 55939	0.15487 75112	88 23	4.00496 12463	76
0.93605 18846	5.01294 54947	0.16590 78361	88 15	3.95226 43878	75
0.92756 09875	4.96786 60538	0.17693 03026	88 6	3.89956 75293	74
0.91860 49094	4.92033 43119	0.18794 39654	87 58	3.84687 06707	73
0.90919 82095	4.87043 10392	0.19894 77822	87 48	3.79417 38122	72
0.89935 60570	4.81824 05226	0.20994 06015	87 39	3.74147 69537	71
0.88909 41880	4.76385 03454	0.22092 11507	87 29	3.68878 00952	70
0.87842 88604	4.70735 11607	0.23188 80216	87 18	3.63608 32367	69
0.86737 68071	4.64883 64589	0.24283 96552	87 8	3.58338 63782	68
0.85595 51894	4.58840 23314	0.25377 43247	86 56	3.53068 95197	67
0.84418 15481	4.52614 72300	0.26469 01166	86 45	3.47799 26612	66
0.83207 37552	4.46217 17234	0.27558 49098	86 32	3.42529 58027	65
0.81964 99644	4.39657 82526	0.28645 63526	86 19	3.37259 89442	64
0.80692 85610	4.32947 08849	0.29730 18370	86 6	3.31990 20857	63
0.79392 81128	4.26095 50677	0.30811 84711	85 52	3.26720 52272	62
0.78066 73195	4.19113 73836	0.31890 30470	85 37	3.21450 83687	61
0.76716 49636	4.12012 53075	0.32965 20072	85 21	3.16181 15102	60
0.75343 98604	4.04802 69653	0.34036 14062	85 5	3.10911 46517	59
0.73951 08099	3.97495 08972	0.35102 68681	84 48	3.05641 77932	58
0.72539 65478	3.90100 58247	0.36164 35409	84 29	3.00372 09347	57
0.71111 56987	3.82630 04227	0.37220 60448	84 10	2.95102 40762	56
0.69668 67291	3.75094 30973	0.38270 84160	83 51	2.89832 72177	55
0.68212 79026	3.67504 17706	0.39314 40446	83 30	2.84563 03592	54
0.66745 72351	3.59870 36716	0.40350 56060	83 8	2.79293 35007	53
0.65269 24519	3.52203 51359	0.41378 49862	82 44	2.74023 66422	52
0.63785 09470	3.44514 14133	0.42397 31992	82 20	2.68753 97837	51
0.62294 97425	3.36812 64840	0.43406 02965	81 55	2.63484 29252	50
0.60800 54504	3.29109 28843	0.44403 52686	81 28	2.58214 60667	49
0.59303 42368	3.21414 15421	0.45388 59368	80 59	2.52944 92081	48
0.57805 17864	3.13737 16225	0.46359 88357	80 29	2.47675 23496	47
0.56307 32704	3.06088 03834	0.47315 90851	79 58	2.42405 54911	46
0.54811 33155	2.98476 30422	0.48255 02516	79 25	2.37135 86326	45
A(r)	D(r)	E(r)	φ	Fφ	r

K = 5.4349098296, K′ = 1.5709159581, E = 1.0007515777, E′ = 1.5706767091,

r	Fφ	φ	E(r)	D(r)	A(r)
0	0.00000 00000	0° 0′	0.00000 00000	1.00000 00000	0.00000 00000
1	0.06038 78870	3 27	0.04919 51488	1.00148 76066	0.00797 98676
2	0.12077 57740	6 54	0.09795 31901	1.00595 04088	0.01597 27570
3	0.18116 36610	10 19	0.14584 95983	1.01338 83449	0.02399 16544
4	0.24155 15480	13 42	0.19248 42494	1.02380 12862	0.03204 94760
5	0.30193 94350	17 3	0.23749 17959	1.03718 89963	0.04015 90322
6	0.36232 73220	20 19	0.28055 00559	1.05355 10766	0.04833 29925
7	0.42271 52090	23 32	0.32138 60670	1.07288 68948	0.05658 38508
8	0.48310 30960	26 40	0.35977 96610	1.09519 55002	0.06492 38899
9	0.54349 09830	29 43	0.39556 46136	1.12047 55228	0.07336 51472
10	0.60387 88700	32 40	0.42862 75917	1.14872 50597	0.08191 93794
11	0.66426 67569	35 32	0.45890 52450	1.17994 15472	0.09059 80283
12	0.72465 46439	38 18	0.48637 98590	1.21412 16208	0.09941 21860
13	0.78504 25309	40 58	0.51107 40138	1.25126 09628	0.10837 25614
14	0.84543 04179	43 32	0.53304 46717	1.29135 41391	0.11748 94454
15	0.90581 83049	45 59	0.55237 70723	1.33439 44250	0.12677 26784
16	0.96620 61919	48 20	0.56917 87466	1.38037 36227	0.13623 16162
17	1.02659 40789	50 35	0.58357 38857	1.42928 18693	0.14587 50978
18	1.08698 19659	52 44	0.59569 82320	1.48110 74384	0.15571 14129
19	1.14736 98529	54 47	0.60569 45851	1.53583 65353	0.16574 82707
20	1.20775 77399	56 43	0.61370 89715	1.59345 30865	0.17599 27682
21	1.26814 56269	58 35	0.61988 74725	1.65393 85266	0.18645 13603
22	1.32853 35139	60 20	0.62437 36797	1.71727 15815	0.19712 98307
23	1.38892 14009	62 0	0.62730 67243	1.78342 80514	0.20803 32624
24	1.44930 92879	63 35	0.62881 98144	1.85238 05926	0.21916 60113
25	1.50969 71749	65 5	0.62903 92100	1.92409 85022	0.23053 16788
26	1.57008 50619	66 30	0.62808 35657	1.99854 75042	0.24213 30872
27	1.63047 29489	67 51	0.62606 35735	2.07568 95405	0.25397 22556
28	1.69086 08359	69 7	0.62308 18462	2.15548 25676	0.26605 03772
29	1.75124 87229	70 19	0.61923 29878	2.23788 03597	0.27836 77989
30	1.81163 66099	71 27	0.61460 38040	2.32283 23203	0.29092 40017
31	1.87202 44969	72 31	0.60927 36149	2.41028 33038	0.30371 75832
32	1.93241 23839	73 32	0.60331 46378	2.50017 34479	0.31674 62424
33	1.99280 02709	74 29	0.59679 24144	2.59243 80185	0.33000 67656
34	2.05318 81579	75 23	0.58976 62623	2.68700 72681	0.34349 50157
35	2.11357 60449	76 14	0.58228 97341	2.78380 63098	0.35720 59222
36	2.17396 39318	77 2	0.57441 10737	2.88275 50068	0.37113 34754
37	2.23435 18188	77 48	0.56617 36598	2.98376 78796	0.38527 07211
38	2.29473 97058	78 31	0.55761 64315	3.08675 40315	0.39960 97596
39	2.35512 75928	79 11	0.54877 42910	3.19161 70942	0.41414 17461
40	2.41551 54798	79 49	0.53967 84809	3.29825 51932	0.42885 68946
41	2.47590 33668	80 25	0.53035 69362	3.40656 09346	0.44374 44843
42	2.53629 12538	80 58	0.52083 46089	3.51642 14148	0.45879 28694
43	2.59667 91408	81 30	0.51113 37664	3.62771 82525	0.47398 94906
44	2.65706 70278	82 0	0.50127 42646	3.74032 76441	0.48932 08915
45	2.71745 49148	82 28	0.49127 37968	3.85412 04436	0.50477 27366
90−r	Fψ	ψ	G(r)	C(r)	B(r)

$q = 0.403309306338378$, $\Theta 0 = 0.2457332317$, $HK = 1.8599580878$

B(r)	C(r)	G(r)	ψ	Fψ	90−r
1.00000 00000	7.56958 97180	0.00000 00000	90° 0′	5.43490 98296	90
0.99966 43156	7.56705 29325	0.01110 10463	89 56	5.37452 19426	89
0.99865 79343	7.55944 77064	0.02220 19579	89 53	5.31413 40556	88
0.99698 28696	7.54678 94142	0.03330 25985	89 49	5.25374 61686	87
0.99464 24694	7.52910 36233	0.04440 28272	89 45	5.19335 82816	86
0.99164 14052	7.50642 60102	0.05550 24979	89 42	5.13297 03946	85
0.98798 56557	7.47880 22428	0.06660 14556	89 38	5.07258 25077	84
0.98368 24869	7.44628 78301	0.07769 95354	89 34	5.01219 46207	83
0.97874 04272	7.40894 79407	0.08879 65593	89 30	4.95180 67337	82
0.97316 92390	7.36685 71893	0.09989 23340	89 26	4.89141 88467	81
0.96697 98856	7.32009 93943	0.11098 66481	89 22	4.83103 09597	80
0.96018 44944	7.26876 73054	0.12207 92686	89 17	4.77064 30727	79
0.95279 63165	7.21296 23044	0.13316 99380	89 13	4.71025 51857	78
0.94482 96828	7.15279 40797	0.14425 83704	89 8	4.64986 72987	77
0.93629 99559	7.08838 02759	0.15534 42469	89 3	4.58947 94117	76
0.92722 34802	7.01984 61207	0.16642 72118	88 58	4.52909 15247	75
0.91761 75278	6.94732 40301	0.17750 68667	88 53	4.46870 36377	74
0.90750 02426	6.87095 31948	0.18858 27648	88 47	4.40831 57507	73
0.89689 05812	6.79087 91481	0.19965 44048	88 41	4.34792 78637	72
0.88580 82522	6.70725 33191	0.21072 12232	88 35	4.28753 99767	71
0.87427 36532	6.62023 25717	0.22178 25863	88 29	4.22715 20897	70
0.86230 78063	6.52997 87323	0.23283 77807	88 22	4.16676 42027	69
0.84993 22921	6.43665 81080	0.24388 60035	88 15	4.10637 63157	68
0.83716 91826	6.34044 09975	0.25492 63501	88 7	4.04598 84287	67
0.82404 09732	6.24150 11966	0.26595 78012	87 59	3.98560 05417	66
0.81057 05141	6.14001 55012	0.27697 92084	87 51	3.92521 26547	65
0.79678 09414	6.03616 32083	0.28798 92768	87 42	3.86482 47677	64
0.78269 56083	5.93012 56192	0.29898 65471	87 33	3.80443 68807	63
0.76833 80165	5.82208 55452	0.30996 93739	87 23	3.74404 89937	62
0.75373 17477	5.71222 68183	0.32093 59022	87 12	3.68366 11067	61
0.73890 03962	5.60073 38100	0.33188 40408	87 1	3.62327 32197	60
0.72386 75024	5.48779 09576	0.34281 14317	86 50	3.56288 53328	59
0.70865 64877	5.37358 23026	0.35371 54168	86 37	3.50249 74458	58
0.69329 05904	5.25829 10413	0.36459 29992	86 24	3.44210 95588	57
0.67779 28032	5.14209 90885	0.37544 08012	86 10	3.38172 16718	56
0.66218 58136	5.02518 66588	0.38625 50154	85 55	3.32133 37848	55
0.64649 19448	4.90773 18631	0.39703 13507	85 40	3.26094 58978	54
0.63073 30999	4.78991 03252	0.40776 49715	85 23	3.20055 80108	53
0.61493 07081	4.67189 48167	0.41845 04298	85 6	3.14017 01238	52
0.59910 56732	4.55385 49133	0.42908 15883	84 47	3.07978 22368	51
0.58327 83254	4.43595 66732	0.43965 15347	84 27	3.01939 43498	50
0.56746 83750	4.31836 23371	0.45015 24856	84 6	2.95900 64628	49
0.55169 48696	4.20123 00521	0.46057 56791	83 44	2.89861 85758	48
0.53597 61539	4.08471 36196	0.47091 12546	83 20	2.83823 06888	47
0.52032 98326	3.96896 22668	0.48114 81189	82 55	2.77784 28018	46
0.50477 27366	3.85412 04436	0.49127 37968	82 28	2.71745 49148	45
A(r)	D(r)	E(r)	φ	Fφ	r

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SMITHSONIAN MISCELLANEOUS COLLECTIONS
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NEW TIMALINE BIRDS FROM THE EAST INDIES

BY
HARRY C. OBERHOLSER

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NEW TIMALINE BIRDS FROM THE EAST INDIES

By HARRY C. OBERHOLSER

Various investigations in the ornithological collection of the United States National Museum have resulted in the discovery of a number of undescribed forms. These birds are chiefly the result of Dr. W. L. Abbott's indefatigable collecting activity, and are mostly from the East Indies and the Malay Peninsula, with a few from outlying localities. Those described in the present pamphlet belong to the family Timaliidae.

All measurements are in millimeters, and have been taken as explained in the author's previous papers. Names of colors are based on Mr. Robert Ridgway's recently published "Color Standards and Color Nomenclature."

Furthermore, the writer's thanks are, as always, due Dr. Charles W. Richmond for numerous courtesies.

ALCIPPORNIS, nom. nov.

Type.—Alcippe cinerea Blyth nec Eyton (=*Hyloterpe brunneicauda* Salvadori.[1])

The above proposed name is intended to apply to the group commonly known as *Alcippe*, but which is now found to be without a tenable generic designation. This genus was first instituted by Blyth in 1844[2] by whom the following species were then included:

"*Alcippe cinerea?* (Eyton)"
Trichastoma affine Blyth
Timalia poioicephala Jerdon
Brachypteryx atriceps Jerdon
?Brachypteryx sepiaria Horsfield
?Brachypteryx bicolor Lesson

No type was originally designated, nor is any species to be considered type by tautonymy. The first legitimate type designation that I have been able to find is that of Gray, in 1846,[3] who selected *Trichastoma affine* Blyth, which is now a member of the genus *Horizillas* Oberholser (=*Malacopteron* Eyton). This means that *Hori-*

[1] Ann. Mus. Civ. Stor. Nat. Genova, ser. 1, XIV, April 22, 1879, p. 210. For explanation of this identification, see the next heading.

[2] Journ. Asiat. Soc. Bengal, XIII, pt. 1, No. 149, for May, 1844, p. 384.

[3] Genera of Birds, I, December, 1846, p. 209.

cillas (olim *Malacopteron*) must now be called *Alcippe* Blyth, unfortunate as this transfer of name may be found to be. For *Alcippe* Auct. nec Blyth the name *Alcippornis*,[1] nom. nov., may be used. The following species and subspecies are referable to this genus:

Alcippornis nepalensis nepalensis (Hodgson)
Alcippornis nepalensis fratercula (Rippon)
Alcippornis nepalensis yunnanensis (Harington)
Alcippornis peracensis (Sharpe)
Alcippornis hueti (David)
Alcippornis morrisonia (Swinhoe)
Alcippornis poioicephala poioicephala (Jerdon)
Alcippornis poioicephala phayrei (Blyth)
Alcippornis poioicephala brucei (Hume)
Alcippornis poioicephala haringtoniae (Hartert)
Alcippornis poioicephala magnirostris (Walden)
Alcippornis poioicephala davisoni (Harington)
Alcippornis pyrrhoptera (Bonaparte)
Alcippornis brunneicauda brunneicauda (Salvadori)
Alcippornis brunneicauda hypocneca (Oberholser)
Alcippornis brunneicauda eriphaea Oberholser
Alcippornis davidi (Styan)

ALCIPPORNIS BRUNNEICAUDA ERIPHAEA, subsp. nov.

Subspecific characters.—Similar to *Alcippornis brunneicauda brunneicauda* from Sumatra and the Malay Peninsula, but upper parts much more rufescent, posteriorly brighter, the pileum not grayish, but brown; lower surface darker, duller, and much more rufescent (less grayish), particularly on sides, flanks, and throat.

Description.—Type, adult male, No. 178218, U. S. Nat. Mus.; Liang Koeboeng (Grot), Borneo, March 25, 1894; Dr. J. Büttikofer. Pileum between olive brown and hair brown; back and scapulars, rather rufescent saccardo's umber; rump similar, but verging more toward the cinnamon brown of the upper tail-coverts; tail between prout's brown and mummy brown, the outer edgings of basal portion of rectrices argus brown; wings fuscous, the outer edgings of quills cinnamon brown, of coverts buffy brown; sides of head grayish drab; sides of neck rather brownish mouse gray; chin, throat, and upper breast, between tilleul buff and drab gray; sides of breast drab; sides of body similar, but tinged with buffy; flanks and crissum, dull grayish cream buff; lower breast and abdomen, dull buffy white; under wing-coverts and axillars cream white, the latter posteriorly a little mixed with drab; iris blue-gray; bill horn color; feet purplish gray.

[1] Ἀλκίππη, Alcippe; ὄρνις, bird.

Measurements of type.—Wing, 70.5 mm.; tail, 57.5; exposed culmen, 11; height of bill at base, 4.5; tarsus, 19.5; middle toe without claw, 11.5.

The very brownish pileum and cervix and the brownish anterior lower parts give this very well-characterized race the appearance of a distinct species. It differs from *Alcippornis brunneicauda hypocneca* of the Batu Islands, western Sumatra, in larger size, more brownish (less grayish) head and nape; more rufescent back and rump; darker, duller, and more rufescent lower parts.

This species has always been called *Alcippe cinerea* Blyth. The necessity for a change of its generic name has already been discussed above; but the readjustment of its specific designation also needs explanation. Blyth's name *Alcippe cinerea* [1] was originally used not as a new specific designation, but to indicate a doubtful reference of the bird that he had in hand and described (*i. e.*, the *Alcippe cinerea* of subsequent authors), to the *Malacopteron cinereus* of Eyton.[2] It of course cannot, under such circumstances, be used for Blyth's species.

There are, however, two tenable names for this bird, not usually cited in its synonymy. The *Napothera phaionota* of Sharpe,[3] is a manuscript name of Kuhl's, found on a specimen in the Leyden Museum, of which Sharpe gives no description, but which he states "is identical with *Alcippe cinerea* Blyth." This is thus virtually a naming of the bird described as *Alcippe cinerea* by Blyth.

A still earlier name is *Hyloterpe brunneicauda* Salvadori,[4] hitherto treated as though belonging to a form of *Muscitrea grisola* or a closely allied species. The brown tail, fuscous bill, and wing of 72 mm. show clearly, however, that it belongs rather to the species commonly known as *Alcippe cinerea*. In view of the above facts this species should now stand as *Alcippornis brunneicauda*. The forms at present recognized are:

Alcippornis brunneicauda brunneicauda (Salvadori)
Alcippornis brunneicauda hypocneca (Oberholser)
Alcippornis brunneicauda eriphaea Oberholser

MIXORNIS GULARIS CHERSONESOPHILA, subsp. nov.

Subspecific characters.—Similar to *Mixornis gularis connectens*, from southern Tenasserim, but larger; upper parts darker; flanks

[1] "*Alcippe cinerea?* (Eyton)" Blyth, Journ. Asiat. Soc. Bengal, XIII, pt. 1, No. 149, for May, 1844, p. 384 ("Singapore").

[2] Cf. also Blyth, *loc. cit.* p. 383.

[3] Notes Leyden Mus., VI, July, 1884, p. 178.

[4] Ann. Mus. Civ. Stor. Nat. Genova, Ser. 1, XIV, April 22, 1879, p. 210 (Ajer Mantcior, western Sumatra).

rather more deeply colored; and with the streaks on the throat much broader.

Description.—Type, adult male, No. 160543, U. S. Nat. Mus.; Trang, Lower Siam, February 14, 1897; Dr. W. L. Abbott. Crown and forehead chestnut, the latter slightly mixed with dark grayish; rest of upper surface between medal bronze and citrine, but upper tail-coverts between mummy brown and dresden brown; tail between prout's brown and mummy brown, with numerous shadowy darker bars, but the basal portion of the outer pairs of rectrices margined interiorly with rather pale brownish, and the rectrices edged basally on outer webs with brown between mummy brown and dresden brown; wings fuscous, the edgings of quills and superior coverts cinnamon brown; lores dusky; a narrow supra-loral stripe, extending to the posterior edge of the eye, citron yellow with obscure streaks of dusky; cheeks light yellowish olive, streaked obscurely with olivaceous; posterior sides of head and sides of neck, light citrine drab; lower surface citron yellow, paler posteriorly and shaded with gray on jugulum, the throat and jugulum streaked with brownish black; sides, flanks, and crissum, light citrine drab; lining of wing massicot yellow; "upper mandible dark leaden; lower mandible leaden blue; feet fleshy brown tinged with green."

Measurements of type.—Wing, 59.5 mm.; tail, 53; exposed culmen, 14; tarsus, 19.

This new subspecies, though intermediate between *Mixornis gularis connectens* of southern Tenasserim and *Mixornis gularis pileata* of Singapore, is yet sufficiently different to be worthy of recognition by name.

MIXORNIS GULARIS ARCHIPELAGICA, subsp. nov.

Subspecific characters.—Similar to *Mixornis gularis chersonesophila,* from Trang, Lower Siam, but upper parts much paler and more grayish (less rufescent); sides and flanks lighter; streaks on anterior lower parts much narrower.

Type.—No. 173211, U. S. Nat. Mus.; Domel Island, Mergui Archipelago, February 27, 1900; Dr. W. L. Abbott.

Measurements of type.—Wing, 61 mm.; tail, 54.5; exposed culmen, 13.5; tarsus, 18.

This race, which is apparently confined to the islands of the Mergui Archipelago, differs from *Mixornis gularis connectens* of the northern Malay Peninsula and Tenasserim (type locality, 10° North Latitude) in its larger size, lighter, much more grayish upper parts, and rather paler flanks.

MIXORNIS GULARIS INVETERATA, subsp. nov.

Subspecific characters.—Similar to *Mixornis gularis connectens,* but larger; paler and less rufescent (more grayish) above.

Type.—No. 249030, U. S. Nat. Mus.; Koh Kut Island, southeastern Siam, December 25, 1914; C. Boden Kloss. "Iris, yellow; upper mandible black; lower mandible plumbeous blue; feet greenish ochre."

Measurements of type.—Wing, 60.5 mm.; tail, 55; exposed culmen, 13; tarsus, 19; middle toe without claw, 13.5.

This race has been included with *Mixornis gularis connectens,* but comparison shows it separable on the above given characters. It resembles *Mixornis gularis chersonesophila,* from the southern and central Malay Peninsula, but differs in its paler, less rufescent (more grayish) upper parts, and somewhat narrower streaking on the anterior lower surface.

MIXORNIS GULARIS VERSURICOLA, subsp. nov.

Subspecific characters.—Resembling *Mixornis gularis inveterata* from Koh Kut Island, southeastern Siam, but smaller; upper parts darker and somewhat more rufescent (less grayish); and streaks on the anterior lower parts averaging heavier.

Type.—Adult male, No. 278480, U. S. Nat. Mus.; Da Bau, Southern Annam, March 22, 1918; C. Boden Kloss. "Iris pale yellow; maxilla black; mandible plumbeous; feet ochreous brown."

Measurements of type.—Wing, 56.5 mm.; tail, 49.5; exposed culmen, 13.5; tarsus, 21; middle toe without claw, 12.5.

This new race differs from *Mixornis gularis connectens* in its more heavily streaked anterior lower parts, darker, more grayish sides and flanks, somewhat darker upper parts, and rather larger size.

Some years ago the present writer called attention [1] to the preoccupation and consequent invalidity of the name *Motacilla gularis* Raffles.[2] This was done on the supposition that *Motacilla gularis* Raffles was the earliest published technical name for the species up to that time commonly called *Mixornis gularis,* and its name was accordingly changed to *Mixornis pileata* Blyth. A recent examination, however, of Horsfield's "Researches in Java" [3] brought to light the fact that Horsfield, in describing this bird as *Timalia gularis* [4] (taking

[1] Smithsonian Misc. Coll., vol. LX, No. 7, October 26, 1912, p. 9.

[2] Trans. Linn. Soc. Lond., XIII, pt. 2, 1822, after October, p. 312.

[3] Cf. Oberholser, Proc. Biol. Soc. Wash., XXXIV, December 21, 1921, pp. 163-166.

[4] Zool. Researches in Java, pt. III, February, 1822, pl. [42], fig. [2], and text p. [1] ("Island of Sumatra").

the specific name from *Motacilla gularis* in the manuscript of Raffles' paper about to be published in the Transactions of the Linnaean Society of London[1]), anticipated Raffles' name, because the part of " Researches in Java " containing the description and plate of *Timalia gularis* appeared in February, 1822, in advance of that part of the Transactions of the Linnean Society containing this portion of Raffles' article, which followed in November or December, 1822. The specific name *gularis* must, therefore, be credited to Horsfield instead of to Raffles; and since *Timalia gularis* Horsfield is not preoccupied by *Motacilla gularis* Gmelin,[2] as is *Motacilla gularis* Raffles, nor found otherwise untenable, it must be continued in use for the species.

MIXORNIS BORNENSIS RUFICOMA, subsp. nov.

Subspecific characters.—Similar to *Mixornis bornensis bornensis*, but paler, and usually more reddish brown above, especially on the pileum; and with the streaks on the anterior lower parts averaging narrower.

Description.—Type, adult male, No. 180591, U. S. Nat. Mus.; Tanjong Tedong, Banka Island, June 4, 1904; Dr. W. L. Abbott. Forehead deep mouse gray, the shafts of the feathers blackish; crown and occiput between chestnut and auburn; rest of upper parts between auburn and amber brown, but upper tail-coverts auburn; tail between fuscous and sepia, but the outer edges of basal portion of rectrices auburn; wings fuscous, the inner margins of the quills basally tilleul buff, the outer edgings of quills and coverts auburn; eyering, lores, and subocular region deep mouse gray; posterior sides of head between chestnut and auburn; sides of neck like the back; chin and throat, creamy white, streaked with brownish black; middle of breast and of abdomen barium yellow, the former broadly, the latter very narrowly, streaked with reddish brown and olivaceous; sides and flanks, grayish olive, obscurely streaked with darker; crissum grayish olive, the centers of the feathers darker and brownish; lining of wing pale ivory yellow.

Measurements of type.—Wing, 61 mm.; tail, 56; exposed culmen, 14.5; tarsus, 19.

MIXORNIS BORNENSIS PONTIA, subsp. nov.

Subspecific characters.—Resembling *Mixornis bornensis bornensis*, but with the streaks on the lower parts much narrower.

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[1] From this manuscript Horsfield quotes as follows: "*Motacilla gularis*, Sir T. S. Raffles's MS. Cat. of a Zool. Coll. made in Sumatra."

[2] Syst. Nat., I, pt. 2, 1789, before April 20, p. 997.

Type.—Adult female, No. 181538, U. S. Nat. Mus., Pulo Laut, off southeastern Borneo, December 18, 1907; Dr. W. L. Abbott.

Measurements of type.—Wing, 62.5 mm.; tail, 57; exposed culmen, 13; tarsus, 20.5.

This race may be distinguished from *Mixornis bornensis ruficoma,* of Banka Island, by its darker, duller, less rufescent (more sooty) upper surface, paler lower parts, and narrower streaks on the throat and breast. It is apparently confined to Pulo Laut.

STACHYRIS NIGRICEPS DIPORA, subsp. nov.

Subspecific characters.—Resembling *Stachyris nigriceps nigriceps,* from Nepal, but bill stouter; lower parts paler; and upper surface lighter, more grayish.

Description.—Type, adult male, No. 169865, U. S. Nat. Mus.; Khaw Sai Dow, Trang, Lower Siam, February 2, 1899; Dr. W. L. Abbott. Pileum fuscous black, conspicuously streaked with dull white; remainder of upper parts between brownish olive and light brownish olive, the rump and upper tail-coverts a little paler; tail olive brown, the outer edges of the rectrices somewhat more rufescent; wings fuscous, but the outer edgings of quills and coverts like the back; lores mouse gray; auriculars and subauricular region tawny olive; sides of neck like the back; chin pale mouse gray; upper throat mouse gray, with on each side a dull white spot, all bordered laterally and posteriorly by a line of chaetura drab; remainder of lower surface light buckthorn brown, but paler on abdomen, and shading to isabella color on flanks and crissum; lining of wing dull warm buff mixed with light brownish gray; "upper mandible black; lower mandible dark horny bluish."

Measurements of type.—Wing, 59 mm.; tail, 51.5; exposed culmen, 15; height of bill at base, 6; tarsus, 21; middle toe without claw, 13.

This subspecies may be distinguished from *Stachyris nigriceps davisoni* by its lighter, less tawny (more grayish) upper and lower parts, and less rufescent edges of the secondaries. From *Stachyris nigriceps coltarti* it is readily separable by its pale throat alone.

CYANODERMA ERYTHROPTERA ERIPELLA, subsp. nov.

Subspecific characters.—Similar to *Cyanoderma erythroptera erythroptera,* from Singapore, but upper surface decidedly darker; anterior lower parts darker, more blackish; posterior lower parts darker and more dingy.

Description.—Type, adult male, No. 181301, U. S. Nat. Mus.; Upper Siak River, northeastern Sumatra, November 23, 1906; Dr.

W. L. Abbott. Sinciput dark neutral gray; remaining upper parts rather light and somewhat reddish argus brown, but the upper tail-coverts chestnut; tail bister, the basal portion of outer edges of rectrices chestnut; wings fuscous, but tertials bister, the outer edges of all the quills chestnut, the superior wing-coverts burnt sienna; sides of head and of neck, with chin, throat, and jugulum, dark neutral gray; breast and sides of body neutral gray, posteriorly washed with pale isabella color; abdomen pale isabella color tinged with grayish; crissum isabella color; lining of wing pinkish buff; "orbital skin cobalt; gular skin pale turquoise."

Measurements of type.—Wing, 60 mm.; tail, 50.5; exposed culmen, 13.5; height of bill at base, 5.5; tarsus, 19; middle toe without claw, 11.5.

CYANODERMA ERYTHROPTERA APEGA, subsp. nov.

Subspecific characters.—Similar to *Cyanoderma erythroptera eripella,* from Sumatra, but with wing and tail shorter; crown nearly all plain slate color; rest of upper parts of a lighter, brighter ferruginous; throat and breast somewhat lighter; posterior lower surface darker and duller.

Type.—Adult male, No. 180588, U. S. Nat. Mus.; Tanjong Tedong, Banka Island (southeast of Sumatra), June 3, 1904; Dr. W. L. Abbott.

Measurements of type.—Wing, 57 mm.; tail, 44.5; exposed culmen, 14, height of bill at base, 6; tarsus, 19; middle toe without claw, 13.

The original description of *Cyanoderma erythroptera*[1] was based on the bird from Singapore, and it therefore must be applied to the race inhabiting the Malay Peninsula. Synonymous are *Timalia pyrrhophaea* Hartlaub,[2] *Brachypteryx acutirostris* Eyton,[3] and *Timalia pyrrhoptera* Bonaparte.[4]

The generic name *Cyanoderma* is commonly used as of neuter gender, and as such was originally proposed, but being a compound appellative, can be only masculine or feminine. Its first usage as either of these genders was feminine by Hume and Davis,[5] and as such it thus should therefore remain.

[1] *T[imalia]. erythroptera* Blyth, Journ. Asiat. Soc. Bengal, XI, pt. II, No. 128, August 1842, p. 794 ("Singapore").

[2] Rev. Zool., VII, for November (=December), 1844, p. 402 ("Malacca. Sumatra"; we select Malacca as the type locality).

[3] Ann. and Mag. Nat. Hist., ser. 1, XVI, October, 1845, p. 228 ("Malacca").

[4] Consp. Gen. Avium, I, June 24, 1850, p. 217 (Boie MS.) (based on "[Timalia] erythroptera Blyth.—Journ As. Soc. XI p. 794"; therefore the type locality is the same, *i. e.,* Singapore).

[5] Stray Feathers, VI, June, 1878, p. 269.

ANUROPSIS MALACCENSIS DRYMODRAMA, subsp. nov.

Subspecific characters.—Similar to *Anuropsis malaccensis malaccensis* from the southern Malay Peninsula, but upper surface very much darker, and lower parts brighter.

Description.—Type, adult male, No. 181304, U. S. Nat. Mus.; Sungei Mandau, eastern Sumatra, November 29, 1906; Dr. W. L. Abbott. Upper surface brussels brown, but the head darker, with blackish shaft stripes, the extreme anterior portion of forehead dull grayish, the upper tail-coverts between auburn and chestnut; tail between mars brown and prout's brown, the broad outer edges of the rectrices basally like the upper tail-coverts; wings fuscous, the edgings of quills and coverts brussels brown, but the lesser coverts lighter and more grayish; lores between smoke gray and pale mouse gray; superciliary stripe, suborbital region, and sides of head except auriculars, deep mouse gray; auriculars dark mouse gray, but inferiorly blackish mouse gray merging into a blackish rictal streak; sides of neck like the cervix, but more grayish inferiorly; lower parts white, but jugulum, sides of breast and of body, together with flanks, crissum, under wing-coverts and axillars, cinnamon buff, paler and duller on jugulum and sides of breast, the sides of breast and of jugulum a little washed with brownish gray.

Measurements of type.—Wing, 69 mm.; tail, 37; exposed culmen, 15; tarsus 28.

This well-marked race seems to be confined to the mainland of Sumatra, since birds from the adjacent islands belong to different subspecies.

ANUROPSIS MALACCENSIS DRIOPHILA, subsp. nov.

Subspecific characters.—Similar to *Anuropsis malaccensis malaccensis,* but paler above and below.

Type.—Adult male, No. 169877, U. S. Nat. Mus.; Khaw Sai Dow, Trang, Lower Siam, February 19, 1899; Dr. W. L. Abbott.

Measurements of type.—Wing, 67.5 mm.; tail, 35; exposed culmen, 16; tarsus, 28.

This is the palest of all the forms of the species. It differs from the Sumatra bird above described as *Anuropsis malaccensis drymodrama,* much as does *Anuropsis malaccensis malaccensis,* but even more decidedly. It apparently extends geographically no farther south than Lower Siam, for birds from Pahang, though somewhat intermediate, belong with the Malaccan race.

ANUROPSIS MALACCENSIS DOCIMA, subsp. nov.

Subspecific characters.—Resembling *Anuropsis malaccensis drymodrama,* from Sumatra, but upper parts, including the wings, much less rufescent (more slaty brown), and rather darker; sides of head darker; the ochraceous of sides and flanks much deeper and brighter.

Type.—Adult female, No. 180584, U. S. Nat. Mus.; Tanjong Tedong, Banka Island (southeastern Sumatra), June 1, 1904; Dr. W. L. Abbott.

Measurements of type.—Wing, 61.5 mm.; tail, 26.5; exposed culmen, 14; tarsus, 28.

This race is very different from all the other forms of *Anuropsis malaccensis* in its much more slaty (less rufescent) upper parts, being in this respect more like the Bornean bird than like any other.

DRYMOCATAPHUS NIGROCAPITATUS NYCTILAMPIS, subsp. nov.

Subspecific characters.—Similar to *Drymocataphus nigrocapitatus nigrocapitatus* from the Malay Peninsula, but with the upper parts darker and duller.

Description.—Type, adult male (?), No. 180572, U. S. Nat. Mus.; Bukit Parmassang, Banka Island, June 15, 1904; Dr. W. L. Abbott. Pileum dull black; cervix, back, and scapulars, mars brown; rump and upper tail-coverts, auburn; inner webs of rectrices blackish mars brown, their outer webs mars brown; wings sepia, the exposed portions when closed mars brown; bend of wing russet; sides of head, including lores, deep mouse gray, streaked obscurely with black and finely with whitish, similar whitish streaks forming a fairly well-defined superciliary stripe; sides of neck like the back; chin and throat, white; jugulum, breast, and middle of abdomen, between tawny and ochraceous tawny; sides of body, flanks, crissum, and lining of wing, between russet and prout's brown.

Measurements of type.—Wing, 68 mm.; tail, 52.5; exposed culmen, 15.5; tarsus, 19; middle toe without claw, 16.5.

Representatives of *Drymocataphus nigrocapitatus* from Sumatra belong also to this new subspecies.

All the synonyms of *Drymocataphus nigrocapitatus* known to the writer belong under the typical race, so the Banka bird is apparently unnamed. These names, including that of the typical form, are:

Brachypteryx nigrocapitata Eyton;[1] *Bessethera barbata* Cabanis;[2] and *Turdirostris nigrocapistratus* Bonaparte.[3]

MALACOCINCLA ABBOTTI ERITORA, subsp. nov.

Subspecific characters.—Similar to *Malacocincla abbotti baweana* Oberholser,[4] but upper surface darker, more rufescent (less grayish); sides of head and neck less grayish; lower parts darker and duller, the flanks, with sides of breast and of body, much more strongly tinged with dull buffy brown; crissum duller.

Description.—Type, adult male, No. 180586, U. S. Nat. Mus.; Buding Bay, Billiton Island, August 6, 1904; Dr. W. L. Abbott. Upper surface between brownish olive and olive brown, becoming somewhat darker on the pileum (where the feathers have pale buffy shaft streaks), and slightly more rufescent on the rump; upper tail-coverts cinnamon brown; rectrices sepia; primaries, secondaries, and primary coverts, brown, between olive brown and fuscous, their outer webs, together with both webs of tertials, greater, median, and lesser wing-coverts, brown like the back; lores and superciliary stripe, between mouse gray and deep mouse gray, mixed more or less with pale mouse gray; rest of sides of head and of neck buffy brown, the auriculars somewhat streaked with the brown of the back, and with narrow, inconspicuous shaft markings of pale buffy; chin and throat, grayish white, the latter buffy grayish on its sides; upper breast dull light pinkish buff; lower breast dull cream color, deepening on lower abdomen into pale ochraceous buff; crissum clay color; sides of breast, sides of body, together with flanks and thighs, buffy brown; lining of wing light pinkish cinnamon, somewhat mixed with light brownish; inner margins of outer secondaries and inner primaries dull vinaceous buff; "iris pale reddish brown; upper mandible dark horn brown; lower mandible leaden; feet pale purplish fleshy."

Measurements of type.—Wing, 74 mm.; tail, 49; exposed culmen, 18; tarsus, 26.5; middle toe without claw, 16.

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[1] Proc. Zool. Soc. Lond., VII, for 1839 (November, 1839), p. 103 ("Malaya" [=Malay Peninsula]).

[2] *B[essethera] barbata* Cabanis, Mus. Heinean., Theil I, 1851, after October 23, p. 76 (in text of footnote) ("wahrscheinlich von den Sunda Inseln oder Malacca." We designate *Malacca* as the type locality).

[3] Compt. Rend. Acad. Sci., XXXVIII, No. 3, January 23, 1854, p. 59 (Verreaux MS.) ("Malacca").

[4] *Malacocincla abbotti baweana* Oberholser, Proc. U. S. Nat. Mus., vol. 52, Feb. 8, 1917, p. 194 (Bawean Island, Java Sea).

With this addition there are now six races of *Malacocincla abbotti:*

1. *Malacocincla abbotti abbotti* Blyth.—Nepal and Assam to Tenasserim.
2. *Malacocincla abbotti olivacea* (Strickland).—Malay Peninsula.
3. *Malacocincla abbotti sirensis* Oberholser.—Pulo Mata Siri, Java Sea.
4. *Malacocincla abbotti büttikoferi* Finsch.—Borneo.
5. *Malacocincla abbotti eritora* Oberholser.—Billiton Island.
6. *Malacocincla abbotti baweana* Oberholser.—Bawean Island, Java Sea.

AETHOSTOMA ROSTRATA AETHALEA, subsp. nov.

Subspecific characters.—Similar to *Aethostoma rostrata buxtoni,*[1] of southern Sumatra, but less rufescent (more sooty) and somewhat darker above; and with the crissum a little more buffy.

Description.—Type, adult male, No. 180268, U. S. Nat. Mus.; Pulo Karimon Anak, eastern Sumatra, June 3, 1903; Dr. W. L. Abbott. Upper parts between prout's brown and mummy brown, becoming somewhat more rufescent on the rump and upper tail-coverts, the longest feathers of the latter, chestnut; tail dark bister, the outer edges except at tips broadly chestnut; wings between olive brown and clove brown, but the outer webs of the quills and edgings of the superior wing-coverts, mars brown, and the lesser coverts like the back; inner edges of basal portion of quills dull tilleul buff; lores light buff; rest of sides of head light buffy grayish; sides of neck like the back; lower parts white, the sides of breast and of body, and the flanks, washed with light grayish; crissum pale warm buff; thighs buffy brown; lining of wing dull pinkish buff; "iris clear brown."

Measurements of type.—Wing, 75.5 mm.; tail, 53.5; exposed culmen, 17; height of bill at base, 5; tarsus, 26; middle toe without claw, 16.5.

Although this new race is apparently confined to Pulo Karimon Anak, off the eastern coast of Sumatra, it seems to be different from *Aethostoma rostrata buxtoni,* with which we consider, at least for the present, the bird from the not far removed Great Karimon Island and the neighboring coast of Sumatra to belong.

AETHOSTOMA ROSTRATA PAGANICA, subsp. nov.

Subspecific characters.—Similar to *Aethostoma rostrata aethalea,* from Pulo Karimon Anak, but smaller; upper parts, flanks, and particularly the sides of head, darker.

[1] The bird currently called *Aethostoma büttikoferi* (*Trichostoma büttikoferi* Vorderman, Natuurk. Tijdsch. Nederl.-Ind., LI [ser. 8, XII], 1892, p. 230; "Lampongs, Zuid-Sumatra") should be known as *Aethostoma rostrata buxtoni* Tweeddale (*Brachypteryx buxtoni* Tweeddale, Proc. Zool. Soc. Lond., 1877, pt. 2, August 1, 1877, p. 367; "District of Lampong, S. E. Sumatra"), since the latter name has priority and is of identical application; and the bird is clearly a subspecies of *Aethostoma rostrata.*

Type.—Adult male, No. 181308, U. S. Nat. Mus.; Upper Siak River, eastern Sumatra, November 21, 1906; Dr. W. L. Abbott.

Measurements of type.—Wing, 69 mm.; tail, 51; exposed culmen, 17; height of bill at base, 5; tarsus, 26; middle toe without claw, 16.

This race from northeastern Sumatra differs from *Aethostoma rostrata buxtoni* from southern Sumatra as from *Aethostoma rostrata aethalea,* though not quite so decidedly.

With the above additions the recognizable subspecies of *Aethostoma rostrata* are as follows:

1. *Aethostoma rostrata rostrata* (Blyth).—Singapore Island.
2. *Aethostoma rostrata leucogastris* (Davison).—Southern Malay Peninsula to Tenasserim.
3. *Aethostoma rostrata aethalea* Oberholser.—Pulo Karimon Anak, eastern Sumatra.
4. *Aethostoma rostrata paganica* Oberholser.—Northeastern Sumatra.
5. *Aethostoma rostrata buxtoni* (Tweeddale).—Southern Sumatra.
6. *Aethostoma rostrata macroptera* (Salvadori).—Borneo.

The generic term *Aethostoma* Sharpe, though treated by its original proposer as of neuter gender, is not properly so used. Being a compound appellative, it must be either masculine or feminine; and, in view of the feminine form of its ending, is probably better used as of this gender.

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REMAINS OF MAMMALS FROM CAVES IN THE REPUBLIC OF HAITI

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REMAINS OF MAMMALS FROM CAVES IN THE REPUBLIC OF HAITI

By GERRIT S. MILLER, Jr.

On March 4 and 5, 1921, Mr. J. S. Brown and Mr. W. S. Burbank, while engaged in geological surveys for the Republic of Häiti, under the direction of the U. S. Geological Survey, examined two caves at the northwest end of the Republic of Haiti. Their object was not to undertake a thorough exploration of the deposits on the cave floors but merely to determine whether or not these deposits contained the remains of mammals representing a fauna older than that which has been found in the kitchen middens of the Dominican Republic.[1] Such older faunas are known in Cuba, Porto Rico and Jamaica, but none has hitherto been recorded from the island of Haiti. The bones obtained by Mr. Brown and Mr. Burbank have been submitted to me for examination and report.

Concerning the caves Mr. Brown writes:

The caves from which these bones were taken are located on the slopes of the mountains north of the northwest end of the central plain of Haiti, northeast of the town of St. Michel de l'Atalye, commonly known as St. Michel, and northwest of the large American-owned plantation, managed by Mr. H. P. Davis and commonly known to Americans as the Davis Plantation. By the Haitians this plantation is called l'Atalye. The distance from the caves to the coast in an air line is about 40 kilometers.

The larger cave is about 3 or 4 kilometers northeast of St. Michel and an equal distance northwest of the Davis Plantation. Its altitude is about 600 meters above sea-level, nearly 200 meters above the central plain. It is one of a large number of caves evidently formed at a fairly remote period when hydrologic conditions differed considerably from those obtaining at present. Many of the caves including the one here referred to are located high on the mountain slope without any apparent relation to present drainage, either surface or subterranean. The caves are dry, there is little evidence of active solution, and they are apparently being filled with residual clay, rain-wash, and general cave breccia material. Many of them contain a thick floor cover of guano left by the thousands of bats that now inhabit or recently have inhabited the caves. The large cave mentioned above is about 40 meters in length, and from 10 to 20 meters in width and height and contains several large columns formed by the juncture of stalactites and stalagmites. It has two large openings separated by a pillar, and a third small opening on the

[1] See Miller, Smithsonian Misc. Coll., Vol. 66, No. 12. December 7, 1916.

sloping hillside, which afford entrance nearly on the plane of the floor. Near the rear there is also an opening or skylight, about 5 meters in diameter, to the surface, through which long hanging roots of the figuier tree grow down into the cave. Rocks and surface wash falling down the skylight have made a small cone of coarse debris beneath it. The cave is the scene of occasional Voodoo ceremonies and contains a few sacred offerings of porcelain ware, food, and money left by the Haitians. Near the center of the cave in the middle of one of the largest open spaces an excavation 1.6 meters deep was made. The hole was a little more than a meter in diameter. Only firm, dry, reddish dirt with a rather granular appearance was encountered. There was very little guano and no bones whatever, the rock floor of the cave appears to be very deep down here, and was not approached by this pit. Another hole was made very near the extreme rear end of the cave about 1 meter from the wall and 5 meters from the cone of debris beneath the skylight. This hole was about a meter in diameter and less than a meter in depth (2½ feet). The material was full of rocks and boulders and hard to excavate. Near the surface a living root of a tree, 15 centimeters in diameters was encountered and the hole was dug partly around it. From very near the surface downwards the hole yielded bones of a small rodent, and about half a meter below the surface a larger vertebrate bone was found.

The smaller cave is located about 2 kilometers northnorthwest of the Davis Plantation and perhaps 3 kilometers east of the larger cave. It is on the south side of a deep dry ravine. The present opening of the cave is somewhat spherical in shape and its diameter is about 30 meters. The roof is arched, all in one chamber, and the floor is convex, the rear half being nearly bare rock, partly covered by a few inches of guano left by bats. The mouth, still large but originally much larger, is choked by a great pile of debris from the cliff that rises above it. This debris has rolled inward as well as outward, covering the floor of the front part of the cave. The excavation here was made at the lowest part of the cave, adjacent to one of the steep vertical rock walls, following down the wall for 1.6 meters. The hole was about 1½ meters in diameter. At the bottom the rock wall sloped inward rapidly and when excavation was stopped the entire bottom of the hole was on rock. The material excavated was about 50 to 60 percent loose stones, with just enough dirt and guano to fill the space between. The upper half meter of this hole yielded no bones whatever, as the material was apparently debris recently slumped in. Below the half meter mark small rodent bones appeared in increasing numbers all the way to the bottom, many resting on the rock floor. At a depth of almost a meter several larger bones were found in undisturbed material, and near the bottom imperfect slivers of a longer bone apparently nearly replaced by calcareous material. In both caves the bones of the small rodents were abundant and many duplicate fragments were rejected. The larger bones, however, are rare, and thorough examination probably would be necessary to secure a satisfactory collection.

In addition to various fragments too imperfect to permit of exact determination the collection includes remains of the following mammals.

RODENTS

ISOLOBODON PORTORICENCIS ALLEN

Large cave: Mandibles, 3 (2 right, 1 left). Probably referable to this species are 2 femora (1 right, 1 left), 1 broken innominate, 3 upper incisors and 6 lower incisors.

Smaller cave: Mandibles, 9 (2 right, 7 left). Probably referable to this species are several fragments of long bones, 6 broken innominates, 2 broken scapulæ, a few phalanges, 5 upper incisors, 9 lower incisors.

APHÆTREUS gen. nov. (Echimyidæ)

Type.—*Aphætreus montanus* sp. nov.

Characters.—Mandible and its teeth resembling those of *Isolobodon* or *Plagiodontia.* Mandibular cheekteeth prismatic, growing from persistent pulps, their essential structure as in the two related genera but the entire toothrow appearing as if compressed antero-posteriorly with the result that the dentine and cement spaces are narrowed, the enamel plates are brought closer together, and the crown of each tooth becomes obviously wider than long instead of apparently longer than wide; inner reentrant angle confluent with postero-external angle, so that the enamel pattern is made to consist of an anterior *Y* and a posterior *I* completely isolated from each other by a band of cement; m_3 nearly as large as m_2.

Remarks.—While the general features of the mandible and teeth indicate that *Aphætreus* is allied to *Plagiodontia* and *Isolobodon* the exact relationship of the genus cannot be determined until the maxillary teeth are known. The increased width and compact structure of the crowns, the large size of m_3, the narrowness of the dentine and cement plates, and the division of the enamel pattern into two separate parts are all specialized features as compared with the conditions found in the two better known genera. All but the last could have been derived with equal facility from a structure similar to that occurring in either genus; the peculiarity of the enamel pattern, however, appears to have come from a type resembling *Isolobodon* rather than *Plagiodontia.* In these genera the maxillary teeth differ strikingly from each other but the mandibular teeth are scarcely distinguishable except by the relative depths of the inner and outer reentrant angles. The outer angle in *Plagiodontia,* extends across about one-third of the width of the crown, so that it meets the much longer posterior reentrant from the inner side at a point conspicuously ectad to the middle of the crown. In *Isolobodon,* however, it extends more than half way across, so that its length is greater than that of the corresponding inner angle; the point of meeting is therefore entad to the middle of the crown. In *Aphætreus* the two opposed reentrants have joined so as to isolate the posterior segment of the enamel pattern, but there is a slight narrowing of the cement band and a bending toward each other of the enamel plates in the region where the points of the reentrants touch in *Isolobodon*. Nothing of the kind occurs at the level where contact takes place in *Plagiodontia*. Another feature which suggests *Isolobodon* is the character of the cement surfaces exposed on the sides of the teeth. In *Plagiodontia* these surfaces are irregularly and minutely pitted; in *Isolobodon* and *Aphætreus* they are transversely ridged.

Division of the enamel pattern of the lower cheekteeth into the elements seen in *Aphætreus* is unusual; but it occurs in various Hystricoid genera which are not necessarily near allies of the present genus or of each other, as *Chinchilla, Dactylomys, Amblyrhiza* and some species of *Echimys*.

APHÆTREUS MONTANUS sp. nov.

Type.—Mandible with full set of cheekteeth, No. 10733 U. S. National Museum. Collected in the larger of the two caves northeast of St. Michel de l'Atalye, northwest end of the Central Plain, Republic of Haiti, by J. S. Brown and W. S. Burbank.

Measurements.—Type: from sigmoid notch to upper border of alveolus of incisor, 45 + mm. (alveolus slightly imperfect); depth at middle of m_3, 6.4; diastema, 11 +; mandibular toothrow (alveoli), 20.0; mandibular toothrow (crowns), 20; crown of first lower molar, 4.2 x 5.2 (5.2 x 5.0);[1] crown of second lower molar, 4.4 x 5.4 (4.8 x 4.8); crown of third lower molar, 4.8 x 4.8 (4.0 x 3.8).

Specimens examined.—Large cave: Mandibles, 2 (right), one with complete set of cheekteeth the other (No. 10734) lacking pm_4 and m_1. Perhaps referable to this species are 2 femora, larger than those supposed to represent *Isolobodon*.

ITHYDONTIA gen. nov. (Echimyidæ)

Type.—*Ithydontia levir* sp. nov.

Characters.—General structure of lower molars as in *Isolobodon* and *Plagiodontia*, but shaft of tooth more compressed antero-posteriorly, and reentrant angle of outer side extending directly inward, without backward slant, its extremity coming in contact with anterior instead of posterior reentrant angle of inner side. Cement transversely ridged on exposed surface of shaft as in *Isolobodon*.

[1] Measurements in parenthesis are those of a specimen of *Plagiodontia* (No. 200412) of approximately equal size.

Remarks.—Though this genus is based on two isolated teeth only its characters appear to be well defined. The curvature of the shaft and the position of the worn surface of the crown on the summit of the shaft exactly coincide with these features in the first and second lower molars of *Isolobodon.* Oriented according to them the teeth in the two genera show no obvious points of difference except that the longitudinal ridges on the inner side of the shaft are wider in *Isolobodon.* The enamel pattern, however, has the peculiar characters that have been described. As in *Isolobodon* the anterior reentrant fold is the longer of the two on the inner side, but instead of curving rapidly forward so as to come almost or quite in contact with the enamel of the anterior wall of the shaft, it extends obliquely inward and backward, meeting the tip of the outer reentrant at a point not far ectad to the middle of the crown. The postero-external fold is directed almost straight inward, without the forward curve which the same fold shows in *Isolobodon.*

That these peculiarities are not a mere abnormal individual development of *Isolobodon* seems sufficiently indicated by their similarity in two teeth from opposite sides and from different individuals, as well as by the absence of tendencies of a similar kind in the 34 jaws which contain teeth among our series of *Isolobodon* remains.

ITHYDONTIA LEVIR sp. nov.

Type.—A right mandibular tooth probably m_1 or m_2, No. 10735 U. S. National Museum. Collected in the larger of the two caves northeast of St. Michel de l'Atalye, northwest end of the central Plain of Haiti, by J. S. Brown and W. S. Burbank.

Characters.—An animal about the size of *Isolobodon portoricensis* Allen; shaft of lower molar, type (right), 2.8 x 4.0 mm., second specimen (left) 3.0 x 4.6.

Specimens examined.—Two lower molars (one right, one left), both from the larger cave. One (the type) was found loose among the small miscellaneous bones, the other was imbedded, near a broken mandible of *Isolobodon,* in a small mass of matrix adhering to the dorsal vertebra of the ground sloth. The second specimen (No. 10736) represents an older individual than the type.

BROTOMYS VORATUS Miller (?)

Larger cave: Three femora (2 right, 1 left).

Smaller cave: A right upper incisor, and three imperfect humeri.

In the absence of skulls and cheekteeth the identification of *Brotomys* among the remains collected in the caves is uncertain. The femora and humeri resemble specimens from the kitchen middens of San Pedro de Macoris, Dominican Republic, the only locality at which the species has hitherto been found. The incisor is smaller than the corresponding tooth of the type, but it shows no obvious peculiarities in structure. It is not the tooth of an introduced rat.

GROUND SLOTH

MEGALOCUUS? sp?

Larger cave: One nearly perfect caudal vertebra, and one imperfect vertebra probably a dorsal; also a fragment which appears to be the proximal end of the radius of a young animal.

Smaller cave: Two imperfect caudal vertebræ. The proximal end and a fragment of the shaft of a rib may have come from the same individual.

The animal appears to be about the size of the Porto Rican *Acratocnus,* but the caudal vertebræ differ in so many details of form from corresponding bones lent me by the American Museum of Natural History through Dr. Matthew and Mr. Lang that there is little probability of generic identity between the two sloths. Dr. Matthew has kindly examined the vertebra from the larger cave. He regards it as representing an animal nearly related to *Megalocnus* of Cuba, though not certainly a member of the same genus. Measurements: Largest caudal vertebra (from larger cave), probably about the sixth of the series (No. 10740); length of centrum, 18 mm.; anterior face of centrum, 19 x 16; posterior face of centrum, 20.5 x 15.5; neural canal, 6.5 x 4.4; greatest width from tip to tip of transverse processes, 46; width of transverse process at middle, 12; depth including posterior zygapophysis, 27. Dorsal vertebra (No. 10739); centrum, 24 x 19; neural canal, 23.6 x 15.

MAN

Smaller cave: The head of a left human femur (No. 10743) was found at a depth of about a meter in undisturbed material associated with the caudal vertebræ of the Ground Sloth and the rib which I suppose to represent the same animal. Its substance is lighter and less infiltrated with mineral matter than the sloth bones. From the same excavation was taken a small fragment of chipped stone (chert) which Dr. Walter Hough has identified as an artifact. The exact level at which this was found was not noted.

UNIDENTIFIED MAMMALS

Smaller cave: Three fragments from a foot (No. 10744) and one piece of a large bone (No. 10745) represent mammals that I have been unable to identify.

The parts of the foot are a broken metapodial and two basal phalangeal extremities, probably the opposite ends of one bone. The piece of metapodial measures: Length 56 mm., greatest diameter of imperfect head about 10.5, least diameter of shaft 5.4. Phalanx: width at base, 11.0; height at base (median), 10.0; width of distal extremity, 9.2; depth of distal extremity at middle 4.6, at side 5.4; width of shaft 10 mm. behind extremity, 6±. In size and form the bones have some resemblances to the corresponding parts in man, seal, and capybara; but the differences from all three are such as to preclude identity. It seems not improbable that they represent a large unknown rodent.

The fragment of large bone is 110 mm. long, 45 mm. wide and 19 mm. thick. In general form it is not unlike a section from the rib of a small finback whale in the region of greatest curvature near the head, but its structure is obviously that of the bone of a land mammal. There is an inner area of loose spongy tissue and an outer dense wall from which, at the broken edges, the spongy material flakes along definite planes of cleavage. The wall varies in thickness from 2.5 to 6 mm. This structure, as well as the condition of the bone, is essentially as in the rib of the small ground sloth from the same cave. A suggestion of ground sloth is also found in the form of the fragment when viewed from the broader side; the general outline is then somewhat like the median portion of the femur of *Acratocnus* in Anthony's figure 2 of plate 73 (Mem. Am. Mus. Nat. Hist., N. S., vol. 2, 1918), though the size indicates an animal much larger than the Porto Rican sloth. The fragment is, however, actually as well as relatively narrower in its lesser diameter, while its surface is smoother and less marked by muscle attachments than that of the femur of *Acratocnus*. While it seems evident that this bone represents a land mammal, perhaps a ground sloth, larger than any known member of the Haitian fauna it is not possible at present to form any clear idea as to what this animal may have been.

OBSERVATIONS ON THE FAUNA REPRESENTED IN THE CAVES

The known indigenous land mammals of the Island of Haiti, bats and *Solenodon* excepted, have been, up to the present time, the three Hystricoid rodents *Plagiodontia*, *Isolobodon* and *Brotomys*, each represented by a single species. The first was living in the early part of the nineteenth century, but recent attempts to find it alive have failed. It has no known very near relative on any other island. The other genera are known from skeletal remains only; *Isolobodon* has been collected in Porto Rico and on two of the Virgin Islands; *Brotomys* has not been found elsewhere than on Haiti, but there is a nearly related genus in the cave deposits of Cuba. That all three of these animals were used as food by pre-Columbian man is clearly shown by the frequency with which their bones occur in kitchen midden deposits. One of them, *Isolobodon,* is the most abundant mammal among the specimens collected by Mr. Brown and Mr. Burbank, while another, *Brotomys,* is probably represented. That the caves were used by early man is indicated by the presence of the chert artifact and perhaps also by the occurrence of the human femur. The deposits in the caves have, however, none of the features commonly seen in heaps of human refuse, such as bits of broken pottery, and an abundance of remains other than mammalian. The considerable distance (about 40 kilometers) from the coast is a further reason for regarding the deposits as not to any important degree human in origin. Moreover, Mr. Brown tells me that he particularly considered the possibility of such origin, but that the evidence all appeared to show that the deposits were the work of natural agencies. It therefore seems reasonable to assume that the assembling of the mammalian remains owes little if anything to the influence of man. Probably the rodents whose bones Mr. Brown found to be so abundant at all levels except in the superficial deposits were carried in for food by the giant extinct owl described by Dr. Wetmore in his report on the birds from the caves.[1]

While the cave fauna includes two of the mammals known from the kitchen middens of the Dominican Republic it also includes two genera of rodents, a small ground sloth, two large unidentified mammals and an extinct owl that have not been found in these obviously recent deposits. The two rodents have no known near relatives on other islands, but the ground sloth is allied to genera previously discovered in Cuba and Porto Rico. The former presence on other islands of an owl resembling in size at least the one now discovered in the extinct fauna of Haiti is indicated by the abundance in Cuban and Porto Rican caves of the remains of rodents too large to have been carried there by such owls as are now living. There seems no reason to doubt that the life represented by the remains from these two Haitian caves formed part of the same older, perhaps Pleistocene, vertebrate fauna whose presence on the other islands of the Greater Antilles has recently become known.

[1] Remains of Birds from Caves in the Republic of Haiti, Smithsonian Misc. Coll., Vol. 74, No. 4, 1922.

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REMAINS OF BIRDS FROM CAVES IN THE REPUBLIC OF HAITI

BY

ALEXANDER WETMORE

Biological Survey, U. S. Department of Agriculture

(PUBLICATION 2708)

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REMAINS OF BIRDS FROM CAVES IN THE REPUBLIC OF HAITI

By ALEXANDER WETMORE,

Biological Survey, U. S. Department of Agriculture

In a small collection of bones, mainly of mammals, secured in two caves in the Republic of Haiti by Mr. J. S. Brown and Mr. W. S. Burbank, during geological studies under direction of the U. S. Geological Survey for the Republic of Haiti, are a few bones of birds that have been placed in my hands for study by Mr. Gerrit S. Miller, Jr. The caves from which the bones were taken, according to information supplied by Mr. Brown, are on the slopes of the mountains northeast of St. Michel de l'Atalye, and in a direct line are about forty kilometers from the coast. Two caverns were visited on March 4 and 5, 1921, and small collections made to determine whether more extended explorations were advisable. The larger of the caves under discussion lay between three and four kilometers from St. Michel at an altitude of about 600 meters above sea level. An excavation near the rear of the cave to a depth of less than a meter through reddish dirt containing many rocks yielded a number of bones. Additional material was collected from a smaller cave on the side of a deep, dry ravine about three kilometers east of the first site. Near the rear wall in this cavern a pit dug to a depth of 1.6 meters through a layer of stones, bat guano and earth yielded bones below a depth of half a meter. For more detailed information regarding these sites reference is made to the paper by Mr. Gerrit S. Miller, Jr.,[1] in which descriptions of the mammal remains are given. The few bones of birds secured include only four species, three obviously recent and the fourth a remarkable owl whose existence has been wholly unsuspected. The latter is an indication of an extinct avifauna that with exploration may perhaps yield even stranger species. Study of extensive collections from caves in Porto Rico revealed seven species of birds not previously known from the island, six of them new to science and the seventh a species of rail described originally from kitchen midden deposits

[1] Remains of Mammals from Caves in the Republic of Haiti, Smithsonian Misc. Coll., Vol. 74, No. 3, 1922.

in St. Thomas and St. Croix.[2] All of these apparently are now extinct, though one, a whippoorwill, is represented by a skin in the Field Museum.

Proper identification of the specimens discussed below has been possible only through the fine series of bird skeletons collected by Dr. W. L. Abbott during his explorations in Haiti.

COLUMBIDÆ

CHÆMEPELIA PASSERINA (Linnæus)

A left humerus, entire save for the distal end, from the larger cave does not differ from that of a modern ground-dove.

CUCULIDÆ

CROTOPHAGA ANI Linnæus

A left humerus was secured in the smaller cave. As this bone is obviously modern this record has no bearing on the supposition that the spread of the ani through the Antilles has taken place during recent times.

TYTONIDÆ

TYTO OSTOLOGA sp. nov.

Characters.—Similar to *Tyto perlata* (Lichtenstein) but much larger (head of metatarsus one and one-half times as broad).

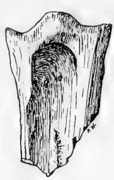

FIG. 1

FIG. 2

Description.—Type, U. S. Nat. Mus., Cat. No. 10746, proximal end of left metatarsus, from a large cave northeast of St. Michel de l'Atalye, Republic of Haiti, collected March 4-5, 1921, by J. S. Brown, and W. S. Burbank.

Metatarsus with inner glenoid facet (fig. 1) more extensive, somewhat more excavated than outer, irregularly quadrangular in outline, sloping toward rear, with posterior margin indented by outer margin of posterior semilunar groove; outer facet slightly more

[2] See Wetmore, Proc. U. S. Nat. Mus., vol. 54, p. 516; Proc. Biol. Soc. Washington, vol. 32, Dec. 31, 1919, p. 235, and vol. 33, Dec. 30, 1920, pp. 77-82.

elevated than inner, intercondylar tubercle broad, elevated inner side at anterior margin straight, outer side rounded, summit obliquely truncated toward outer side, sloping broadly in rounded outline posteriorly to terminate at the margin of the posterior semilunar sulcus so that it entirely separates the two glenoid surfaces; anterior surface (fig. 2) excavated deeply and abruptly beneath the median tubercle, where there is a slight overhang, anterior end of groove in outline elliptical, with outer side more abruptly delimited, and inner with wall more sloping; tubercle for tibialis anticus elongate, elliptical, slightly elevated, somewhat roughened; the two superior foramina slightly nearer to upper end of this tubercle than to proximal end of anterior groove, the outer foramen very slightly higher than the inner, and nearer the median line; both foramina small, placed in floor of anterior groove; inner margin of bone below head with a sharp ridge marking a tendinal attachment, inclined inward to form an overhang over the margin of the anterior groove; anterior semilunar groove only slightly indicated; posterior semilunar groove broad and deeply cut, slightly deeper at outer side; external head of talon triangular in lateral outline, with tip rounded, slight in size; internal head of talon somewhat broken at margin and below but much more extensive than the external division, forming a plate-like projection, concave on outer face, sloping outward to join anterior margin at a clean cut angle; outer superior foramen opening in posterior sulcus below and slightly within internal head of talon; inner superior foramen opening on outer face of outer head of talon not far from its center.

Measurements.—(Of type) lateral diameter of head at proximal end 17.5 mm.; greatest width of anterior groove 9.5 mm., anteroposterior thickness through external head of talon 11 mm.

Range.—Known only from large cave between three and four kilometers northeast of St. Michel de l'Atalye, Republic of Haiti. (Extinct.)

Remarks.—In addition to the head of the metatarsus described as type this huge barn owl is represented in the bones from this same cave by second and fourth metatarsal trochlea (Cat. No. 10747), that in all probability formed part of the metatarsus described as the type, and by the distal end of a right radius. These fragments are similar in outline to those in the common barn owl (*Tyto perlata*) but, like the head of the metatarsus, are comparatively speaking of gigantic size. The fourth trochlea is 13.5 mm. in width from the external sulcus to its free end. The second trochlea measures 11.7 mm. from the internal sulcus to its posterior end. The expanded end of the radius is 9 mm. broad.

In a series of six specimens of the common barn owl (*Tyto perlata*) the width of the proximal end of the metatarsus varies from 10.5 to 11.8 mm. and the length (measured from the top of the intercondylar tubercle to the lower margin of the third trochlea) from 70.0 to 82.0 mm. In *Tyto glaucops* these measurements are respectively 10.0 mm. and 64.0 mm. and in *T. bargei* 8.0 mm. and 5.6 mm. On this basis the tarsus in *Tyto ostologa* should have measured in the neighborhood of 120 mm. in length. The head of the tarsus is as robust as in a large snowy owl and was of course much longer.

Though *T. ostologa* may have possessed structural peculiarities of which we know nothing, the fragments at hand are so similar in conformation to the corresponding bones in *Tyto perlata* that there has been no hesitancy in placing the species in the genus *Tyto*.[3] It is much larger than any previously described in this group and so adds another remarkable form to those previously known from Haiti. As a natural corollary to the occurrence of *ostologa* in this cave we may suppose that the large rodents, described by Mr. Miller from the same deposits, formed the prey of this owl, so that we are indebted to the owl for the formation of the bone deposits. These may be considered as remains from pellets regurgitated by the bird, as similar formations of smaller mammalian remains in Porto Rico are attributed to the activities of *Tyto cavatica* Wetmore (extinct) and *Gymnasio nudipes* (Daudin). It may be remarked that *Tyto glaucops,* the modern barn owl of Haiti, is smaller than *T. perlata.*

TYRANNIDÆ

TOLMARCHUS GABBII (Lawrence)

A left humerus was secured in the smaller cave.

[3] It may be noted that the genus *Badiostes* Ameghino (Bol. Inst. Geogr. Argentino, vol. XV, Nov. and Dec. 1894, p. 601) which has been attributed to the Tytonidæ, appears from the figures and description to be related to the Falconidæ. Other extinct species ascribed to the Tytonidæ have been placed in the same genus as the barn owl and are all more or less similar to it in size.

SMITHSONIAN MISCELLANEOUS COLLECTIONS
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EXPLORATIONS AND FIELD-WORK OF THE SMITHSONIAN INSTITUTION IN 1922

(Publication 2711)

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CONTENTS

EXPLORATIONS AND FIELD-WORK OF THE SMITHSONIAN INSTITUTION IN 1922

INTRODUCTION

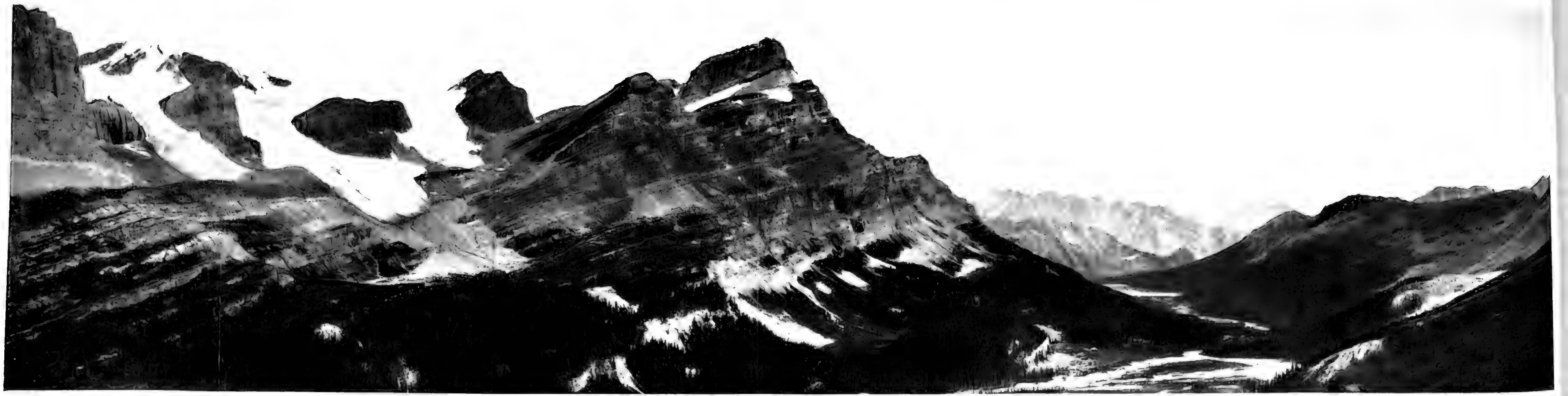
The present pamphlet, describing briefly the various explorations and field expeditions initiated, or cooperated in by the Smithsonian Institution and its branches, serves as an announcement of the results obtained, many of the investigations being later described more fully in other publications of the Institution. The collections resulting from many of these expeditions are shown to the public in the National Museum.

Scientific exploration has always been an important phase of the Institution's work in the " increase and diffusion of knowledge " and during the 76 years of its existence practically every part of the globe has been visited by Smithsonian field parties and our knowledge of the regions increased. There will always be important work in the nature of scientific exploration to be done, and had the Institution the means at its command, more extended investigations of great value to science and interest to the layman could be undertaken.

GEOLOGICAL EXPLORATIONS IN THE CANADIAN ROCKIES

Secretary Charles D. Walcott continued explorations in the Canadian Rockies for evidence bearing on the pre-Devonian formations north of Bow Valley, Alberta, and south along the new Banff-Windermere motor road, which passes from the Bow Valley over Vermilion Pass and down the Vermilion River Canyon to the Kootenay River and thence over Sinclair Pass to the broad Columbia River Valley north of Lake Windermere in British Columbia.

The first half of the season was unfavorable owing to dense forest fire smoke and inefficient trail men, but the latter part of August and all of September fine weather and capable men enabled the party to push the work vigorously. A fine section of pre-Devonian strata was studied and measured in the upper part of Douglas Lake Canyon Valley, and many fine photographs taken (figs. 3-12). This beautiful valley is only 12 to 15 miles (19.3 to 24 km.) in a direct line east and northeast of Lake Louise Station on the Canadian Pacific Railway,



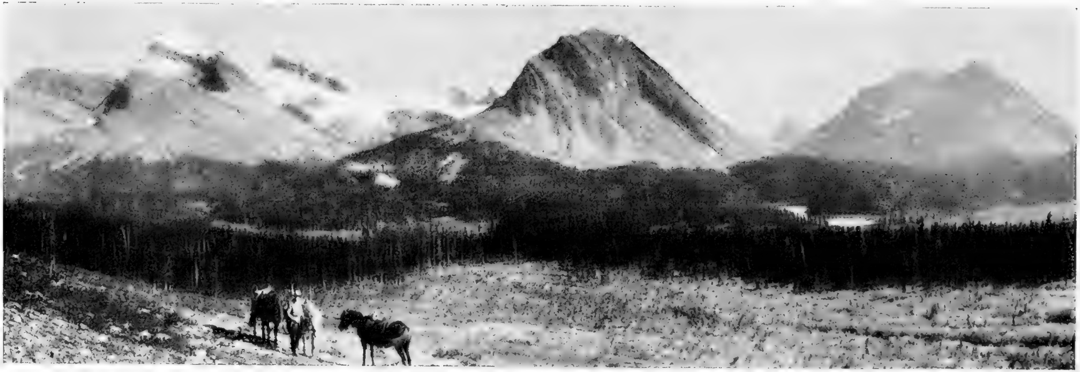


Fig. 2.—Looking south from Overlook view above camp at head of Red Deer River. On the left the snow clad summit of Mount Douglas (10,615 feet, 3,018 m.), and just back of it Mount St. Bride (10,875 feet, 3,314.7 m.) with its snow fields and small glacier. To right of horses Oyster Mountain (9,100 feet, 2,730 m.) with Fossil Mountain (9,655 feet, 2,896 m.) on the right.

Locality: South side of Red Deer River about 10.5 miles (16.8 km.) northeast of Lake Louise Station on the Canadian Pacific Railway, Alberta, Canada. (C. D. Walcott, 1922.)

FIG. 3.—Great cliffs of the sentinel mountains Douglas (10,615 feet, 3,018 m.) and St. Bride (10,875 feet, 3,262 m.) overlooking Douglas Lake and its broad canyon valley. The north side of these mountains is shown in figure 2.

Locality: View taken from above timber line on east side of Douglas canyon valley nearly opposite Mount St. Bride, looking west and northwest, 13.5 miles (21.6 km.) north-northeast of Lake Louise Station on the Canadian Pacific Railway, Alberta, Canada. (Mr. and Mrs. C. D. Walcott, 1922.)

Fig. 4.—Profile view of Bonnet and Trifid glaciers and great cliffs from Lake Gwendolyn.
Locality: View from outlet of Lake Gwendolyn in upper part of Douglas canyon about 12.5 miles (20 km.) east in air line from Lake Louise Station on the Canadian Pacific Railway, Alberta, Canada. (C. D. Walcott, 1922.)

FIG. 5.—Panoramic view of Bonnet glacier and ice fall with a great lateral moraine from which the ice has retreated in very recent times. A much older moraine is shown on the left. View taken from summit of an ancient moraine. (See figs. 4 and 6.)

Locality: Same as figure 4. (C. D. Walcott, 1922.)

Fig. 6.—Lower ice fall of Bonnet glacier with radial series of crevasse and above, on right, columnar crystallization on a great scale. (See figs. 4 and 5.)

Locality: Same as figure 4. (Mr. and Mrs. C. D. Walcott, 1922.)

Fig. 7.—Cliffs south of Mount St. Bride (10,875 feet, 3,262 m.) with two branches of Trifid glacier. The cliffs are formed of Devonian limestones above with the Mons formation (Ozarkian) below.
Locality: Same as figure 3. (Mr. and Mrs. C. D. Walcott, 1922.)

but as far as known it had not been visited, except by trappers long ago, until the summer of 1921 when Walter D. Wilcox and A. L. Castle camped in it and photographed some of its more striking features. Wilcox called it the "Valley of the Hidden Lakes,"[1] but for geologic description and reference "Douglas Canyon" is more simple.

Mount Douglas (10,615 ft., 3,018 m., figs. 2 and 3) towers for 4,500 feet (1,371.60 m.) above the canyon bottom, and Lake Douglas

FIG. 8.—Lake Gwendolyn, the gem of the upland valley, with Bonnet glacier and the northwest cliffs of Bonnet Mountain.

Locality: The lake is about 12.5 miles (20 km.) east-northeast of Lake Louise Station on the Canadian Pacific Railway, Alberta, Canada, and 7,500 feet (2,250 m.) above sea level. (Mr. and Mrs. C. D. Walcott, 1922.)

(fig. 1) fills the ancient pre-glacial channel for two miles or more. This superb canyon valley with its forests, lakes, glaciers and mountain walls and peaks (figs. 1, 3-10) should be opened up to the mountain tourist who has the energy to ride along a fine Rocky Mountains Park trail (fig. 12) from Lake Louise Station up the Pipestone and Little Pipestone rivers to the upper section of the Red Deer River, or from the Station by the way of Lakes Ptarmigan and Baker to the Red Deer camp and thence to Douglas Lake and Canyon Valley.

[1] Bull. Geog. Soc. Philadelphia, Vol. XX, 1921.

FIG. 9.—Gwendolyn glacier and Overlook point at the head of the eastern upland of Douglas canyon valley. This fine view shows the tongues of Gwendolyn glacier on the slope east of the lake seen in figure 8. (Mr. and Mrs. C. D. Walcott, 1922.)
Locality: Same as figure 8.

FIG. 10.—Lake Gwendolyn and glacier with moraine above. Halstead Pass, on the left, is at the head of the Panther River drainage, and Cascade divide is above a branch of Cascade River. (See fig. 7.)
Locality: Same as figure 7. (C. D. Walcott, 1922.)

The trail into Douglas Lake from the Red Deer River is not cut out for three miles, but 10 pack horses were led through the forest on a mountain slope without difficulty. This part of the trail should be opened up by the Rocky Mountains Park service and made part of the Pipestone-Red Deer-Ptarmigan circuit.

FIG. 11.—Limestone rock fall from mountain side on right of picture. The horses and riders indicate the size of the blocks.

Locality: Douglas Lake canyon about 1.5 miles (2.4 km.) above Lake Douglas and about 13 miles (20.8 km.) east-northeast of Lake Louise Station on the Canadian Pacific Railway, Alberta, Canada. (Mr. and Mrs. C. D. Walcott, 1922.)

Game is abundant. The party saw 144 mountain goats, many black tail deer, and marmots on the Alpine slopes of Douglas Canyon (figs. 7 and 10), and at the head of the Red Deer-Pipestone divide, mountain sheep.

The measured geologic section was from the base of the Devonian above Lake Gwendolyn across the canyon to the deep cirque below Halstead Pass where the great Lyell limestone forms the crest of the ridge. (See fig. 10.) The section includes the Ozarkian Mons formation down to the Lyell formation of the Upper Cambrian.[1]

A short visit was made to Glacier, B. C., where Mrs. Walcott measured the recession of Illecillewaet glacier, which she began to record in 1887. The recession the past four years has been at the rate of 112.5 feet (34.29 m.) per year, and all of the lower rock slopes are now free from ice. (See figs. 13 and 14.)

FIG. 12.—Rocky Mountains Park trail on north side of head of Red Deer River, en route from Lake Louise to Douglas Lake canyon. *Locality:* Same as figure 2.

On our way south from the Bow Valley no stops were made for photography or geologic study until camp was made on the Kootenay River about six miles (9.6 km.) below the mouth of the Vermilion River. The Kootenay Valley is deep and broad, with the high ridges of the Mitchell Range on the east and the Brisco Range on the west. (Figs. 15 and 16.) In places the old river terraces extend for miles along the river with a varying width. This greatly facilitated the

[1] Explorations and Field-work of the Smithsonian Institution in 1919, p. 15. Smithsonian Misc. Coll., Vol. 72, No. 1, 1920.

FIG. 13.—Photograph of Illecillewaet glacier taken in 1898, for comparison with one taken 24 years later in August, 1922. In this photograph the bare space between the glacier and the dark bushes represents the recession of the ice between 1887 and 1898.

Locality: Two miles (3.2 km.) south of Glacier House, British Columbia, Canada. (George and William Vaux, 1898.)

FIG. 14.—Remnant of Illecillewaet glacier photographed in August, 1922.
Locality: Same as figure 13. (Mrs. C. D. Walcott, 1922.)

Fig. 15.—Looking eastward across Kootenay River from the Banff-Windermere motor road, to the Vermilion range. The "gap" of the Vermilion River is on the right.
Locality: Same as figure 16.

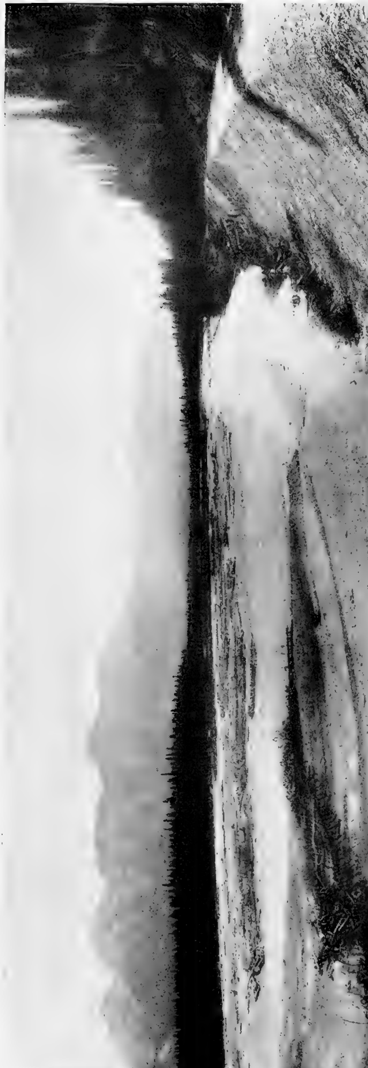


Fig. 16.—Panoramic view looking east and south across Kootenay River toward Mitchell Range, from the Banff-Windermere motor road, about 8 miles (12.8 km.) below Kootenay crossing, British Columbia, Canada. (C. D. Walcott, 1922.)

building of the motor road, as long, level and straight sections were readily surveyed and fine gravel was at hand for surfacing the road bed.

FIG. 17.—Illustrating a thrust fault. The bedded limestones have been dragged and bent upward on the west (left) side of fault, the plane of which slopes northeast at about 45°. The thin layers of limestone above the thick strong layer which slid over the limestones beneath are broken and crowded against the massive bed on the upper side of the fault.

Locality: North side of the Banff-Windermere motor road about one-half mile (.8 km.) below Radium Hot Springs, Sinclair Canyon, British Columbia, Canada. (Mr. and Mrs. C. D. Walcott, 1922.)

Note face in upper left corner.

A view in the forest section of the Kootenay Valley is shown by figure 20, and a more difficult section for road building by figures

15 and 16. The motor road is a fine public work and opens up for pleasure and business direct connection through the main ranges of the Rockies between the Bow and Columbia River valleys.

The limestones and shales of both ranges are upturned and sheared and faulted so as to make it very difficult, without detailed areal maps and unlimited time, to work out the structure and the complete stratigraphic succession of the various formations. (See fig. 17.)

Fig. 18.—West slope of Stanford range south of Sinclair Pass, with white quartzite band at base of Silurian limestones. About six miles (9.6 km.) above Radium Hot Springs, British Columbia, Canada. (Mr. and Mrs. C. D. Walcott, 1922.)

The Silurian limestones, with their fossil coral beds above the white quartzite of the Richmond transgression (see fig. 18) were found in the upper portion of Sinclair Canyon, and not far away black shales full of Silurian graptolites (fig. 19). Lower down the canyon thin bedded gray limestones yielded fossils of the Mons[1] formation not unlike those so abundant at the head of Clearwater Canyon, 73 miles (117.4 km.) to the north, and Glacier Lake, 94.6 miles (152.21 km.)

[1] Smithsonian Misc. Coll., Vol. 72, No. 1, p. 15, 1920.

north. It is evident that in the ancient and narrow Cordilleran Sea that extended from the Arctic Ocean 2,000 miles (3,218 km.) or more south between the coast ranges of the time and the uplands of the central portion of the North American continent, there was a similarity of Lower Paleozoic marine life along the shores and in its shallow waters. Evidences of this and of strong currents and persistent wave action occur all the way from central Nevada to Mount

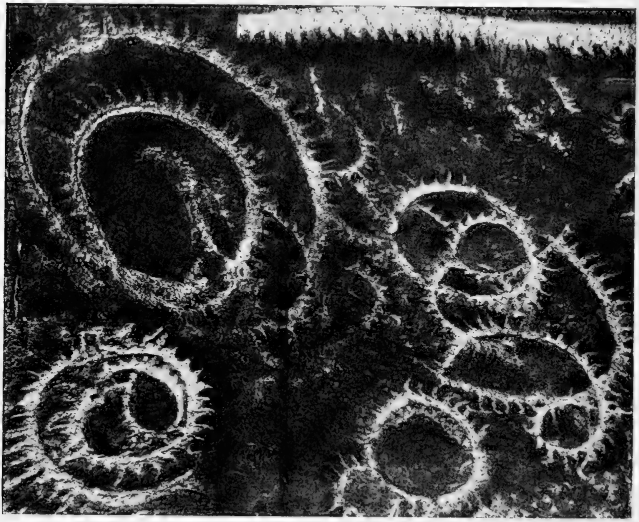


FIG. 19.—Graptolites that flourished on the muddy bed of the sea in Silurian time. The coiled form *Monograptus convolutus* Hisinger is found both in Europe and America. The straight form is very abundant in some of the partings of the shale.

Locality: Sinclair Canyon about 3.25 miles (5.2 km.) above Radium Hot Springs, in cliff on south side of Banff-Windermere motor road, British Columbia, Canada.

Robson in British Columbia. The record of the marine life and deposits of mud and sand is most complete, and it has been great sport running down the various clews that have been encountered from time to time.

The lower Sinclair Canyon opens out into the Columbia River Valley through a narrow canyon eroded in the upturned and faulted limestones. Some conception of the character of the canyon may be obtained from figures 21-23.

Fig. 20.—Looking south through the forest on a tangent of the Banff-Windermere motor road.

Locality: About 9 miles (14.4 km.) below Kootenay River Crossing, British Columbia, Canada. (Mr. and Mrs. C. D. Walcott, 1922.)

Fig. 21.—Looking westward through narrow entrance to Sinclair Canyon on Banff-Windermere motor road. Brisco Range, British Columbia, Canada. See figures 22, 23. (Mr. and Mrs. C. D. Walcott, 1922.)

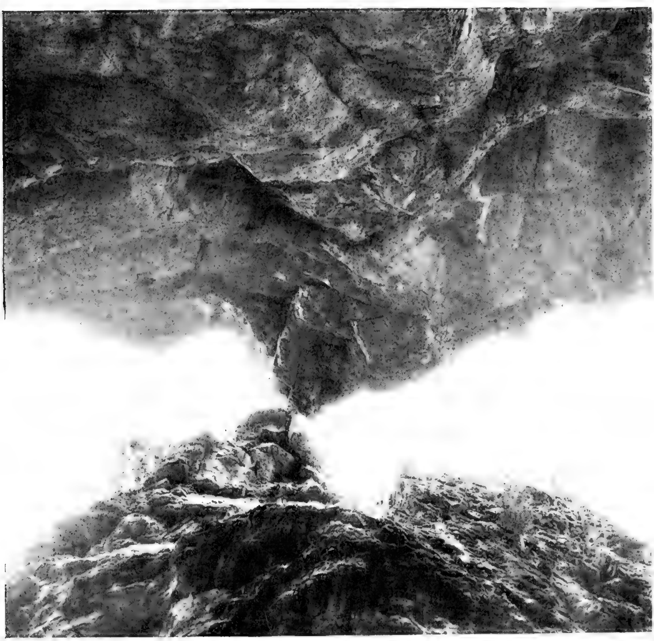


FIG. 22.—A view of the sky from the Banff-Windermere motor road near the entrance to the canyon from the Columbia River Valley. See figure 21.

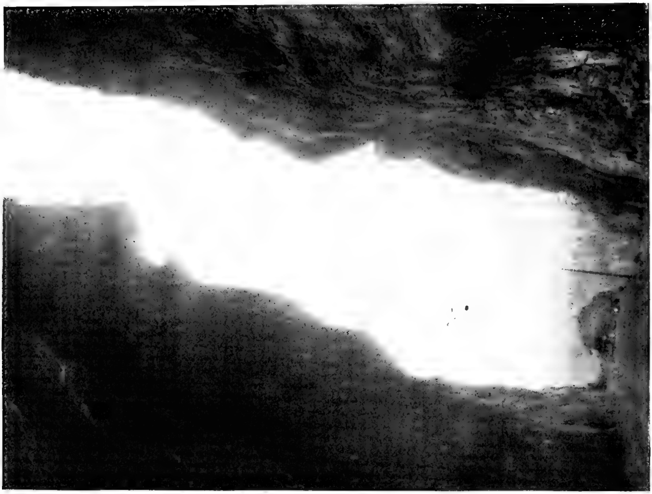


FIG. 23.—Looking westward near sunset towards the Selkirk Mountains through west entrance to Sinclair Canyon on the Banff-Windermere motor road, Brisco Range, British Columbia, Canada.

Profile of lion's head near top of cliff on left side, profile of ape's head on right side. (Mr. and Mrs. C. D. Walcott, 1922.)

FIG. 24.—A beautiful cluster of white saxifrage in a sheltered spot among limestone boulders.

Locality: South branch of the headwaters of Clearwater River, 22 miles (35.2 km.) north of Lake Louise Station on the Canadian Pacific Railway, Alberta, Canada. (Mrs. C. D. Walcott, 1922.)

FIG. 25.—A group of white heather, *Bryanthus*, growing on limestone soil.

Locality: Near head of Red Deer River 10.5 miles (16.8 km.) northeast of Lake Louise Station on the Canadian Pacific Railway, Alberta, Canada. (Mrs. C. D. Walcott, 1922.)

FIG. 26.—Purple gentian growing on a south slope of a limestone ridge at about 7,000 feet (2,100 m.) elevation.
Locality: Same as figure 25. (Mrs. C. D. Walcott, 1922.)

FIG. 27.—A fine plant of Zigadenas growing on a slope of limestone débris.
Locality: Same as figure 25. (Mrs. C. D. Walcott, 1922.)

FIG. 28.—Mrs. Walcott sketching a wild flower in water colors on a frosty morning in camp. The camp fire kept the open tent warm and comfortable. *Locality:* Vermilion River canyon between the Banff-Windermere motor road and the river, British Columbia, Canada. (C. D. Walcott, 1922.)

FIG. 29.—Getting acquainted with a young broncho. Baby Nancy and her mistress at Hillsdale camp, Bow Valley, Alberta, Canada. (C. D. Walcott, 1922.)

The living evidence of the heat developed by the upturning and compression of the strata under the eastward thrust of the massive Selkirk Mountains is that of Radium Hot Springs in Sinclair Canyon, and Fairmont Hot Springs, 15 miles (24 km.) or more to the south.

During the summer Mrs. Walcott sketched in water colors 24 species of wild flowers, or their fruit, that were new to her collection now on exhibition in the great hall of the Smithsonian building. Some of her photographs of wild flowers are shown by figures 24-27, and sketching in camp by figure 28.

The party at the end of the season camped on the eastern side of the Columbia River Valley at Radium Hot Springs postoffice, where the veteran prospector, John A. McCullough, has made his home for many years. He and Mrs. McCullough were most courteous and obliging to the party which then consisted of the Secretary and Mrs. Walcott, Arthur Brown, Paul J. Stevens, packer, and William Baptie, camp assistant.

Familiar scenes in connection with the life on the trail are illustrated by figure 29.

The Commissioner of the Canadian National Parks, Hon. J. B. Harkin, and the members of the Parks service in the field, especially Chief Inspector Sibbald and Chief Game Warden John R. Warren, were most helpful, also the officials and employees of the Canadian Pacific Railway.

PALEONTOLOGICAL FIELD-WORK IN THE UNITED STATES

Dr. R. S. Bassler, curator, division of paleontology, U. S. National Museum, working in collaboration with the State Survey, was in the field six weeks in June and July, in a continuation of stratigraphic and paleontologic studies begun a year earlier in the Central Basin of Tennessee. This work is so extensive that a number of seasons of field-work will be necessary for its completion. In 1921 the study and mapping of the Franklin quadrangle, an area of about 250 square miles, just south of Nashville, was well advanced but so many new stratigraphic problems arose that the State Geologist, Mr. Wilbur A. Nelson, suggested the field season of 1922 be devoted to the further study of the Franklin quadrangle and to stratigraphic studies in contiguous areas. Accordingly, the mapping of the Franklin quadrangle was completed and data secured for the preparation of a geological report upon the area, to be published by the State. Stratigraphic studies were then undertaken in the adjacent contiguous areas and some of the classic geologic sections of Central Tennessee were visited and studied in detail. Dr. E. O. Ulrich, associate in paleontology in the National Museum, joined in this work on account of his life-long interest in the stratigraphy of Central Tennessee, and with the aid of his assistant, Mr. R. D. Mesler of the U. S. Geological Survey, numerous detailed sections and about a ton of carefully selected fossils were secured for the National Museum.

The classic section at Nashville, Tennessee, in which the proper delimitation of the formations has long been in dispute, was studied

FIG. 30.—Section at Nashville, Tennessee, illustrating sequence of Ordovician formations. (Photograph by Bassler.)

with especial care and ample collections of fossils were secured to verify the stratigraphic results.

The deep sea origin of all limestones has long been taught in spite of the trend of evidence that many limestone formations were laid down in shallow seas. The shallow water origin of limestone is well illustrated in the section of Ordovician strata exposed near the blind asylum at Nashville which has been studied by several generations of geologists. At the base of this section, as shown in figure 30, is the Hermitage formation which was evidently formed along ancient shore lines because it is composed of beach worn fragments of shells and other fossils. Above this comes the Bigby limestone, the source of much of the Tennessee brown phosphate and which also is made up almost entirely of the comminuted remains of fossils. Next is the Dove limestone, an almost pure, dove-colored, lithographic-like limestone which shows its shallow water origin in the worm tubes penetrating it and its sun-cracked upper surface. A slab of this limestone a foot thick, as shown in figure 31 and now on

Fig. 31.—Stratum of dove limestone showing sun-cracked upper surface and penetrating worm tubes, indicative of shallow water origin. (Photograph by Bassler.)

exhibition in the National Museum, well illustrates the polygonal upper surface and the penetrating worm tubes, both features indicative of the origin of the rock on old mud flats which were periodically above water and thus became sun cracked. The succeeding Ward limestone is of the more typical blue variety but here the rock is filled with millions of fossil shells which under the influence of weathering are changed to silica and are left free in great numbers in the soil. This section is only a portion of the entire geological sequence at Nashville but it well illustrates the various types of limestone outcropping throughout the Central Basin.

ASTROPHYSICAL FIELD-WORK IN CALIFORNIA, ARIZONA, AND CHILE

The Astrophysical Observatory of the Institution did some notable work at Mount Wilson on the spectra of the sun and stars. Some discrepancy had appeared between the work of 1920 and the early work of the observatory prior to 1910 on the distribution of energy in the sun's spectrum as it is outside the atmosphere. It appeared necessary to go over this ground again, as the result is used in everyday work at the two field stations in Chile and Arizona, in computing the solar constant of radiation, so the work was repeated by Messrs. Abbot and Aldrich with as much variety in conditions as was possible. The results of the different experiments were in close accord, and in accord with the work of 1920, so that the new determination is now going into effect in the computations in Arizona and Chile.

At the invitation of Director Hale, of the Mount Wilson Observatory, Messrs. Abbot and Aldrich employed the great hundred-inch telescope there in connection with a special vacuum bolometer and galvanometer designed and constructed at Washington in order to measure the heat in the spectrum of the brighter stars. In other words, they attempted to investigate the distribution of radiation in the stellar spectra with the bolometer as they have long done with regard to the spectrum of the sun. When one thinks of taking the light of a star, which looks like a firefly up in the sky, separating it out into a long spectrum, and observing the heat in the different parts of the spectrum, it seems a practical impossibility. Nevertheless, the observers succeeded in doing this for ten of the brighter stars, and they also observed the sun's spectrum with the same apparatus. In this way it was possible to represent the distribution of radiant energy in the different types of stars from the bluest to the reddest ones, and to know the displacement of the maximum of energy from shorter to longer wave-lengths as the color of the stars tended more and more towards the red.

The outlook for further investigations of this kind is hopeful, and it will have a notable value in the estimation of the temperatures of the stars and the study of stellar evolution.

The two field stations at Mount Harqua Hala, Arizona, and Mount Montezuma, Chile, are continued in operation. The station on Mount Harqua Hala, under the direction of Mr. Moore, has been much improved during the year. Owing to the driving rains and high winds, it proved necessary to sheathe the adobe building there with galvanized iron. At the same time all cracks for the entrance of wind, snow, and noxious insects and animals were closed. A small building was erected to house the tools and electrical appliances used for charging storage batteries and other purposes, and in this was arranged a shower bath ingeniously contrived to give a continuous shower as long as desired with only about a gallon of water. Cement water reservoirs for collecting and preserving the rain and snow water from the roofs have been constructed, with a total storage

FIG. 32.—Mount Harqua Hala Solar Observing Station, Arizona.

capacity of about two thousand gallons. A small porch was attached to the dwelling quarters and the rooms have been neatly painted and curtained. A "listening in" wireless outfit has been erected, and a so-called "Kelvinator" or sulphur dioxid refrigerating device for keeping provisions and cooling water for drinking purposes has been installed.

The observatory owns a Ford truck which is kept in a small garage built at the foot of the trail, and weekly mail and supply service is maintained from Wenden to the mountain top. A telephone line is just being erected to connect from Wenden to the observing station.

The cost of these various improvements, which have made living on the mountain very much more comfortable, has been borne by funds provided for the purpose by Mr. John A. Roebling, of New Jersey, to whom the Institution is greatly indebted for his generous interest in its solar radiation program.

A notable case of fluctuation in the solar radiation has recently been reported from the Arizona station. A fall of 5 per cent in the solar heat occurred, beginning about the 15th of October and

FIG. 33.—Mount Harqua Hala and garage at foot, Arizona.

reaching its minimum on the 21st, and then quickly recovering to the normal by the 25th. By inquiry at the U. S. Naval Observatory, it is learned that a very notable new group of sun spots was formed, the first indications appearing about the 17th of October and the group reaching great dimensions by the 21st when it neared the limb of the sun and shortly disappeared over the edge, due to the solar rotation. This occurrence is nearly parallel to that of March, 1920, when a similar great drop in the solar heat occurred and a very extraordinary sun-spot group passed over the sun.

EXPEDITION TO EXAMINE THE NORTH PACIFIC FUR SEAL ISLANDS

The Department of Commerce wishing to obtain exact information as to the status of the fur seal herd on the Russian seal islands, situated off the coast of Kamchatka and known as the Komandorski or Commander Islands, with special reference to the effect of the treaty of 1911 entered into by the United States, Russia, Japan and Great Britain for the protection of the fur seals in the North Pacific Ocean, requested the detail of the head curator of biology of the Museum, Dr. Leonhard Stejneger, to accompany an expedition to Alaska and adjacent regions during the summer of 1922. The expedition, under the immediate leadership of Assistant Secretary of Commerce C. H. Houston, was primarily organized for the purpose of studying the conditions of the fisheries of Alaska as well as the other economic and commercial problems of that territory in so far as they are included in the activities of the Department of Commerce. Among others it included Mr. W. T. Bower, Bureau of Fisheries, Assistant in charge of Alaska, and Dr. Alfred H. Brooks, U. S. Geological Survey, in charge of Alaskan Geology. Capt. C. E. Lindquist was engaged as special assistant to Dr. Stejneger.

The expedition left Seattle, Washington, in the U. S. Coast Guard Cutter *Mojave,* Lieut. Comm. H. G. Hamlet commanding, on June 20, 1922, and proceeded by the inside passage to southern Alaska, making short stops at various places for inspection of canneries, hatcheries, factories, mines, etc. At Juneau, an excursion to Mendenhall glacier was undertaken. On June 27, Cape St. Elias, the "landfall" of Bering in 1741, was rounded, and the *Mojave* stopped at Cordova, the principal town in Prince William Sound. From here Mr. Huston and a small party went overland to Fairbanks, returning by the recently opened Central Alaska Railroad to Seward, where they again boarded the *Mojave* on July 4. The stay of the cutter at Cordova was taken advantage of by Stejneger and Lindquist to arrange a visit to Kayak Island. The Russian commander, Vitus Bering, in May, 1741, left Petropaulski, Kamchatka, on board the *St. Peter* under orders to sail eastward until discovering America. After a stormy voyage a cape with high land beyond was clearly made out on July 16, old style, and on July 20 the *St. Peter* came to anchor off an island which is now known as Kayak Island. Steller, who accompanied the expedition as a naturalist, was only allowed to go with the crew sent ashore in a boat to fill the empty water casks at a small creek on the western shore of the island. Accompanied by

FIG. 34.—U. S. C. G. C. *Mojave* in Dutch Harbor, Alaska. (Photograph by L. Stejneger.)

FIG. 35.—Steller's landing place, Kayak Island, Alaska. (Photograph by L. Stejneger.)

his cossack, he explored as much of the island as he could during the short stay of about 6 hours, collecting plants, birds and other natural history objects. This was the first landing of a scientific man in Alaska for the purpose of making observations and collections.

The principal object of the trip to Kayak Island was to verify Steller's description, to locate the place where he made his celebrated landing and where the water was obtained, and to make such collections of natural history objects as circumstances would allow. Passage for the 50-mile trip to Katalla was secured on the motor boat *Pioneer*. Leaving Cordova at 2 a. m. on June 29, it did not reach Katalla until 9.30 p. m. owing to its grounding at ebb tide on the extensive mudflats at the mouth of Copper River. Another motor boat was hired at Katalla, but it was not possible to leave until the following day, so that Kayak Island was not reached until 6.15 p. m. A landing was effected at the mouth of a creek which, from Steller's description, can be none other than the one at which Bering's crew took in water. Owing to the fast failing daylight, the party at once set out along the beach in the direction of the mainland for the distant hill described by Steller, but came to an abrupt halt after a laborious walk of about two miles along the bouldery beach at a comparatively recent fall of huge blocks of conglomerate rock among which the ocean waves were breaking so furiously as to stop further progress. The remaining few moments before darkness set in were utilized in collecting a few plants accessible along the beach at the foot of the precipitous cliffs which prevented access into the interior of the island. Returning, Cordova was reached at 4 p. m.

The fair weather which had favored the expedition hitherto changed to fog and rain after leaving Seward. Passing through Shelikof Strait opposite Katmai, a glimpse was had of the mountains on Kodiak Island still white, as if covered with snow, from the ash deposited during the eruption of the Katmai volcano in 1912. The passage through Unimak Pass was successfully accomplished in spite of the heavy fog on July 10, and the *Mojave* anchored off the Akutan Whaling Station which was visited. Two finback whales were stripped of their blubber during the inspection. Arriving at Unalaska at 3.30 p. m. the outfit and baggage of Stejneger and Lindquist were at once transferred to the U. S. Coast Guard Cutter *Algonquin* which was lying ready to take Secretary Huston and Mr. Bower to the Pribilof Islands for an inspection of the fur seal rookeries there, leaving Unalaska the same evening.

FIG. 36.—Whaling station, Akutan, Alaska. (Photograph by L. Stejneger.)

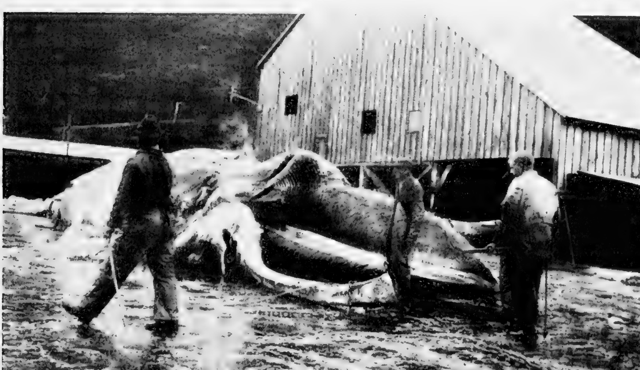


FIG. 37.—Carcass of fin back whale, whaling station, Akutan, Alaska. (Photograph by L. Stejneger.)

The visit to the Pribilofs was favored with cool cloudy weather which showed up the rookeries to the best advantage. The increase in the number of seals on the beaches, a result of the elimination of pelagic sealing by the treaty of 1911 between the United States, Great Britain, Japan and Russia, was very remarkable, notwithstanding the handicap of the excessive increase of superfluous and therefore disturbing young males due to unfortunate legislation which stopped land killing for five years following the signing of the treaty. By drastic measures the proper numerical ratio between the sexes has almost been accomplished by now, and a complete restitution of the fur seal herd to its former maximum is confidently predicted for the not distant future, if pelagic sealing is not resumed. An improved method in stripping the skin from the body of the dead seal and subsequent cleaning of the skin was being tried out for the first time on an extensive scale and was shown to be a great improvement on the old method. Greatly improved methods were also observed in the handling of the blue foxes. The air of prosperity and progressiveness pervading the whole establishment as compared with conditions 25 years ago was very notable, bearing testimony to the efficiency of the management of the islands by the Bureau of Fisheries.

The *Algonquin* with Stejneger and Lindquist on board returned to Unalaska to fill up with fuel oil preparatory to the trip to the Commander Islands, a distance of approximately 1,100 miles. At Dutch Harbor, while the vessel was taking in oil, the opportunity was taken advantage of to examine the small group of Sitka spruce planted there nearly 100 years ago by the Russian Admiral Lütke while visiting the island in the corvette *Seniavin.* A fire during the summer of 1896 came very near destroying the stand, but timely aid saved most of the trees. The little isolated grove, the only one west of Kodiak Island, showed the effects of the fire. There are now 15 trees left, all looking healthy, the foliage being dense and dark, and the lower branches sweeping the ground. The south side of the trees was covered with blossoms and last year's cones, but no seedlings were seen anywhere. Among the large trees, however, there were a couple of saplings about 10 feet high, which had been smothered to death, but which show that fertile seeds have been produced occasionally. The largest tree was measured and found to be 8 feet in circumference 3 feet from the ground. About a foot higher it divides into three distinct trunks.

The Commander or Komandorski Islands were reached on July 24. These islands form the most western group of the Aleutian Chain.

FIG. 38.—Wharf at Unalaska. (Photograph by L. Stejneger.)

FIG. 39.—Dutch Harbor, Alaska, U. S. C. G. C. *Algonquin* taking in oil. (Photograph by L. Stejneger.)

It consists of the two islands, Bering and Copper, situated about 100 miles east of Kamchatka. They belong to Russia and at the time of the visit were controlled by the Vladivostock government under Miliukof. The conditions of the inhabitants were found to be better than expected. Perfect order was maintained, no foreign traders or disturbers were present, and the people, though reduced both in number and resources, were not starving thanks to the abundance of fish and the cargo of necessities which had been sent them in exchange for the furs of the past season. They were lacking, however, in clothing, shoes and fuel. The party on the *Algonquin* was received with open arms, especially as the officers and crew of the

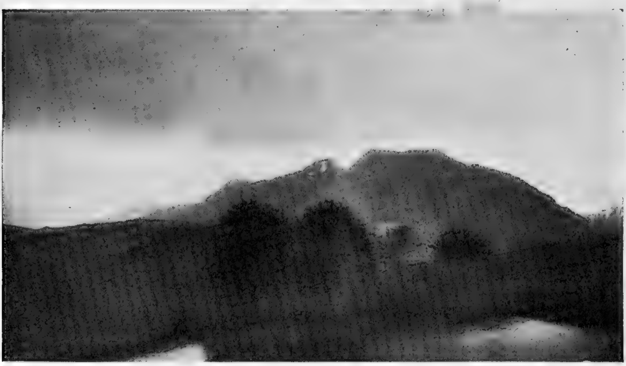


FIG. 40.—Grove of Sitka spruce, Dutch Harbor, Alaska. (Photograph by L. Stejneger.)

cutter supplemented the scanty stores of the communities with generous donations of necessities and a few luxuries. Immediately after landing the baggage and outfit of the expedition, the *Algonquin* left for Unalaska.

The first important business was the examination of the only remaining fur seal rookery on Bering Island. The South Rookery had long since ceased to exist, and the great North Rookery, one of the most important on the islands had been greatly reduced. The actual state of affairs was found to be much worse than anticipated. At his last visit to this rookery which he had studied and mapped in 1882, 1883, 1895, 1896 and 1897, Stejneger had estimated the number of breeding seals located there to be about 30,000. On July 28, 1922.

FIG. 41.—Preobrazhenski village, Copper Island. (Photograph by L. Stejneger.)

FIG. 42.—Nikolski village, Bering Island. (Photograph by L. Stejneger.)

there were scarcely 2,000 left. Regular killing had been stopped and for the present the Komandorski seal herd is non-productive.

The weather which had been stormy and foggy now settled down to a continuous fog and rain which interfered greatly both with observations and collecting. The latter was confined mostly to insects and plants. An interesting addition to the flora of the Commander group was the finding of *Cypripedium guttatum*, apparently confined to a single locality on Bering Island on a hillside south of the great swamp back of the Nikolski village.

On August 8, the first clear day for weeks, the *Mojave* arrived and after staying a couple of hours proceeded with the completed

FIG. 43.—Harbor of Petropaulski, Kamchatka. (Photograph by L. Stejneger.)

party to Petropaulski, the capital of Kamchatka. The delay had been caused by the necessity of the *Mojave* returning from Anadir to Unalaska for fuel oil.

At Petropaulski the town was found to be in the possession of the "whites," *i. e.*, the officials of the Vladivostock government supported by an "army" of about 50 men, while the "reds," *i. e.*, the portion of the male population recognizing the authority of the Far Eastern Republic, were holding the hills about four miles out. Two days were spent here examining into the conditions and gathering statistics of various kinds. A member of the Swedish Scientific Kamchatka Expedition which has been collecting natural history objects for the National Museum in Stockholm for a couple of years, Dr. René

Malaise, a well-known entomologist, was met here and some of his interesting collections were examined.

The next objective of the *Mojave* expedition was an inspection of the Japanese fur seal island off the eastern coast of Sakhalin in Okhotsk Sea, usually known as Robben Island.

On August 13, the *Mojave* passed the Kuril chain through Amphitrite Strait but on account of fog did not anchor off Robben Island until the 15th in the evening. The party was there met by three Japanese officials of the Karafuto provincial government who with the greatest liberality placed all the desired information and statistics at the disposition of the American investigators. Robben Island is

FIG. 44.—Robben Island, Okhotsk Sea. Part of fur-seal rookery. Breeding place of innumerable murres. (Photograph by L. Stejneger.)

a small, elongated, flat-topped rock, nowhere higher than 50 feet, only 1,200 feet long and less than 120 feet wide, surrounded by a narrow gravelly beach 30 to 120 feet wide, on which the rookery is located. A couple of low houses for the sealing crew, which is stationed here during the summer season, are located on the western slope. When Stejneger visited and photographed the rookery in 1896 the seals occupied a small spot on the east side. Since the Japanese took over the island from the Russians in 1905, the number of fur seals has gradually increased until now the animals not only occupy the entire eastern beach but are extending the rookery at both ends on to the west side of the island. The Japanese have closely followed the methods employed in managing the American seal herd on the Pribilof Islands, and the result has been equally gratifying. The history of the sealing industry on this rock is most instructive as it proves in the most convincing manner that "protection does protect." After examining and photographing the rookery the party was entertained by the Japanese Commissioners with refreshments in a large tent erected for the occasion.

From Robben Island the *Mojave* proceeded to Hakodate, Japan, where additional important information relating to the Russian fur seal islands was obtained from Mr. Koltanovski of Vladivostock, who was on his way to the Commander Islands with a staff of assistants to assume charge of the fisheries there during the coming winter. In

1 2 3 4 5 6 7 8

FIG. 45.—Members of the expedition at Robben Island. (Photograph by L. Stejneger.)

1. E. Takamuku, Chief of Fisheries Section, Karafuto Government.
2. W. T. Bower, U. S. Bureau of Fisheries.
3. C. H. Huston, Assistant Secretary of Commerce.
4. L. Stejneger, U. S. National Museum.
5. S. Okamoto, Otomari, Karafuto.
6. K. Fujita, Karafuto Middle School.
7. C. E. Lindquist, Oakland, Calif.
8. A. H. Brooks, U. S. Geological Survey.

Yokohama, the next stopping place, an interview with Col. Sokolnikof, who had been administrator of the Russian fur seal islands for ten years, was productive of valuable information, as was also a visit to the Imperial Fisheries Bureau in Tokyo, thanks to the kind assistance of Prof. K. Kishinouye of the Imperial University. Mr. K. Ishino, the fur seal expert of the bureau, was kind enough to allow inspection of a series of photographs which he had taken during the trip to the Commander Islands in 1915 and 1916. An interesting excursion was also undertaken to the Biological Station at Misaki, but as the season had not opened yet, only the buildings and the apparatus of the station could be examined.

Messrs. Stejneger and Lindquist having now completed the task of inspecting the fur seal rookeries, left the *Mojave* in Yokohama and took passage in the *President Jefferson* sailing for Seattle, Washington, on September 2. Dr. Alfred H. Brooks returned in the same steamer.

EXPLORATIONS IN AUSTRALIA AND CHINA

Through the generosity of Dr. W. L. Abbott, Mr. Charles M. Hoy continued his work of collecting specimens of the very interesting fauna of Australia. The work was terminated during the winter and Mr. Hoy returned to the United States in May, 1922. The results of this expedition are of especial value for two reasons: First, the Australian fauna has heretofore been but scantily represented in the National Museum, and, second, the remarkable fauna of that continent is being rapidly exterminated over large areas. The specimens received during the year bring the total up to 1,179 mammals, including series of skeletal and embryological material; 928 birds, with 41 additional examples in alcohol, and smaller collections of reptiles, amphibians, insects, marine specimens, etc. The accompanying photograph (fig. 46) shows part of an exhibition case in the National Museum with mounted specimens mostly from the Hoy collection.

This expedition has been so important that the main features of its history may now be appropriately recapitulated. Doctor Abbott arranged early in 1919 to send Mr. Hoy to Australia. Departure from San Francisco took place early in May and collecting was begun at Wandanian, New South Wales, on June 19. From this time until the middle of January, 1922 Mr. Hoy was constantly in the field. The regions visited were as follows: New South Wales (June to December, 1919), South Australia, including Kangaroo Island (December, 1919, to the end of March, 1920), West Australia (May to September, 1920), Northern Territory (October to end of November, 1920), New South Wales (January and February, 1921), Tasmania (April to June, 1921), northern Queensland (July, 1921, to January, 1922). As the main object of the expedition was not to visit the unexplored portions of Australia but rather to secure material from regions where settlement of the country is producing rapid change in the fauna, travel was of the ordinary kind, by boat, rail and wagon road. Tent life was an important element in the living conditions, and at times it was rendered difficult by the heavy rains which in some districts broke a long-continued drought just at the time of Mr. Hoy's arrival. Detailed accounts of the work, with photographs of many of the animals collected, and with passages from Mr. Hoy's letters have been published in previous numbers of this series of Exploration pamphlets (Smithsonian Misc. Coll., vol. 72, No. 1, pp. 28-32; vol. 72, No. 6, pp. 39-43).

FIG. 46.—Part of exhibition case in National Museum showing some of the kangaroos collected by Mr. Hoy in Australia.

Dr. Abbott's unfailing interest in the national collections is shown by the fact that he has now arranged to send Hoy to China for the purpose of obtaining vertebrates from certain especially important localities in the Yang-tze valley, a region with which Hoy has been familiar for many years. Departure for the field took place on December 15, 1922.

GERRIT S. MILLER, JR.

BIOLOGICAL EXPLORATIONS IN SOUTHEASTERN CHINA

In the summer of 1921 Mr. A. de C. Sowerby returned to China to continue the work of exploration interrupted by the war. This work, which is made possible by the generosity of Mr. Robert S. Clark of New York, will now be carried on in the region south of the Yangtze, and the zoological results will come to the National

Museum. While it is too soon for any full report on the explorations in which Mr. Sowerby is engaged, the following passages from a letter dated December 1, 1921, give some idea of the conditions under which the work is being done.

In the Interior of Fukien Province,
S. E. China, December 1, 1921.

Here I am over 200 miles from the coast up a tributary of the Min River, right at the back of beyond of the province, as you might say. I couldn't sit idle in Shanghai, so I decided to have a shot at this province. I took steamer to Foochow and was very fortunate in meeting a young American named Carroll, engaged in the lumber business, who was on his way to the very spot I had decided to visit, and he offered me the hospitality of his boat—an adapted river-boat, shallow draft, but comfortable—and his pleasant company. Naturally I accepted, and so here I am. We went away up a side stream, too small for boat traffic—to a spot in the back hills—or mountains, about 5,000 feet—where his company is opening up a forest, and there we camped a week, scouring the whole neighborhood, and having a few good hard tries for serows. Though we failed to get anything big, I did pretty well with small mammals. Next we came back to the main stream, where I am camped, while he has gone on up stream to transact some business. He expects to return here to-morrow or the next day, when we will go down stream to a place where a couple of tigers have been killing a lot of people, and see if we can't get a shot at them. Then on back to Foochow, whence I shall return to Shanghai for Christmas. After that I have fixed up with a party to go up the Yangtze as far as Wuhu, then inland to a place called Ning-kuo-fu, taking in some forested country on the way in the hopes of getting some *Cervus kopschii,* across the divide into Chekiang Province and down some stream to Hangchow. The other fellows are out for sport pure and simple, but I shall have time to do some collecting. So you see I am panning out pretty well. I shall come back to this province again as soon as possible, as it is simply full of stuff. The only trouble is that the cover is so dense that trapping and shooting are extremely difficult. I already have a collection of 94 mammals—including 14 species—some interesting birds, fish, frogs, etc. The rats are a puzzle. As far as I can make out I have five different species of Epimys.

I have met Caldwell, the man who saw the famous "Blue tiger," and he tells me it was of such a color that he thought it was a chinaman in his blue coat in the brush. But he had a good enough view of the animal to be perfectly certain of what it was. And the only reason why he did not shoot it was that it was just above two boys who were working in a field, and had he shot it it must have fallen on top of them. Indeed, it was actually stalking them when he saw it. Yen-ping-fu is a wonderful animal centre. Caldwell got a tufted muntjac and a leopard just back of his compound, and wild cats, palm-civets and what not actually in it.

This is very, very beautiful country. I have never seen anything quite like it. The whole country is hilly and mountainous, and covered with heavy underbrush, and woods of spruce, pine, and deciduous trees. The rivers and streams are clear as crystal, studded with rock, and exquisitely beautiful. The underbrush is a terror to get through by reason of its denseness and the sword-grass that occurs everywhere and cuts like a razor. I like the people, and find them very friendly. At this moment I am camped in the local temple of a small village, my things spread all over the place. I am the centre of interest for the whole countryside. People come and burn incense and *chin chin joss,* and then stop to look at me and have a good chin wag. It doesn't seem to worry them that I have dead rats on the altar. And the small boys bring me in rats, and mice, and shrews, and bats. Truly they are a most remarkable people. And there have been ever so many cases of murdered missionaries in the province in bygone days. I don't believe these people are pure Chinese. Some of them have most remarkably bushman-like faces. They say that there are real aborigines in the province, and the natives call them dog-faced men

By the way, there was a tiger reported here this afternoon! One man came in and said he saw it take a chicken. And there isn't any door to this temple. What would you do under the circumstances? All the tigers in this province are man-eaters! I have made plans to try conclusions with this particular fellow to-morrow—but he may assume the offensive first. Don't think me an alarmist. I'm not. I'm merely telling you the cold truth about things. The other day when we were on our way up here we pulled up for the night beside a village. And all along the shore were the fresh tracks of two tigers. There was a lovely stretch of white sand, and it was bright moonlight, and so I kept the cabin window open and my rifle handy . . . . and I'll swear I woke up every 20 minutes and had a look out of the window. Next day we heard that 15 people had been killed by tigers in the neighborhood during the past month or so.

HEREDITY EXPERIMENTS IN THE TORTUGAS

Dr. Paul Bartsch, curator, division of mollusks in the Museum, has continued his heredity studies, for which mollusks of the genus *Cerion* are used as a basis. He visited the various colonies transplanted to the Florida Keys from the Bahamas, Curacao, and Porto Rico and made a careful study of the new generations which have arrived since last year. He reports a loss of all the material which was placed in cages last year for the purpose of studying the crossing products of selected pairs. A little experimenting led him to believe that this loss was due to the fact that the fine screen Monel wire used for the cages, which not only covered the sides but also tops of these structures, prevented dew formation on the vegetation in the inside of the cages and thus inhibited the moisture required by these organisms. A heavy dew forms at the Tortugas during the night, the time during which Cerions are actively foraging for food, which is largely gained by plowing immediately below the surface for fungal mycelial threads. It is more than likely that the lack of dew also prevented the proper formation of mycelia in the area enclosed by the wire meshes and the Cerions may therefore not only have been famished for want of water, but likewise starved.

Dr. Bartsch believes that these were the controlling factors for he found that by placing a piece of Monel wire over a board at some little distance from the board and leaving a portion of the same board uncovered, the part over which the wire was stretched was found dry in the morning, while the uncovered portion was duly covered with moisture. To overcome this all the tops of the cages were removed and a narrow fringe of wire, turned down at the distal edge, was placed around each to prevent the Cerions from escaping. The cages were then stocked with the same elements used a year ago.

Two additional cages were built. The sides and top of one were covered with paraffine treated cheesecloth and in the other the sides only were covered with this material. In these, specimens were placed in order to make sure that the contentions expressed above were the active factors in the killing off of last year's material, and that the attaching of the Cerions to the wire mesh of the sides of the cages, which become decidedly warm when the sun shines upon them, was not responsible.

The Newfound Harbor hybrid colony was found flourishing. A lot of dead specimens was brought to Washington for record.

Two new mixed colonies were established, consisting of 500 Florida grown specimens of *Cerion viaregis* Bartsch taken from Colony E, Loggerhead Key, and 500 *Cerion incanum* Binney from Key West. It is hoped that these two colonies will reproduce the conditions existing in the hybrid colony on Newfound Harbor Key. It was deemed wise to establish these colonies so that in the event a fire should sweep over the Newfound Harbor colonies the experiments might be continued in these additional places. The first of these colonies was placed on the east end of Man Key in a small, low meadow, which suggested the conditions in which the hybrid colony on Newfound Harbor Key is existing. The other colony was established on the north end of the little key east of Man Key, which may be called Boy Key.

Five hundred each of *Cerion viaregis, Cerion casablancae* and *Cerion incanum* were sent to Dr. Montague Cooke at Honolulu for colonization in the Hawaiian Islands.

Thanks to the good offices of the Navy Department, Dr. Bartsch was granted the use of a seaplane for a week. This was under the command of Lieut. Noel Davis and Lieut. L. F. Noble. By means of this plane Dr. Bartsch was able to fly at low altitude over all the keys between Miami, and the Tortugas and West Cape Sable and the eastern fringe of islands. During past years he had spent as much time as was available in the exploration of the Florida Keys, for the native *Cerion incanum* in order to establish the present extent of the colonies and to note what variation might exist in the members thereof. These colonies are usually found in the grassy plots on the inside of the keys and frequently in small grassy plots, which are difficult to discover as one approaches these mangrove fringed islands by water. To discover such colonies has usually meant cutting through the mangrove fringe to reach the interior, and there was danger of missing the smaller grassy plots. Flying over these keys made it easily possible to see all favorable places and to mark them on the charts. This will now permit a direct attack upon the places in question and determine positively the extent of existing colonies. Dr. Bartsch feels that at least a year of solid work was saved by the four days during which these explorations were made, to say nothing about saving an endless amount of punishment by mosquitoes which usually infest these mangrove fringed islands.

This aerial survey of the Bay of Florida also adduced the fact that the milky condition of that stretch of water which has obtained for some time and was probably responsible for the killing off of the greatest part of the marine flora and fauna of the region, has subsided, a state of affairs also noted in the Bahamas last year. It was found that the water was clear everywhere and that the channels as

FIG. 47.—A great white heron at Newfound Harbor Key. This is the younger brother or sister of the two now in the National Zoological Park, sent there by Dr. Bartsch in 1920 and 1921.

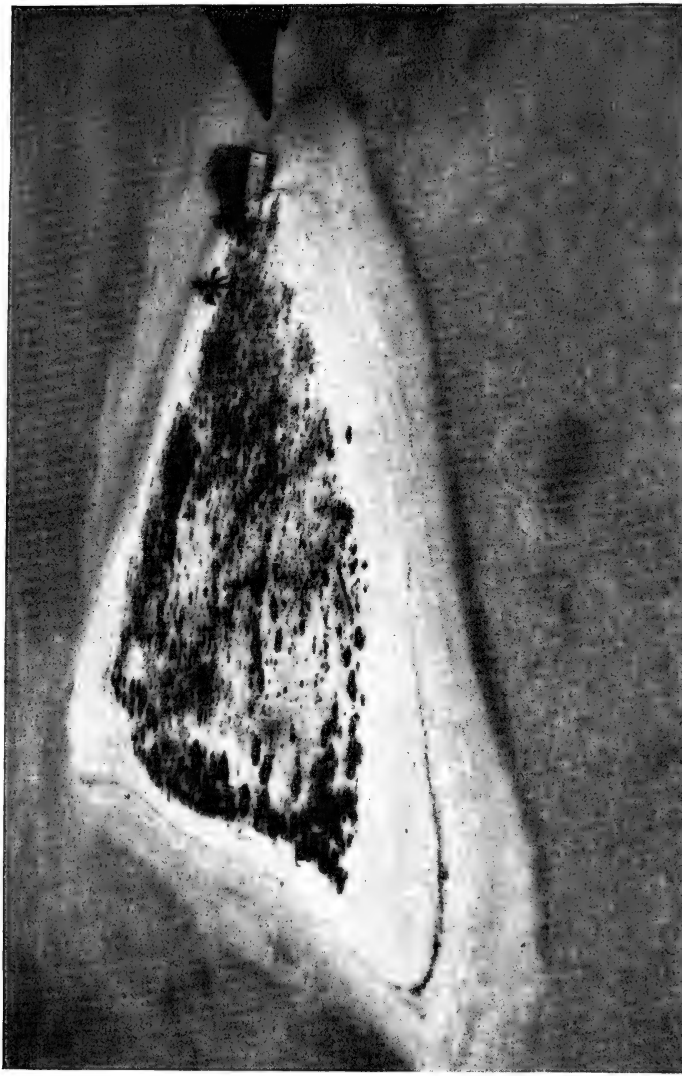


FIG. 48.—A photograph of Bird Key taken from the seaplane, showing the warden's house before removal and the scanty remnants of vegetation.

FIG. 49.—Upper figure showing the wave undermined condition of the warden's house on Bird Key before removal. Middle figure, the new location of the warden's house in the midst of the tern colony. Lower figure, Mr. Bethel, the warden, and his home in the new location.

well as the shallow flats were being repeopled by plants and animals. It will be interesting to note what, if any, change in the flora or fauna may ensue; that is, to what extent an additional West Indian element may be injected into the lower Florida reaches. The partial stamping out of the old fauna without serious physiographic or oceanographic changes in the region as far as physical features are apparently concerned is a rather interesting phenomenon and the re-establishment of a new flora and fauna will be equally noteworthy.

As heretofore, careful notes on the birds observed on the various keys visited were kept. One of the remarkable things resulting from the use of the seaplane was the finding of several colonies of the great white heron (*Ardea occidentalis*) which in previous years had been found breeding singly in the mangrove bushes. Two colonies of at least fifty each were found and several other colonies of lesser number. A photograph of a young of this year is shown in figure 47.

During Dr. Bartsch's stay at the Tortugas, the Navy Department, at the request of the U. S. Biological Survey, moved the warden's house on Bird Key. This necessitated the removal of a large number of eggs of the breeding terns which were on the point of hatching. Dr. Bartsch staked out the place to be invaded and removed all these eggs, giving the terns breeding in the area adjacent to the marked place each an additional egg, which all the birds accepted without protest. In this way, 2,420 foster parents were established and it is hoped many young sooty terns saved. Of the nests destroyed, only eight contained two eggs. All the others had one only. Figure 48 shows a photograph taken of Bird Key from the seaplane, by Dr. Bartsch, and figure 49 shows the old and new location of the warden's house.

There were but seven nests of the noddy tern in this region. The noddy tern on Bird Key is disappearing rapidly. Dr. Bartsch does not believe that there are 800 birds there at the present time. This is largely due to the fact that the vegetation was destroyed almost wholly by a hurricane a few years ago, and no serious efforts have been made to replace it. Unless some relief is found in this matter, both the sooty and noddy will undoubtedly become decidedly diminished in numbers because the young birds will not find the shade essential to their protection. It is again suggested, as heretofore, that a row of Australian pines and coconut trees be planted all around Bird Key, preferably alternately, and that the pines be kept topped so that they will become bushy and furnish a nesting site for the noddies. These trees grow very rapidly and should, in a very little while, furnish adequate home sites for the noddy tern. At the present time

FIG. 50.—Near view of two noddies on their tree nests, on Bird Key, taken five years ago.

FIG. 51.—This illustration shows transition stages from the tree breeding habit to the sand breeding stage depicted on the next plate. The upper figure shows a nest of dead twigs placed on the ground. The middle figure shows a number of nests placed among débris and rubbish on the site of the blown down house, while the lower figure shows an egg placed on a board.

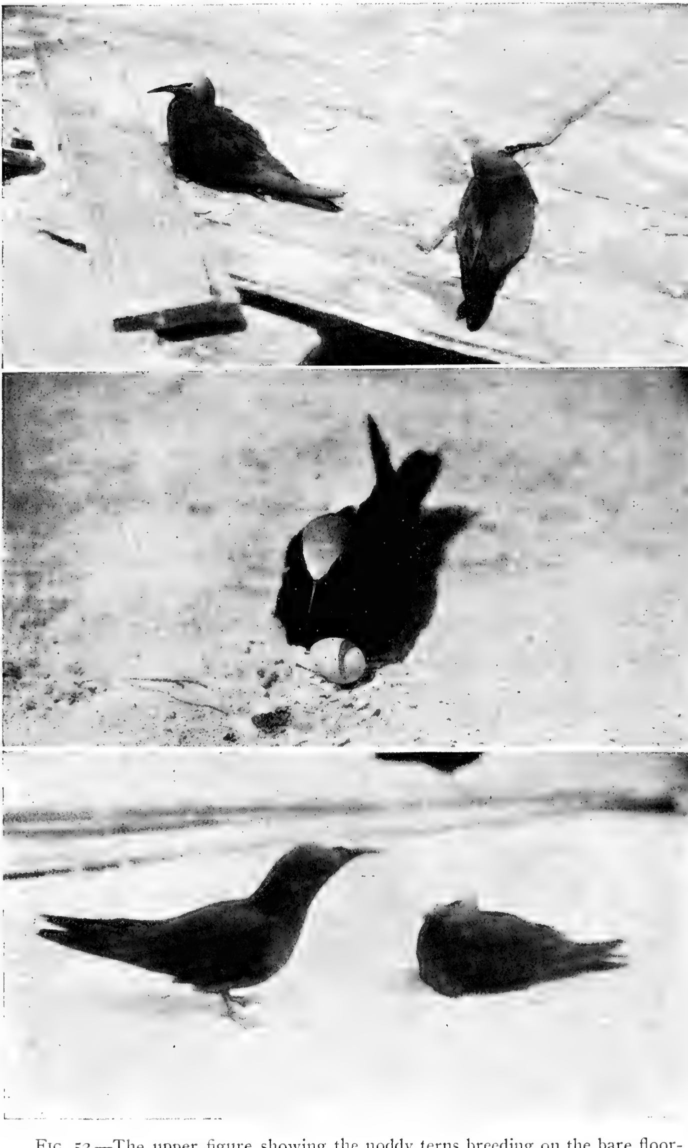


Fig. 52.—The upper figure showing the noddy terns breeding on the bare flooring, the major remaining portion of the structure of the blown down house. The middle picture shows a noddy and her egg on the bare sand, and the lower figure shows another pair in a similar location.

the noddy terns, which are tree and bush building birds, are making their homes in clumps of grass wherever these are available, or on old boards or even in bare sand. Their habits in the last 10 years have changed on this key almost completely, resulting in the shrinking of the colony from about 4,000 birds, as estimated by Dr. Watson, to about 800, Dr. Bartsch's estimate, at present. Figures 50, 51, and 52 show the changes that have taken place. The photograph of figure 50 was taken five years ago; the other two this year.

Another interesting observation made on birds was the large number of thrushes found, chiefly on Garden Key. These included the veery, the olive back, the hermit, Alice's and Bicnell's thrush, all rather emaciated. Evidently the place did not furnish adequate food for them. It was interesting to see these birds mingle with the colony of exceedingly active white rumped sand pipers, which frequented the outer sandy beach of Garden Key, and to watch them chase sand fleas on the beach for food.

COLLECTING TRIP TO JAMAICA

In February, 1922, Mr. John B. Henderson, a Regent of the Smithsonian Institution, desiring living specimens of Antillean Zonitid and Thysanophoroid landshells for anatomical study in connection with a monograph on these groups in preparation, proceeded to Jamaica to collect them. He made trips to Bog Walk on the Rio Cobre River, to Holly Mount on the summit of Mount Diablo, to Momague and to Brownstown in the Province of St. Anns. From the latter point he proceeded to St. Acre to complete for the Museum its series of fossil land shells occurring there in a Pleistocene deposit. From Brownstown he continued along the north coast to St. Anns Bay, collecting at numerous stations. A final trip was made to Morant Bay along the southeast coast. Although the time spent in the island was only a fortnight, the results were most satisfactory. About 40 species of land mollusks were expanded and preserved for study and as many more were collected for their shells only. Mr. Henderson also visited Panama for the purpose of learning the possibilities of obtaining suitable craft from the Canal Zone authorities for contemplated future dredging operations at Colon and Panama.

THE MULFORD BIOLOGICAL EXPLORATION

The National Museum has received the zoological material, other than reptiles, batrachians and fishes, collected by the Mulford Biological Exploration of the Amazon Basin, an expedition financed by the H. K. Mulford Co. of Philadelphia. The party consisted of Dr. H. H. Rusby, of the College of Pharmacy of Columbia University, director and botanist, W. M. Mann, assistant custodian of hymenoptera, National Museum, assistant director, N. E. Pearson of the University of Indiana, ichthyologist, O. E. White of the Brooklyn Botanic Garden, botanist, G. Schultz McCarty and two Bolivian students, Manuel Lopez and Martin Cardenas, who were detailed by

FIG. 53.—Start of mule train, La Paz, Bolivia. (Photograph by N. E. Pearson.)

the Bolivian Government to study entomology and botany with the expedition members, and was accompanied by Mr. Gordan MacCreagh and J. Duval Brown, moving picture photographers, representing the Amazon Film Company.

The expedition left New York on June 1, 1921, and proceeded to Arica, Chile, and from there to La Paz, Bolivia, where arrangements were made for transportation across the mountains. At Pongo de Quime (Alt. 11,500 ft.) above the timber line, a stop was made for several days and considerable zoological material gathered. From here to Espia the journey was by mule train. Espia is a spot at the junction of the Megilla and La Paz rivers which form the Rio Bopi. In August it was exceedingly dry and not very productive of specimens.

FIG. 54.—Nest of Hoatzin, Little Rio Negro, Bolivia. (Photograph by Mann.)

Mositana Indians at their village down the river built balsas or rafts and towed them up to where the party waited and the members floated down the Bopi into the Rio Beni and to Huachi, a small settlement, and remained in this vicinity for over a month, with several excursions to nearby regions, as Covendo where the mission is located, and up the Cochabamba River to Santa Helena, a locality visited

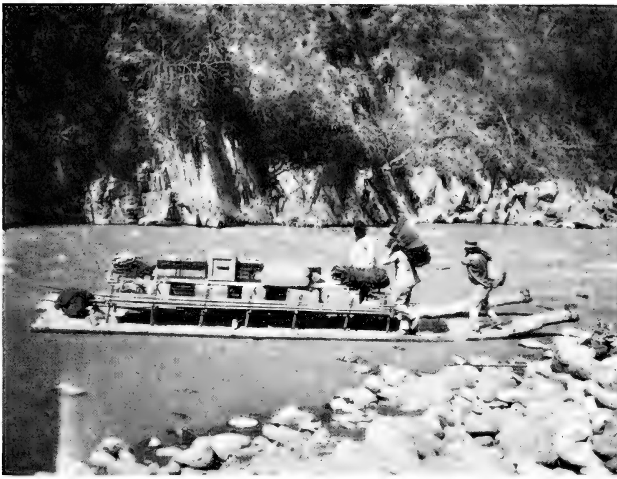


FIG. 55.—Loading a balsa, Rio Bopi, Bolivia. (Photograph by N. E. Pearson.)

FIG. 56.—Camp of Balseros (raft men), Mositana Indians, Rio Bopi, Bolivia. (Photograph by N. E. Pearson.)

FIG. 57.—Young tapir, Rio Beni, Bolivia. (Photograph by N. E. Pearson.)

FIG. 58.—Mósitana Indian girl at loom, Covendo, Bolivia. (Photograph by Mann.)

rarely by the Indians on hunting trips. This hilly, forested country was rich in animal life and large collections were made.

From Huachi the Beni was descended to Rurrenabaque, a short distance above the head of navigation on the Rio Beni, and over three months spent in this vicinity, with side trips across the pampa to Lake Rocagua, and to Tumupasa, a small village situated at the very edge of the Amazon Valley, and to Ixiamas, an isolated pampa region beyond Tumupasa.

Dr. Rusby, director of the expedition was compelled to return to the United States from Rurrenabaque, because of bad health. The

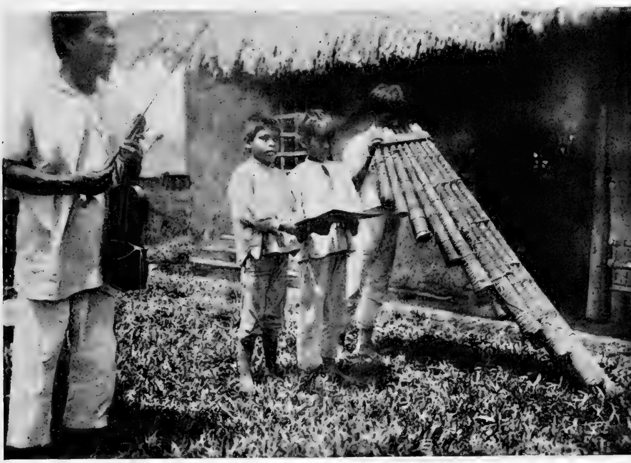


FIG. 59.—Church music, Ixiamas, Bolivia. (Photograph by Mann.)

party under Dr. Mann then went down river to Riberalta and afterward returned as far as the Little Rio Negro, where they spent several days collecting, and making short trips in the vicinity of Cavinas and up the Rio Madidi. In the region near the Lower Madidi several villages of Gorai Indians were visited and a small lot of ethnological material gathered.

A final stop was made at Ivon, at the mouth of the river of that name. Then the party proceeded to Cachuela Esperanza and from there to the Madeira-Mamore Railroad in Brazil where steamer was taken for Manaos and to New York.

The collection of living animals made by Dr. Mann on this expedition reached the National Zoological Park on April 15, 1922. In

FIG. 60.—Wasp nest made of clay, Rio Beni, Bolivia. Suspended from branch of tree over water.

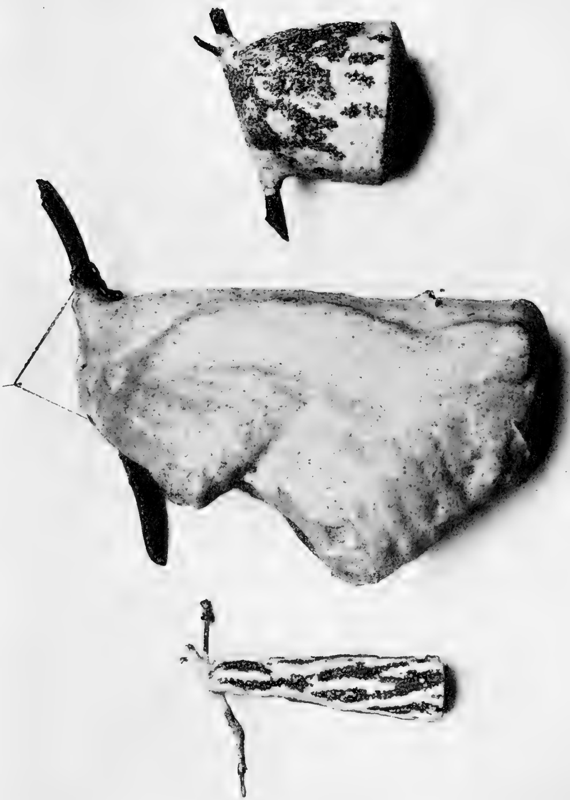


Fig. 61.—Wasp nests made of carton or paper-like substance, Rio Beni, Bolivia.
Suspended from branch of tree over water.

addition to a few specimens lost from the effects of the journey the collection included 15 mammals, 50 birds, and 17 reptiles that arrived in perfect condition. Among these are a number of very rare species never before exhibited in the Zoological Park. The red-faced spider monkey, black-headed woolly monkey, pale capuchin, choliba screech owl, Bolivian penelope, short-tailed parrot, Maximilian's parrot, blue-headed parrot, Cassin's macaw, golden-crowned paroquet, Weddell's paroquet, orange-crowned paroquet, and golden-winged paroquet are new to the collection. These and other rarities are mostly from Rio Beni, Bolivia, and the upper Rio Madeira, Brazil, localities from which animals seldom find their way into collections. Of special interest also are such rare birds as the festive parrot, Amazonian cacique, and white-backed trumpeter, and a number of reptiles. Very few collections containing so many rare species in such perfect condition have ever been received at the National Zoological Park.

The collection of insects secured by Dr. Mann was one of the largest single accessions ever received in the Division of Insects of the National Museum, estimated at 100,000 specimens. Only a small part has yet been examined. Some rare wasps' nests, made of carton and clay, were brought back in perfect condition. Ants received especial attention, and many biological observations were made upon them.

BOTANICAL EXPLORATION OF THE DOMINICAN REPUBLIC

Dr. W. L. Abbott spent the winter and spring of 1922 in further botanical exploration of the Dominican Republic, and was able not only to rework much of the region about Samaná Bay, but to make a thorough investigation of the entire southern portion of the Province of Barahona, as well as the cordillera north of San Francisco de Macorís. In the Province of Barahona he visited Barahona City, Paradis, Trujín, Enriquillo (Petit Trou), Los Patos, Polo, Maniel Viejo, and Cabral. The first four are small villages on or near the seacoast, south of Barahona City. The land here is for the most part low, rocky, and semiarid, except in the immediate vicinity of occasional springs and streams, but rises rapidly toward the interior to the Bahoruco Mountains. As the rock is limestone, caves and underground streams are frequent. One cave in particular, situated near Los Patos, is regarded by Dr. Abbott as promising valuable results to the ethnologist. Trujín, the most southern station reached on this trip, is on a large salt lagoon. Herman's coffee plantation, about 1,500 feet above Paradis, is of interest as being the source of earlier botanical collections by von Tuerckheim and by Fuertes.

Polo, a small settlement in the mountain region west of Barahona City, is situated on the edge of a long flat valley about one mile wide, evidently at one time the bottom of a lake. Just east of this village the Loma de Cielo rises to a height of 4,200 feet, while four miles northeast of Polo the Loma la Haut reaches an elevation of 4,500 feet. The former is covered with wet forests, while the timber of the latter is rather poor, having suffered from both the hurricane of 1905 and numerous recent forest fires. Forest fires have almost entirely destroyed the pine forests about Maniel Viejo, south of Polo, leaving nothing but dry scrubby thickets and bare slopes.

Exploration in the region of San Francisco de Macorís was confined to the vicinity of Lo Bracito, a small village on the southern slopes of Quita Espuela. These slopes are covered by humid thickets and forests, having, in fact, a reputation of being one of the wettest spots in the Dominican Republic and consequently affording a flora rich in ferns and mosses.

A collection of over 3,000 plants was procured, nearly 50 per cent of which are cryptogams. Many of the flowering plants collected represent shrubs and timber trees that are likely to prove of great interest.

Although the results of this expedition were chiefly botanical, Dr. Abbott collected also in other branches of natural history, his collections including specimens of mammals, birds, reptiles, fish, land shells, insects, and earthworms, as well as a small assortment of archeological material.

BOTANICAL EXPLORATION IN CENTRAL AMERICA

Botanical exploration in Central America during 1921 and 1922 was made possible by the cooperation of the Gray Herbarium of Harvard University, the New York Botanical Garden, Mr. Oakes Ames, the U. S. Department of Agriculture, and the National Museum. It was undertaken in order to obtain material for use in the preparation of a flora of Central America and Panama, which is now under way. Mr. Paul C. Standley left Washington in December, 1921, going by way of New Orleans to Guatemala, and directly to the Republic of Salvador.

Salvador, although the smallest of the Central American republics, has been the least known botanically, and previously hardly any collecting had been done there. With the fullest assistance of the Salvadorean Department of Agriculture, especially that furnished by Dr. Salvador Calderón, it was possible to make extensive collections

FIG. 62.—Scene near San Salvador, the Cerro de San Jacinto in the distance. The hills are composed wholly of volcanic ash.

FIG. 63.—Amate or wild fig tree (*Ficus* sp.) in San Salvador.

of plants in widely separated localities, covering nearly all parts of the country. All except three of the 14 departments were visited, and collecting was carried on in most of them. Five months were spent in the work, and 4,600 numbers, represented by about 15,000 specimens of plants, were obtained. The central and western parts of the country are densely populated and intensively cultivated, the moun-

FIG. 64.—Eruption from the secondary crater of the volcano of San Salvador in 1917. (Photograph by Dr. V. M. Huezo.)

tains being given over to the culture of coffee, which is often planted up to the very summits of the highest volcanoes. On this account, most of the natural vegetation has been destroyed, and conditions are not so favorable for botanical work as in the other Central American countries. There are forests still remaining on some of the volcanoes, and in the mountain chain known as the Sierra de Apaneca, which lies close to the Guatemalan frontier, and here it is possible to get some idea of the former state of the vegetation. In eastern Salvador there are extensive areas still uncultivated, but this land lies at a low altitude, where the flora is less interesting than at higher elevations. The highest mountains, it should be noted, are much lower than those of the neighboring countries, the largest of the Salvadorean volcanoes attaining an elevation of less than 2,500 meters. All the mountains are of comparatively recent volcanic origin,

FIG. 65.—Giant Ceiba tree in the city of San Salvador.

and several of the volcanoes are still active, an eruption of the volcano of San Salvador having wrecked the capital in 1917.

It is expected that there will be prepared for publication in Salvador a list of the species of plants obtained by this expedition, including also those collected by the Salvadorean Department of Agriculture, which is actively engaged in botanical exploration. Thus far only a small part of the collections has been studied critically, but it is already evident that a considerable number of undescribed plants is contained in them, besides many that are rare and little known. The flora of Salvador is essentially like that of the Pacific slope of Guatemala (which likewise has been but imperfectly investigated), but it is of great interest to find here many species that heretofore have not been known to extend north of Costa Rica and Panama.

Particular attention was devoted to securing the vernacular names employed in Salvador, and many hundreds were obtained. A part

Fig. 66.—Gathering Salvadorean balsam in forests of the Balsam Coast. (Photograph by Dr. V. H. Huezo.)

of the country was occupied before the Spanish conquest by people who spoke a dialect of the Nahuatl language, the idiom spoken also by the inhabitants of the Valley of Mexico, although not or scarcely known in the intervening territory of Guatemala. A large part of the names now used here for plants are of Nahuatl origin, some of them being the same as those employed in Mexico, while others are quite different. Besides these philological notes, much information was secured regarding economic applications of the plants of the country. Salvador is especially rich in valuable cabinet woods, a remarkably large number of plants with fruits or other parts that are edible occur, and hundreds, probably, of the native plants are employed by the country people because of real or supposed medicinal properties. The most interesting of all the native plants is the balsam

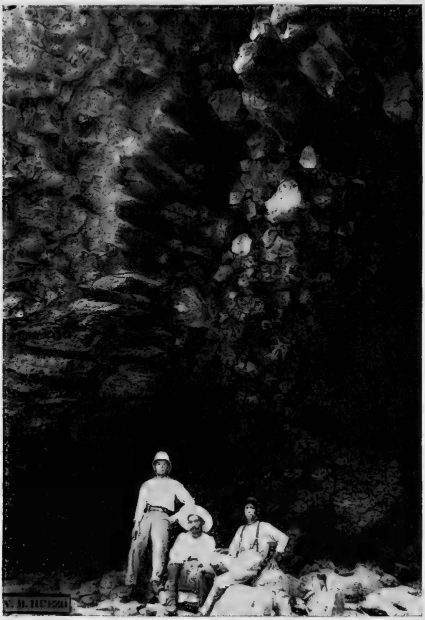


FIG. 67.—Basaltic formation in the Department of La Libertad, Salvador.

tree (*Toluifera pereirae*), from whose sap is secured the article known as Salvadorean balsam or sometimes, erroneously, as balsam of Peru, because of the former belief that it came from Peru. Although this tree is widely distributed in tropical America, the balsam is gathered almost exclusively in Salvador, and in a limited portion of the country, known as the Balsam Coast. Other noteworthy trees are the giant ceibas and the *amates* (*Ficus* spp.) or wild figs, which are sometimes called the "national tree" of Salvador. They are

FIG. 68.—Coconut trees in a Salvadorean finca.

FIG. 69.—Coast of Salvador, in the Department of La Libertad. The rocks are mostly of recent volcanic origin. (Photograph by Dr. V. M. Huezo.)

common and characteristic features of the landscape, and almost every country dwelling has its particular *amate* tree.

Mr. Standley left Salvador early in May and proceeded to the north coast of Guatemala, where superior facilities for work were furnished through the kindness of the United Fruit Company. About three weeks were spent at Quiriguá, a locality long famous archeologically because of the ruins of an ancient Mayan city which are located here. Over a thousand numbers of plants were collected, chiefly trees and shrubs, many of them of great interest. The most conspicuous feature of the vegetation of this part of Guatemala is the enormous plantations of bananas which are grown to supply the markets of the United States. Adjoining these plantations are boundless areas of swamp and hilly woodland which remain in their natural condition. Especially noteworthy are the "pine ridges," low hills covered with scattering pine trees and occasional groups of the cohune palm. The vegetation on these hills is strikingly like that of the Everglades region of southern Florida, and the whole country looks about as Florida might if it were crumpled up into hills, instead of being almost perfectly level.

After leaving Quiriguá, about a week was spent in collecting at Puerto Barrios, on the north coast of Guatemala. The land here is nearly all swampy, but at this time of the year (early June), at the end of the dry season, it was possible to walk about in the swamps and gather plants that at other seasons of the year are inaccessible.

Altogether six months were spent in Salvador and Guatemala, and a collection of over 6,000 numbers of plants was obtained, which will add materially to previous knowledge concerning the Central American flora. The data concerning distribution and the notes upon vernacular names and economic applications will contribute greatly to the completeness of the flora of Central America which it is proposed to publish.

BOTANICAL EXPLORATION IN COLOMBIA

Between the months of April and October, 1922, Dr. Francis W. Pennell, curator of the herbarium of the Philadelphia Academy of Natural Sciences, and Ellsworth P. Killip, of the Division of Plants, National Museum, carried on botanical exploration in the Republic of Colombia. The expedition was organized by the New York Botanical Garden, the Gray Herbarium of Harvard University, the Philadelphia Academy of Natural Sciences, and the National Museum as part of a general plan, adopted in 1918, for botanical research in northern South America. Financial assistance was given also by Mr. Oakes

FIG. 70.—Arid valley of the Dagua River, Colombia. The transition from a luxuriant rain-forest to this dry "pocket" is very abrupt. (Photograph by T. E. Hazen.)

FIG. 71.—View to the north from La Cumbre, in the Western Cordillera, Colombia. The wooded valleys are filled with orchids. (Photograph by T. E. Hazen.)

Ames. Mrs. Pennell accompanied her husband, returning in July, and Dr. Tracy E. Hazen, of the Biological Department of Columbia University, was a member of the party from July to September, giving special attention to photography.

FIG. 72.—Dense forest at La Cumbre, Colombia. Plants of the Tropical Zone here mingle with the subtropical vegetation.

The Republic of Colombia occupies the northwestern corner of the continent of South America, facing both the Caribbean Sea and the Pacific Ocean. The Andes Mountain chain, extending northward in practically a single range from its origin in southern Chile, divides at the southern boundary of Colombia into three branches, known as the Western, Central, and Eastern cordilleras. Between the Western and the Central cordilleras lies the valley of the Cauca River; between the Central and the Eastern, the Magdalena River. On the present trip it was possible to visit only the Western and Central cordilleras, the Cauca Valley, the city of Bogotá in the Eastern Cordillera, and one or two localities on the Pacific slope. The expedition entered the country at Buenaventura, the principal seaport on the Pacific, and at once established headquarters at the village of La Cumbre, in the Western Cordillera, for the purpose of studying the vegetation of the central part of this range. Descending to the

FIG. 73.—View from the summit of the Western Cordillera toward the Pacific slope, Colombia. The peaks are more angular than noted in other regions.

city of Cali the party proceeded up the Cauca Valley to Popayán, the southern portions of both the Central and the Western cordilleras being explored from this point. Subsequently trips were made to Salento, in the northern part of the Central range, and to Ibagué and Bogotá, material being collected at historic localities along the Quindiu Trail. Dr. Pennell sailed from the north coast, after exploring the northern portion of the Western Cordillera, Dr. Hazen and Mr. Killip returning by way of Buenaventura and the Panama Canal. Approximately 7,200 numbers were collected, sufficient material being secured to make nearly equal sets for each of the institutions associated in the expedition. Particular attention was paid to orchids, a group in which Mr. Ames is especially interested. To dry these specimens required the use of artificial heat, the plants being put between driers and corrugated boards, bound tightly in packages, and placed over a charcoal-burning heater.

As might be expected from its physiography, the vegetation of Colombia is extremely diverse. Within a few miles may occur a luxuriant tropical flora, the more open woods of the temperate zone, and the low alpine growth familiar on our American mountain tops. Again, as in the Dagua Valley, one may ride through a dense rain-forest, filled with ferns, mosses, and aroids, to emerge suddenly in an arid, desert-like region where cacti and acacias are the conspicuous plants.

FIG. 74.—Crest of the Western Cordillera at El Derrumbo, 9,500 feet altitude, Colombia. Here occurs the stunted growth of the temperate zone.

Since Colombia lies between the first and eleventh parallels, the development of its vegetation is little influenced by latitude. The controlling factors are altitude and precipitation, the rainfall ranging from 400 inches a year to almost perpetual dryness. Four zones of plant life may be recognized, the limits being approximately as follows: Tropical, from sea-level to 5,000 feet; Subtropical, from 5,000 to 9,000 feet; Temperate, from 9,000 to 12,000 feet; Páramo, above 12,000 feet. The tropical forests are very dense; giant-leaved aroids, bromeliads, and heliconias are most abundant; everywhere are palms and bamboos. In the subtropical forests orchids become more common, many of them being of great beauty; tree trunks are densely

FIG. 75.—Raft-building on the Cauca River, Colombia. The ever-present bamboos and palms supply the material needed.

FIG. 76.—Crossing the Vieja River, a tributary of the Cauca, Colombia. As there is no bridge at this point, cargo must be removed from the mules and transported in native dug-out canoes.

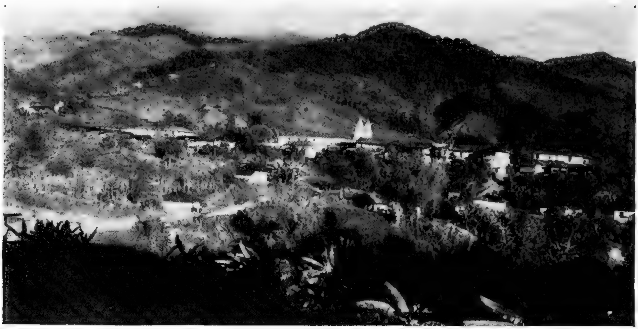


FIG. 77.—Village of Salento, in the Central Cordillera, Colombia. Through this town passes the historic Quindiu Trail, reaching from Cartago to Ibagué.

FIG. 78.—Upper valley of the Quindiu River, Colombia. The forest land is being cleared out for pasture. (Photograph by T. E. Hazen.)

covered with mosses, hepaticae, and ferns. In this zone occasionally occur oak forests, recalling vividly our northern woods, and blackberries are to be found. The Temperate Zone is a region of small-leaved, usually dwarfed trees, of blueberries and other ericaceous shrubs, and of open hillsides, where geraniums and Andean genera of the rose family are numerous. The Páramo is the bleak open country between timberline and the snows. Here flourish densely woolly espeletias, bizarre senecios, and many other brilliantly flowered herbaceous plants.

Travel in Colombia is by railroad, by boat, and by horse or mule. Railroad construction has necessarily been slow, no road having yet been built over the Central Cordillera, while only a single line crosses the Western Range. In the Cauca Valley construction is being pushed, though only a small portion of the line has been completed. Boat travel is fairly satisfactory, and the scenery along many of the streams is very picturesque. The Cauca, navigable for good-sized steamers between Cali and Puerto Caldas, winds its way down a broad valley, in the main keeping to the western side, the banks lined with palms and bamboos. On one hand are the hills of the Western Cordillera; on the other, the higher mountains of the Central range. But to the botanist travel by horse or mule, though slower, is far preferable, since it affords opportunity to collect thoroughly in specially favorable places. So inadequately known is the flora of Colombia that even along the regular routes of travel many species are found that are either new, unrepresented in American herbaria, or known only from specimens preserved in European collections.

The Colombians are of Spanish descent and are mostly well educated, many of them having studied in American and European universities. Even among the lower classes illiteracy was rarely met with. The Indians, found chiefly in the mountainous regions of the interior, seem to be peaceful and industrious. No "wild savages" were seen, although members of the expedition reached remote corners of the country. Indian women delight in gay colors, a blue waist and a scarlet dress being a particularly favorite combination; the men dress more somberly and more scantily, often wearing merely a black smock reaching barely to their knees. The negroes are confined mainly to the coastal strips and to the warmer parts of the main valleys.

Perhaps the most lasting impression one brings back from Colombia is that of the unaffected friendliness of the people. Everyone, from

FIG. 79.—Upper valley of the Quindiu River, Colombia. Part of the forest has been supplanted by pastures. The palm is *Ceroxylon andicola*, or a closely related species.

FIG. 80.—Páramo above Bogotá, Colombia. From this lake arises one of the important tributaries of the Orinoco River.

the highest official to the lowliest peon, showed marked courtesy and hospitality to the members of the expedition. Customs officials made entrance into the country easy; railroad men were most helpful in

Fig. 81.—Apparatus for drying specimens. The bundle of plants rests upon two poles. From this, cloth is draped about the charcoal-burning heater, being lined with woven wire to prevent its being blown into the fire.

every way; landowners continually were placing their haciendas at the disposal of the party. Much of the success of the expedition was due to this universal spirit of friendly cooperation.

VISIT TO EUROPEAN HERBARIA

Mrs. Agnes Chase, assistant custodian of the Grass Herbarium, National Museum, visited several of the larger herbaria in Europe during 1922 for the purpose of studying the grass collections. Five weeks were spent in Vienna. The herbarium of Professor Eduard Hackel, whose work on the genera of grasses in Engler & Prantl's Pflanzenfamilien is the accepted one in current use, is deposited in the Naturhistorisches Staatsmuseum, Vienna. Professor Hackel has described about 1,200 species from all parts of the world, probably half of them from South America. The types of all but about 50 were found. Most of the missing types were found later in the herbaria whence he had borrowed material. Besides this collection, of greatest importance to American agrostology, the Vienna herbarium was found to contain many American types of Weddell, Philippi, Doell, and Mez, as well as classic collections such as Lechler's plants of Chile, D'Orbigny's from the Andes, Mandon's from Bolivia, and Spruce's from the Amazon, upon which many species are based.

A visit was made to Prof. Hackel at Attersee in western Austria, and important but unrecorded items in the recent history of agrostology were secured.

In Munich were found the types of Nees's Flora Brasiliensis, a few of Doell's and several of Mez's. At the Museo e Laboratorio di Botanica in Florence, Italy, types of Poiret, Poiteau, and Bosc were studied. Poiret was the author of the grasses in the supplement to Lamarck's Encyclopedia. His descriptions, like Lamarck's, are indefinite. It was necessary to see his plants to be certain of his species. Poiteau botanized in Santo Domingo in the latter part of the 18th century, and made a brief visit to the United States. Bosc was a friend of Michaux, and came to Charleston in 1798, where Michaux had established a propagating garden. During the next two years he collected in the Carolinas. In Pisa there is a small but very important collection, that of Joseph Raddi, whose Agrostografia Brasiliensis, published in 1823, is the earliest work devoted to South American grasses. These were collected by Raddi himself in 1817-18. The Agrostografia contains 64 species of grasses, of which 33 are de scribed as new. A number of these had never been identified. The specimens were found to be unusually ample and well preserved, and photographs were obtained of them. (Fig. 82.)

Ten days were spent at the Delessert Herbarium at Geneva. This herbarium contains, besides full series of the more recent collections, several old herbaria. Of great importance to the agrostologist is the herbarium of Palisot de Beauvois, whose small volume "Essai d'une nouvelle Agrostographie," published in 1812, has caused much trouble for the agrostologist, because of his misunderstanding of the structure of grasses. An examination of his specimens, fragmentary though they are, cleared up many difficulties. At Delessert a number

FIG. 82.—*Raddia brasiliensis,* named by Bertoloni for Joseph Raddi in a preliminary paper. Raddi himself referred the species to *Olyra* and gave it a new species name. It is recognized today as *Raddia brasiliensis.*

of grasses collected by Rafinesque in the United States were also found. Types of Nees, Schrader, Kunth, Willdenow, Sprengel, Link, Pilger, and Mez were studied at the herbarium of the Botanical Garden, Berlin.

Visits were made to the Rijks Herbarium at Leiden, and to the herbarium of the Jardin Botanique d'l'État at Brussels.

Two very profitable weeks were spent at the herbarium of the Paris Museum. In this institution the Lamarck Herbarium and that of Michaux are segregated. Dr. A. S. Hitchcock had studied these collections in 1907. Mrs. Chase made drawings and took some additional photographs. The Paris Herbarium is exceedingly rich in early American collections, such as those of Humboldt and Bonpland, Poiteau, Gaudichaud, Bourgeau, and D'Urville. The Fournier Herbarium, the basis of Fournier's Mexicanas Plantas, was of very great interest.

An important early paper on American species of *Paspalum* was by LeConte, 1820, an American of French descent. His herbarium is deposited in the Academy of Sciences, Philadelphia. When the collection there was studied a few years ago some of his species were not represented. Dr. Asa Gray, in a biographical note on LeConte, states that LeConte took his collection with him on a visit to France and that he was very generous in allowing his friends to have specimens. It was a great satisfaction to find the missing LeConte specimens in the Paris Herbarium.

Two weeks were spent in London, studying the grasses in the Kew Herbarium and in the herbarium of the British Museum. Both of these herbaria contain much that is of greatest importance to American agrostology.

Botanizing in herbaria does not afford the same pleasure as does botanizing in the field, but it is not without its thrills of discovery. Current concepts of several species were found to be erroneous; that is, our ideas were those of later authors instead of those of the original ones.

RECENT DISCOVERIES OF ANCIENT MAN IN EUROPE

Under a grant from the Joseph Henry Fund of the National Academy of Sciences, and upon the conclusion of his work as chairman of the American Delegation to the XX International Congress of Americanists at Rio de Janeiro, Dr. Aleš Hrdlička proceeded to Europe to examine the more recent discoveries of skeletal remains of early man and several of the most important sites where these discoveries have been made.

In this quest Dr. Hrdlička visited Spain, France, Germany, Moravia and England. The important specimens studied included the jaw of Bañolas in Spain; the La Quina site and specimens in southern France; the La Ferrassie skeletons, now beautifully restored, in Paris; the Obercassel finds in Bonn; the Ehringsdorf discoveries and site at Weimar and at Ehringsdorf; the Taubach site near a village of that name, with the specimens at Jena; and the principal Předmost skeletons now preserved in the Provincial Museum at Brno, as well as the site of these important discoveries at Předmost (in northern Moravia) itself. In addition to these, thanks to the courtesy of Dr.

FIG. 83.—Side view of the reconstructed La Quina skull.

Smith Woodward, Dr. Hrdlička was enabled to submit to a thorough study the Piltdown remains at the British Museum of Natural History, and to see there the originals of the Boskop skull as well as the highly interesting Rhodesian skull and parts of skeleton, from South Africa. He was finally once more able to see, at the Royal College of Surgeons, London, the originals of the Galley Hill and Ipswich skeletal remains.

FIG. 84.—Top view of a cast of the intracranial cavity of the La Quina skull, showing the shape of the brain. The brain, compared with modern specimens, is small and especially low.

The examination of the specimens and the visits to the sites where most of them were discovered, produced a deep impression on the one hand of the growing importance as well as complexity of the whole subject, and on the other of the vast amount of the deposits in western and central Europe bearing remains of early man and giving great promise for the future. It was also once more forcibly impressed upon the mind of the observer how much more satisfactory is the handling of the original specimens than of even the best made casts.

So far as the scientific results of the trip are concerned, Dr. Hrdlička feels confident that he was able to reach a definite conclusion and position as to the human nature of the Piltdown jaw; to satisfy himself on the more or less intermediary nature, between Neanderthal and the present type of man, of the Obercassel, the Předmost and some other crania; and to see the admirable restorations of both the La Ferrassie and the very important La Quina discoveries, the latter including the highly interesting and, so far as ancient remains of man are concerned, unique specimen of a well-preserved skull of a child.

Plaster casts of nearly all the important specimens not yet represented in the U. S. National Museum were obtained for the Institution.

MEETING OF INTERNATIONAL CONGRESS OF AMERICANISTS IN BRAZIL

The twentieth meeting of the International Congress of Americanists at Rio de Janeiro, Brazil, was attended by Dr. Walter Hough and Dr. Aleš Hrdlička, who were delegated by the Department of State and the Smithsonian Institution. Through the aid of the Carnegie Endowment for International Peace means were supplied for the journey of these delegates. A successful meeting of the Congress is reported, the effect of which on the promotion of anthropological science in Brazil is believed by the delegates to be important. While there was not time to travel in Brazil more than in the environs of Rio, it was interesting to view the resources of the capital as an index to the progress of the country. In this center there is a historical department, a national library, a national museum, fine arts institution, botanic garden, athletic club, and all the activities relating to engineering, sanitation, commerce, etc., reflecting modern conditions. There is seen a tendency at present to lay more stress on historical researches than on science, but the nucleus is here to be developed in such a way as the future affords. In some lines science is being adequately treated as in General Rondon's work among the Indians,

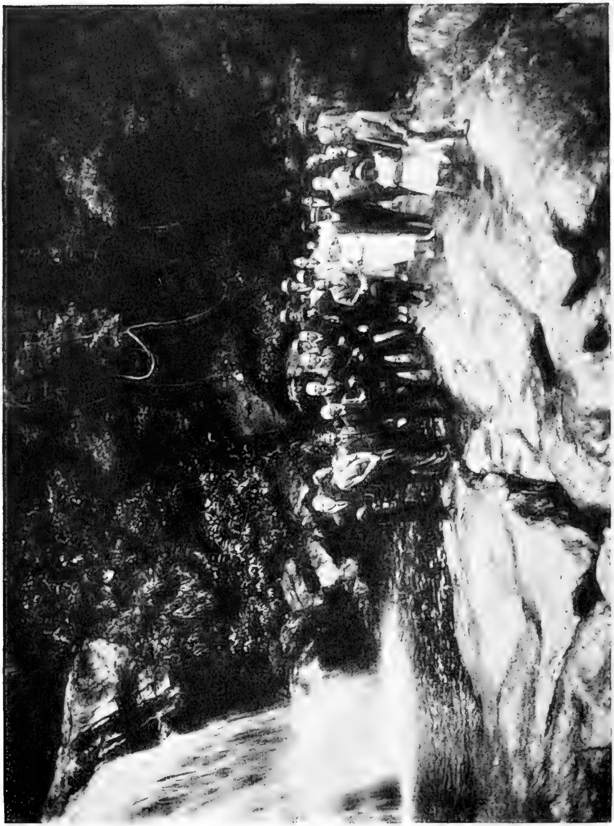


FIG. 85.—Members of the International Congress of Americanists at Cascatinha on road to Tijuca, September, 1922. Rio de Janeiro, Brazil.

which has resulted in the gathering of important collections and in the publication of valuable ethnological studies, especially by General Rondon's assistant, Dr. E. Roquette-Pinto.

EXPLORATION OF THE PALEOLITHIC REGIONS OF FRANCE AND SPAIN

During the month of September, 1922, Mr. M. W. Stirling, aid in the Division of Ethnology, National Museum, in the company of of Mr. P. J. Patton, a student in the University of Paris, explored the paleolithic regions of southern France and northern Spain. All of the important sites where remains of ancient man have been discovered were visited, and in addition a great many caves unknown to science were entered.

The idea has become prevalent in America that this region has been practically exhausted archeologically. Although the previous existence of paleolithic man in this locality has been known for half a century, it may be truly said that the work of exploration has hardly begun.

The habitations of the Stone Age are closely linked with the limestone formation which overlies large areas in this part of Europe. These may be said to fall into two classes, *i. e.,* rock shelters and caverns. The former are undercuts in the limestone, made by the rivers during the early Pleistocene or late Pliocene. A general elevation of the land has caused the streams to deepen their channels, thus leaving the undercuts well above the surface of the water. These were utilized as dwelling places by paleolithic man and in many instances were artificially modified. There are literally miles of relic bearing deposits of this class that have not yet been touched. The possibilities in this field are very great.

The caverns of the Dordogne region are for the most part comparatively small, while those in the department of Ariege are immense caves of a most spectacular nature. Of the former class are the grottoes of Font du Gaume, Combarelles, La Mouthe, Marsoulas, Montesquieu, and others. Of the latter class are the immense caves in the neighborhood of Foix, as for example, Salignac, Ussat, and Niaux. The tunnel of Mas d'Azil is the remnant of such a cave.

Many of these caverns have become blocked with sediment owing to the fact that they frequently slope downward from the entrance. Messers. Stirling and Patton entered at least a dozen such caves which had become sealed at varying distances from their mouths. The opening of such caves has heretofore been left almost entirely to chance. Scientific endeavor at this work should produce most

Fig. 86.—Pal, a typical village of Andorre, showing slate roofs and stone construction of houses. Note the terraces on the bare rock hillside back of the village. Every foot of soil is made available for cultivation.

Fig. 87.—An old bridge in Andorre. The verdure in this scene is exceptional. Andorre as a whole is practically treeless.

fruitful results. The sealing of these caves has been a fortunate accident of nature, since the contents are by this means preserved intact.

Of the regions visited, that in the neighborhood of Altamira, in Spain, and Ussat, in France, give most promise of rich returns to the archeologist.

A few days were spent in the republic of Andorre. This little semi-independent state contains much of interest to the ethnologist. Here one finds medieval customs and usages still functioning in the same manner that they did in the middle ages.

Located in the rugged mountains between the Spanish province of Lerida and the French department of Ariege, it is very difficult of access. Preserved from innovations by rival jealous potentates as well as by the conservative temper of its inhabitants, it has kept its medieval institutions almost intact. The administration of minor matters of justice and legislation is in the hands of local councils chosen from the heads of families in each of the six parishes into which the state is divided. The central government is vested in two *viguiers,* one nominated by France and the other by the Bishop of Urgel in Spain. Serious crimes and important cases in dispute are brought before them for judgment. There being no written laws, their decisions are given according to their consciences, and are final.

The population is entirely self-sufficient, and each family is an independent unit, raising their own produce, grinding their own meal, and making their own clothing. The primitive nature of their farming and household implements and utensils make an interesting study.

ARCHEOLOGICAL FIELD-WORK ON THE MESA VERDE NATIONAL PARK, COLORADO

In the year 1922, from May to August, inclusive, Dr. J. Walter Fewkes, chief of the Bureau of American Ethnology, continued his archeological investigations, begun 15 years ago, on ruins of the Mesa Verde National Park, Colorado. The brief season's work was financed with small allotments from the Bureau of American Ethnology and the National Park Service. He had for assistants Messrs. W. C. McKern and J. H. Carter, who contributed much to the success of the summer's work. The site of the field operations was the so-called Mummy Lake village, better named the Far View group of mounds (fig. 88) through which runs the government road to Mancos. The group is situated about 4¼ miles north of Spruce-tree Camp, contains 16 large stone buildings, many indicated by mounds of stone, sand, and a luxurious growth of sage brush. The three of

FIG. 88.—Mound in Far View House Group, before excavation. Situated at Far View Junction, Mesa Verde National Park, Colorado. A few sage bushes have been removed, but otherwise no change. (Photograph by Geo. L. Beam. Courtesy Denver and Rio Grande Western Railroad.)

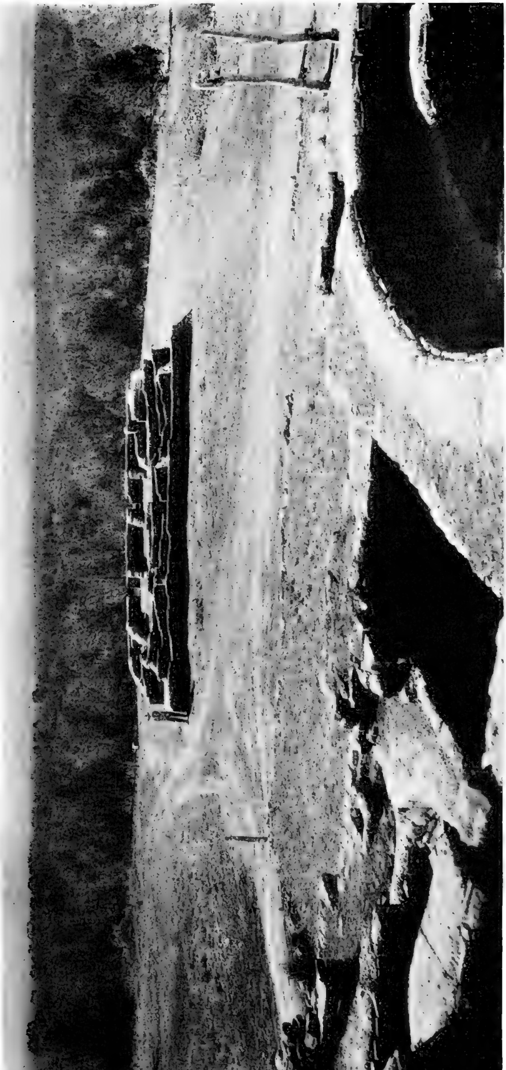


FIG. 89.—Pipe Shrine House looking south from Far View House, Mesa Verde National Park, Colorado. (Photograph by Geo. L. Beam. Courtesy Denver and Rio Grande Western Railroad.)

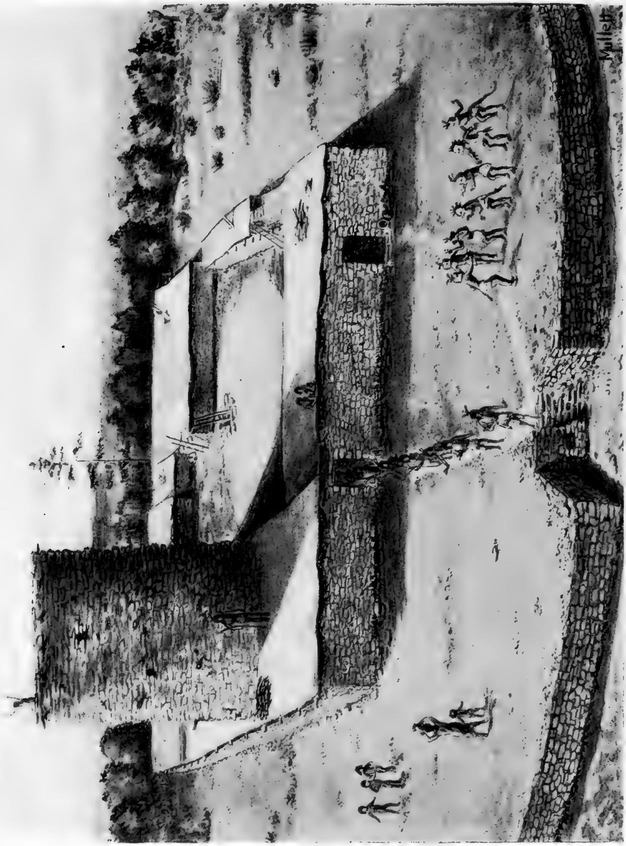


Fig. 90.—Restoration of Pipe Shrine House, Mesa Verde National Park, Colorado. Made from data collected during field-work in 1922 by the Bureau of American Ethnology of the Smithsonian Institution.

View from the south showing priests carrying offerings to the shrine of the mountain lion in the recess of the retaining wall and a line of dancers personating bird gods.

these which have thus far been excavated belong to different types; but it is desirable to examine and repair them all in order to discover other types. Indian corn, the national food of the cliff-dwellers, should be again planted in this area so that the future student or tourist could behold a Mesa Verde village in approximately the same environment as in prehistoric times. The first of the mounds was excavated by the Bureau of American Ethnology in 1916, and was called Far View House, and the particular mound chosen for excavation in 1922 lies about 100 feet to the south of it (fig. 89) or on the southern edge of the sage-brush area.

FIG. 91.—Distant view of Pipe Shrine House. This view shows the whole north wall and the east wall foreshortened. The group of men at extreme left are looking at skeleton in cemetery. (Photograph by Geo. L. Beam. Courtesy Denver and Rio Grande Western Railroad.)

The only noticeable characters of the mound when work began were a saucer-like central depression, and an elevated rim, which led Dr. Fewkes to suspect a buried subterranean kiva surrounded by a series of rooms above ground. The mound was covered by a dense growth of vegetation. No walls were seen when this was removed, and much accumulated sand, earth, and stone had to be removed before any masonry was visible. Complete excavation revealed a remarkable building or pueblo (figs. 89, 91) presenting to archeologists several new problems for solution.

The large depression turned out to indicate a central kiva (fig. 92) quite unlike that of any other on the Mesa Verde National Park. This room has no central fireplace; no ventilator or deflector to dis-

FIG. 92.—Interior view of kiva of Pipe Shrine House, looking north, showing shrine where pipes were found on floor. The ruin in the distance is Far View House. (Photograph by Geo. L. Beam. Courtesy Denver and Rio Grande Western Railroad.)

tribute fresh air; but in place of these a segment of the floor was separated from the remainder by a low curved ridge of clay. This area was a fireplace, as indicated by the large quantity of ashes and burnt wood it contained, and many artifacts mixed with the ashes showed that it served also as a shrine. Among other objects in it were

FIG. 93.—Several pipes from shrine on the floor of the kiva of Pipe Shrine House. Reduced a little less than one-half.

a full dozen decorated tobacco pipes made of clay, some blackened by use, others showing no signs that they had ever been smoked. Several of these are figured in the accompanying illustration. There were fetishes, a small black and white decorated bowl, chipped flint stone knives of fine technique, and other objects. For many years it had been suspected, that the ancient inhabitants of the Mesa Verde cliff dwellings were smokers, but these pipes (figs. 93, 94) are the first objective evidence we have to prove it, and the fact that these objects were found in the shrine of a sacred room would indicate that they were smoked ceremonially, as is customary in modern pueblo rites. Evidently the priests when engaged in a ceremonial smoke sat about this shrine and after smoking threw their pipes as offerings into the fireplace. Probably as with the Hopi every great

FIG. 94.—Pipes and other objects in shrine, as found. In addition to pipes many other objects were found, among which may be mentioned small black and white bowl, flint knives, idols, and "septarian nodule." (Photograph by J. W. Fewkes.)

ceremony opened and closed with the formal smoking rite at this shrine, and one can in imagination see the priests as they blew whiffs of smoke to the cardinal points to bring rain.

The discovery of pipes for ceremonial smoking in a Mesa Verde kiva is a significant one, indicating that the ancient priests of the plateau, like the Hopi, smoked ceremonially. Moreover the forms of the prehistoric pipes (fig. 93) thus used differ materially from those of modern pueblos, in size and shape, although a few formerly used by the Hopi have much in common with them.

The walls of the kiva show structural variations from a standard Mesa Verde kiva. There were eight instead of six small mural pilasters, an addition of two to the usual number; evidently the roof of this subterranean chamber was vaulted and as its size was large it needed more than the regulation number of supports for the roof

FIG. 95.—Interior of Pipe Shrine House looking southwest across the central kiva. (Photograph by W. R. Rowland, Durango, Colorado.)

beams. Although the means of entrance to the room is unknown there was probably a hatchway in the roof, but no sign of a ladder was discovered and no vertical logs to support rafters were seen.

The stones and plastering of the inner walls of the kiva indicate everywhere a great conflagration; the beams of the roof had completely disappeared, and the color of the adobe covering of the walls was a bright brick-red. The kiva measured about 24 feet in diameter and was about the same depth. Its roof served as the floor of a court surrounded by one-storied rooms. There was no large banquette on its south side (fig. 95) as almost universally occurs in a regular Mesa Verde kiva. A conspicuous slab of rock set in the floor near the rim of the shrine was possibly reserved for an idol or the altar during ceremonies.

Midway in the length of the west side of the ruin there remain foundations of a circular tower whose wall once rose, like a minaret, several feet above the roofs of surrounding rooms. The altitude of this tower was no doubt formerly sufficient for a wide outlook, and its top, rising above the cedars, served as the elevation from which the sun priests watched the sun's position on the horizon at sunrise and sunset. It was perhaps built as an observatory for determining time for planting and other agricultural events, and may likewise have been used in certain solar rites.

Fig. 96.—Storage jars in place as found in northeast corner room of Pipe Shrine House. Four of these made of corrugated and one smooth white ware with black decoration. (Photograph by J. W. Fewkes.)

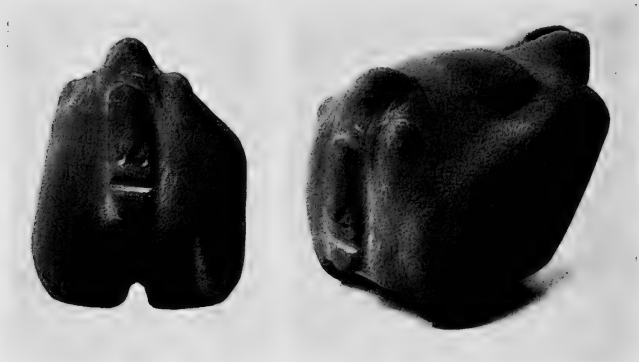
The chambers surrounding the central kiva do not appear adapted for habitations; several were more likely used for storage of food, or for other secular purposes. In a room situated on the northeast angle several pottery vessels were found arranged in a row (fig. 96). It would appear that the site of the kiva was dug out by the ancients before these rooms were built, and that the rooms forming the north side were built later than the others and constructed of poorer masonry than those of the south side, where the masonry compares very well with the best on the Mesa. The east rooms are well made and resemble those of Sun Temple. There are two entrances or passageways through the south side, midway between which on the outer surface there is set in the wall a large stone with a spiral incised figure supposed to represent the plumed snake; and near the southwest corner there are smaller mural designs representing two snakes.

The presence of shrines outside Pipe Shrine House is significant as the first of their kind ever found on the Mesa. On the northeast corner of the ruin there is a small square enclosure with walls on three sides, one of which is the wall of the northeast side of the ruin. Reset in the north wall of this enclosure is a stone, found a little distance away, bearing an incised circle or sun symbol; and within the shrine were found several waterworn stones; also an iron meteorite, a fossil nautiloid, and many stone concretions and waterworn

FIG. 97.—Mountain Lion Shrine, or Shrine of the South. Stairway constructed by aborigines. Square enclosure is shrine as found. South wall of Pipe Shrine House shown above. (Photograph by Geo. L. Beam. Courtesy Denver and Rio Grande Western Railroad.)

stones. A stone slab found nearby bears on its surface an incised circle, the symbolic representation of the sun, indicating the presence of a sun shrine nearby. Waterworn stones, by a confusion of cause and effect, are supposed to be efficacious in rain-producing.

South of Pipe Shrine House the ground slopes gradually (fig. 97), the earth being held back by a retaining wall. Aboriginal stone steps lead down to an enclosure which was a shrine, rectangular in shape, built in a recess of the retaining wall opposite the western doorway on the south side of the ruin. Within this shrine were a number of waterworn stones sufficient to fill a cement-bag, surrounding a large crudely fashioned fragment of a stone idol of the mountain lion. Although the head and forelegs were broken from the body the hindlegs were intact; a long search for the broken anterior end of the idol was a disappointment. The indentations on the surface due to chipping were plainly seen; and the tail was especially well made, resting along the dorsal line. This position of the tail is, in fact, what led the writer to identify the rude image as a representation of the mountain lion, for among the Hopi a picture of the puma painted on the north side of the warrior chamber has a similarly placed tail. The Hopi priests say that a Mountain Lion clan formerly inhabited the same cliff dwellings in the north as the Snake people. The position of



A *B*

Fig. 98.—Stone idol of a bird. Views from front *A*, and one-half lateral *B*. Pipe Shrine House. Size: 4¼ x 2¼ x 2¾ inches.

this shrine and the accompanying idol would indicate that the puma was the guardian of the south while at Walpi this animal is associated with the north. Among the Hopi, the mountain lion is also the guardian of cultivated fields.

Lest, in the future, vandals loot this shrine, it was protected by a wire netting set in cement spread on top of the walls, but the contents were left as originally found. South of the mountain-lion shrine, about 20 feet distant, was another enclosure, also a shrine, containing many waterworn stones, but its idol or guardian animal had disappeared. This receptacle was likewise protected by a wire net. Although it had no beast-god image; several stone idols (fig. 98) were found in the adjacent dump around Pipe Shrine House—evidently belonging to other cardinal points—but no other shrines were discovered.

The heads of two stone idols, homeless or without a shrine, were picked up outside the walls of Pipe Shrine House, on rock piles between the retaining wall and the south side of the ruin. One of these (fig. 99) is thought to represent the head of a mountain sheep, another a serpent, and a third (fig. 98) a bird. The instructive thing about these idols, next to their crude technique, is the fact that stone images rarely occur on the Mesa Verde, few similar stone idols or images having previously been reported from ruins on this plateau. Their crude form reminds one of pueblo idols.

FIG. 99.—Stone idol of a mountain sheep. Pipe Shrine House. Size: 3 x 5 x 6 in.

An aboriginal cemetery, ransacked of its mortuary contents years ago by vandals, was found near the southeast corner of Pipe Shrine House. The human skeletons found in this cemetery show the dead were buried as a rule in an extended position. In cave burials the bodies were flexed or in a seated posture. The accompanying pottery contained food and drink for the deceased. On the western fringe of this graveyard Dr. Fewkes discovered about a dozen human skeletons that had escaped desecration, one or two of which were buried only a few inches below the surface; the deepest grave was shallow, not more than three feet deep. All the skeletons that were found were well preserved, considering their antiquity, and had been buried in an extended position on a hard clay bed. They lay on their backs at full length with legs crossed and heads oriented to the east, generally accompanied by mortuary vessels of burnt clay and other objects. Several whole pieces of typical Mesa Verde pottery were taken out of the soil of this and another cemetery southeast of Far View House. These vessels once contained food and water, the spirit of which was thought to be suitable food for the spirit of the defunct. One of these skeletons (fig. 100) was as fresh as if buried a few years ago and the bones were so well preserved that they were left *in situ*. Every bone of one skeleton remains where it was found and was not raised from the position in which it was interred over 500 years ago. Walls of a stone vault (fig. 100) were constructed around the skeleton, reaching to the surface of the ground, and to a wooden frame firmly set in cement was nailed a wire netting, above which one of the workmen constructed a waterproof wooden roof hung on hinges. By raising this roof the visitor may now behold the skeletal remains of a man about 45 years old, 5 feet 6 inches tall, as he was laid out in his grave centuries ago. Visitors called him a mummy; his flesh had not dried as is sometimes the case with the cliff-dwellers, but turned into a brownish dust. So far as known this is the first time care has been taken to preserve a skeleton of a Pueblo in its aboriginal burial place so that it may be seen by visitors. It shows the environment of the defunct and satisfactorily answers the question whether the cliff-dwellers were pygmies.

In a refuse heap a short distance east of the sun shrine of Pipe Shrine House were found a hundred worn-out grinding stones and metates with many stones once used for pecking, all evidently thrown in a heap when they were no longer needed.

The grading of the area about Pipe Shrine House was a work of considerable magnitude, as the surface was very irregular and overgrown with vegetation. The soil, earth and stones fallen from the rooms had raised mounds of considerable magnitude around the ruin.

Pipe Shrine House appears to have served as a ceremonial building rather than a habitation—a kind of temple, originally constructed for the accommodation of the inhabitants of the neighboring Far View House. The tower was probably devoted to the worship of Father Sun and other celestials; the kiva to that of Mother Earth and terrestrial supernaturals.

In the thick cedars south of Far View House there were two mounds, one of which (fig. 101) was completely excavated by Dr. Fewkes, who found in it a fine central kiva surrounded by low walls of rooms, the whole probably being the house of one clan, for which the name, One Clan House, seems appropriate. It was probably the

FIG. 100.—Cyst constructed around skeleton in cemetery southeast of Pipe Shrine House, and two partial skeletons. The rock walls were built around the skeletons by Dr. Fewkes. (Photograph by Geo. L. Beam. Courtesy of Denver and Rio Grande Western Railroad.)

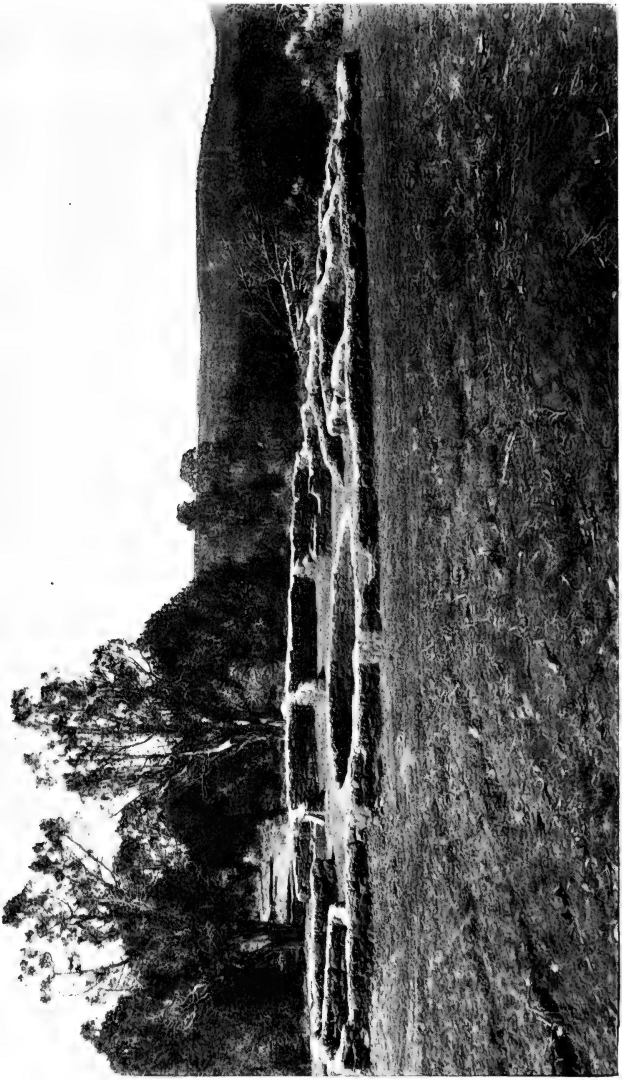


FIG. 101.—One Clan House, looking north. (Photograph by Geo. L. Beam. Courtesy Denver and Rio Grande Western Railroad.)

residence of a single social unit having a men's room or kiva in the center of the women's rooms or those used for grinding and storage of corn, sleeping, cooking, and other purposes.

The kiva (fig. 102) of this ruin is typical of a cliff-house sanctuary. Its architecture is normal, the floor being cut down a short distance into the solid rock and covered with a white earthy deposit. The roof was supported on six pilasters between each pair of which there is a banquette, that on the south side being larger than the others. In the floor there is a circular fire pit, near which is a deflector facing a ventilator. There is also a large *sipapû* or ceremonial opening in the floor. The surface of the north banquette has its ledge lowered to a level below that of the others, and in the wall above it is a recess that served, no doubt, for the idol. A slab of stone formerly used to close this recess lay on the kiva floor below it. A structural peculiarity was observed in the wall of One Clan House. As a rule kiva walls are built of horizontal masonry, but here the walls above the banquettes were made of upright stone slabs.

A well-worn trail, probably originally made by Indians, connects Far View House, Pipe Shrine House, and One Clan House with Spruce-tree House. Since the Indians abandoned the Mesa this trail has been deepened by stock seeking water and by herdsmen; it was also formerly used by all early tourists who visited the ruin on horseback before the construction of roads.

An important result of the archeological work of the Bureau of American Ethnology at the Mesa Verde the past summer, 1922, is new information on the use of towers revealed by the excavation and repair of Far View Tower. This building (fig. 103) is situated north of Far View House, about midway between it and "Mummy Lake," and when work began on it no walls were visible; the site was covered with sage bushes, and fallen stones strewn over the surface had raised a mound a few feet high, which is now a fine circular tower surrounded by low walled basal rooms. Three kivas were revealed on the south side where formerly no evidences of their existence appeared. Two of these (figs. 104, 105) were completely excavated and a third showed evidences of a secondary occupation. After this kiva had been used for a time, no one knows how long, it was filled with debris and fallen stones on which new walls were built by subsequent occupants. The masonry of the rooms they built is much inferior to that of their predecessors, the original builders of the kivas, and probably contemporaneous with the low walls east and north of the tower.

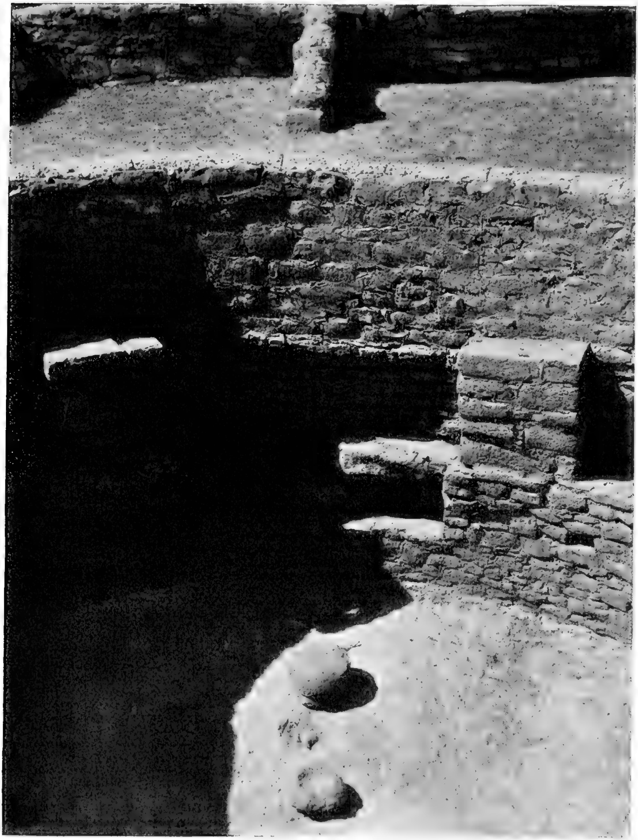


FIG. 102.—Kiva of One Clan House, from the north. Showing two pilasters, ledge on banquette for altar, conical corn fetish, sipapu and mortar. (Photograph by Geo. L. Beam. Courtesy Denver and Rio Grande Western Railroad.)

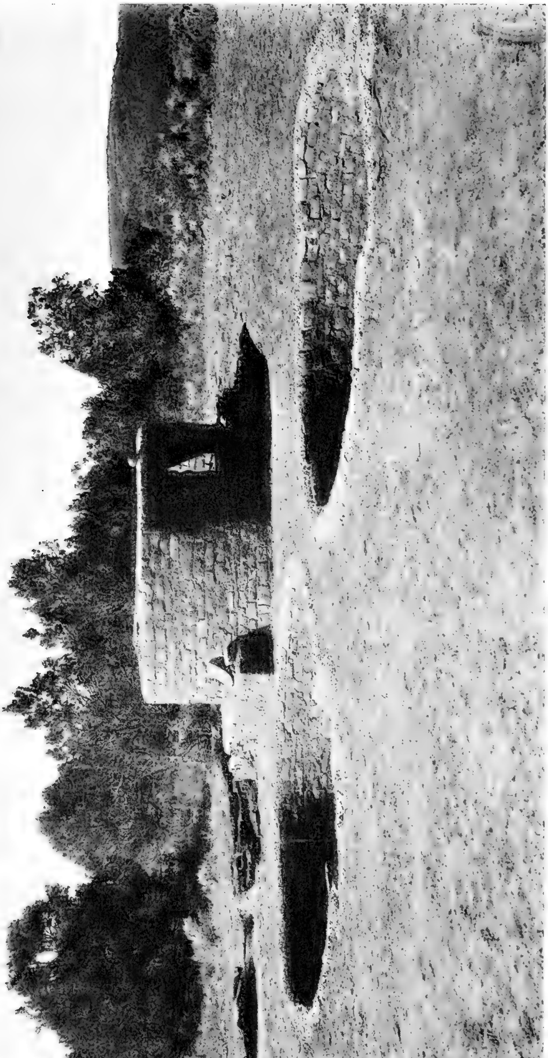


FIG. 103.—Far View Tower, looking north, showing tops of two kivas. Doorway in shadow; object above doorway germ idol or "corn mound." (Photograph by Geo. L. Beam. Courtesy Denver and Rio Grande Western Railroad.)

FIG. 104.—Kiva A, Far View Tower, looking south, showing ventilator opening and large banquette. (Photograph by W. R. Rowland, Durango, Colorado.)

FIG. 105.—Kiva B, Far View Tower. (Photograph by W. R. Rowland, Durango, Colorado.)

The main object in excavating Far View Tower was to discover the use of these buildings, many of which occur on the Mesa Verde and still more in the canyons and tablelands west of the park. These structures are commonly supposed to have been used to detect enemies approaching the settlements. This was one of their functions; they were undoubtedly constructed to enable the observer to see or signal a long distance. Nordenskiöld suggested that Cedar Tree Tower had a religious character, which appears feasible. It is believed that one of their uses, perhaps the main one, was to observe the position of the sun on the horizon and thus to determine the seasons of the year by noting the corresponding points of sunrise and sunset. The sun priests of the early cliff dwelling determined the time of planting and other necessary calendar data for the agriculturists in the same way as the Hopi who use the following method: The line of the horizon silhouetted against the sky between the rising of the sun at the summer and winter solstices is divided into a number of parts each corresponding to a ceremony or other important event.[1] The point of sunset at the winter solstice is likewise used for the same purpose. Having determined in this way that the time for planting has come, the sun priest informs the speaker chief who makes the announcement standing on the highest roof of the pueblo. These towers were not only lookouts from which by horizontal sun observations the seasons were determined, but likewise sun houses or chambers where certain sun rites were performed. There is a room dedicated to sun ceremonies connected with the Great Serpent worship among the modern Hopi; and it is instructive to note that incised spiral designs representing the great snake frequently occur on stones of which towers are built. These towers may be square, circular, or D-shaped in form; may have one or many chambers; and may be accompanied with kivas or destitute of the same. Commonly the rising or the setting sun illuminates their summits. Sun Temple, on the Mesa Verde, may be regarded as a complicated tower with many chambers but in function practically the same as that of a simple one-chamber tower. The complex of rooms at Far View Tower should be looked upon as an architectural unit, composed of a tower, probably when in use as high as the tops of the neighboring cedars; three subterranean ceremonial rooms, circular in form and similar to cliff-house kivas; and a cemetery situated on the south. The rooms for habitation surrounding the tower do

[1] It would be very instructive in this connection to determine by excavation whether the two towers known as Küküchomo, on the East Mesa of the Hopi, were used for the same purpose as those at Mesa Verde.

not belong to this complex but indicate a secondary occupation; their masonry is crude; their number shows that the population was insignificant. The few people who occupied them came later than those who erected and used the tower.

There remain several large mounds in the Mummy Lake area awaiting excavation: some of these cover pueblos or houses of many clans, others small one-clan houses. The superficial appearance of these mounds seems to indicate types somewhat different from any yet described. One of the most unusual is a mound lying a few

FIG. 106.—Megalithic House. Mainly distinguished by walls made of huge stones on edge. (Photograph by Geo. L. Beam. Courtesy Denver and Rio Grande Western Railroad.)

hundred feet north of Mummy Lake, near the government road. When discovered nothing appeared above ground except a row of large unworked stones set on edge, forming one wall of a small room. On excavation walls of other rooms appeared, one of which was paved with flat stones. The ruin had a single subterranean kiva, of regulation shape and size, the walls characterized by large stones. This ruin, called Megalithic House (fig. 106), belongs to a type which there is every reason to suspect is represented elsewhere on the Mesa. Cyclopean walls similar to those of Megalithic House have been previously reported from the bluff overlooking the junction of the Yellow Jacket and McElmo Canyons, and at various places in the

FIG. 107.—Pottery from cemetery of Pipe Shrine House: *a*, Red food bowl; *b*, Coiled brown ware, archaic decoration; *c*, Effigy jar, black on white; *d*, Ladle, black on white; *e*, Effigy jar, black on white; *f*, Vase, rough ware; *g*, Mug, gray with glossy black figures; *h*, Mug, gray with black decoration.

a, Diameter 11", height 4"; *b*, diameter 6½", height 3"; *c*, height 4¼", length 6", width 4"; *d*, diameter 3½", handle 3½" long; *e*, length 3¼", height 1⅜", width 2"; *f*, height 3¾"; *g*, height 4½"; *h*, height 4½".

San Juan Valley. In some instances the walls are made of much larger stones, but always vertically placed.

An examination of the numerous artifacts or small objects like stone implements, pottery (fig. 107), and the like, that were collected in the excavation of the rooms above mentioned, impresses one with the unique character of several, and the differences of the ceramics from those of Spruce-tree House and Cliff Palace. We find characteristic cliff-house forms of indented and corrugated ware differ from those of Far View Tower which more closely resemble those found at Pipe Shrine House; other forms do not occur in cliff houses. Many specimens of apparently coiled ware were decorated with stamps, one

Fig. 108.—Stone with parallel grooves, possibly used as a pottery stamp. Pipe Shrine House. Size: 2¾ x 2¾ x 5 inches.

of which is shown in figure 108. Among pottery types may be mentioned: *a*, food bowls with shiny black interiors and small grooves with corrugations on their exteriors; *b*, pottery showing coils (fig. 109) on their exteriors and painted designs on their interiors. The black and white ware is coarse and the designs used in decoration are simple and not very artistic. Representations of a few of these archaic types appear in the accompanying figures. The excavations at Far View House, Pipe Shrine House, and other surface pueblos show that there are several divisions of corrugated ware which should be considered. We should not rely wholly on geography in a comparative study of ceramics in the Southwest; age may also be considered. It is probable that types of architecture have changed since man settled on Mesa Verde, and that pottery also has changed seems probable, but direct observations regarding that change are necessary. Take for instance the type known as effigy jars and vases. No clay effigies of men or animals had been recorded from Mesa Verde before the present year. Jars representing birds, quadrupeds, and a clay representation of the foot of a human effigy were excavated at Pipe Shrine House. A more archaic pottery distinguished by black figures on white ware is not the same as the black on white ware found in cliff dwellings, which would appear to indicate that the pottery from the cemetery of Pipe Shrine House was earlier than that of Spruce-tree House, and yet we find at the former locality pottery fragments equal in technique and almost identical in

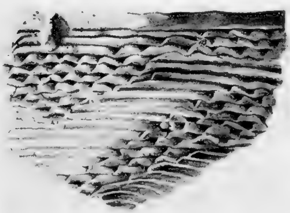


FIG. 109.—Fragment of corrugated pottery. One-third natural size. (Drawing by Mrs. George Mullett.)

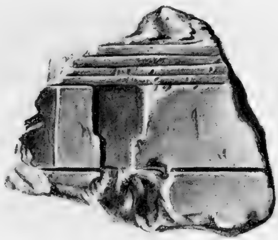


FIG. 110.—Stone with carved T-doorway in intaglio. (Drawing by Mrs. George Mullett.) Size: 5⅛ x 5 x 3¾ inches.

ornament with the best taken from the latest cliff houses on the park. There is evidence from the character of the pottery that some of the Mesa Verde pueblos were inhabited later than Cliff Palace, rendering it easy to accept the theory that the Mesa Verde caves became so crowded with buildings that their inhabitants were compelled to move out and, having constructed pueblos, to settle on the mesa tops near their farms.

Several objects, some of which are of doubtful use, were found near Pipe Shrine House. One of these is the stone shown in figure 110, on which is engraved a T-doorway and roof beams, a specimen which, so far as known, is unique. A bare mention of the various forms of stone weapons and mortars and pestles, implements, pottery objects, bone needles, scrapers and the like would

FIG. 111.—Fossil shell used as an arrow polisher. Pipe Shrine House. Size: $2\frac{3}{4}$ x $1\frac{3}{4}$ x $1\frac{3}{8}$ inches.

FIG. 112.—Cool Spring House on Cajon Mesa, Hovenweep National Monument. (Photograph by J. W. Fewkes.)

enlarge this report to undue proportions. An implement hitherto undescribed (fig. 111) is made of a fossil bivalve shell with two grooves for arrow polishing. This object is ornamental as the outer surface of the shell valves give it an artistic look.

In order to protect them from the weather, the tops of the walls of rooms in Pipe Shrine House, One Clan House, Far View Tower and the kivas of the same were covered with a cement grout. The walls of Far View House were treated in the same way and it is to be hoped that these ruins will not need additional protection from the elements for several years to come.

At the close of his season's work on the Mesa Verde National Park, Dr. Fewkes visited Cool Spring House (fig. 112), a large undescribed ruin on Cajon Mesa, in Utah, about 10 miles west of the junction of McElmo and Yellow Jacket canyons. Cool Spring House, like Cannon Ball Ruin, is situated about the head of a canyon and consists of several more or less isolated rooms. It takes its name from a fine spring below the mesa rim. This ruin is situated so far from white settlers that its walls are at present in no danger of being mutilated, but there is danger that the neighboring towers will soon be torn down, if not protected. As it is proposed that Cool Spring House be added to the towers in Square Tower Canyon and Holly Canyon to form the proposed Hovenweep National Monument, it would be most unfortunate if these three groups of ruins should be allowed to be destroyed by vandals.

OBSERVATIONS AMONG THE ANCIENT INDIAN MONUMENTS OF SOUTHEASTERN ALASKA

In the spring of 1922, the Bureau of American Ethnology dispatched a special investigator, Dr. T. T. Waterman, to examine the remains of native villages in southeastern Alaska. A number of these interesting old settlements were scrutinized, in the company of native informants. There is much of interest in and about these old-time villages, though signs of Indian occupancy are rapidly vanishing. The principal objects of remark are the totem-poles, for which this part of America is celebrated. Every village site shows a number of these columns, though some have fallen, some have been cut down with axes, and some have been hauled away bodily as curiosities, sometimes to distant cities. In spite of the fact that they are carved out of nothing more enduring than wood (usually yellow cedar) some of them are of such tremendous size and solidity that they have stood for many generations. Here and there on the old village-sites, there still may be seen among the poles the framework of one of the old-time Indian houses.

The area in which totem-poles were originally in use was very definitely limited. Nowadays small replicas are being cut for sale

FIG. 113.—A fine example of totemic art, from the Alaskan town of Howkan (central pole). Striking features of totemic art are, (1) the love of complexity, and (2) the fact that the whole pole is an artistic *unit*. A figure merges into the ones above it and below it in the most clever way. This is well shown in the splendid column in the center. (Photograph by Julius Sternberg, for the Smithsonian Institution.)

out of all sorts of wood, and stone, by all sorts of people, many of whom have not the faintest notion of how to do it properly. Originally, poles were not set up anywhere south of Frazer River. The Indians of Puget Sound, for example, never heard of these columns until late years. The Indians of the east coast of Vancouver Island had totemic columns, but the custom had never spread to the island's western side. To the northward, totem-poles were carved by all the tribes as far north as the Chilkat (a Tlingit group living not far from Haines, Alaska). The Indians to the north and west of them,

FIG. 114.—The degeneration of totemic art under civilized influences. It would be a pity to discuss this wretched thing, except to note that the clever joining of one figure to the next is completely forgotten. The carvings show (at the bottom) the Sun, above that two Beavers, and, at the top, an Eagle. The house behind it is called "Eagle-leg house." The house-posts represent the legs and feet of the eagle. (Photograph by Julius Sternberg, for the Smithsonian Institution.)

however, knew nothing of such columns. Beyond these lived the Eskimo and Aleut, to whom the whole matter is absolutely foreign. The whole idea of art from which the totem-pole rose, was limited strictly to the coast region.

It is safe to say that totem-poles are peculiar. As a matter of fact they represent a very highly developed, and very highly perfected, art. For many generations the Indians hereabouts were developing a special "knack," and special ideas, and the matter has gone so far that other people (even some civilized artists) seem to have a hard time even in copying their handiwork.

In looking over these monuments, one is impressed by the fact that there has been a gradual change in artistic style even on the part of the Indians themselves. Unfortunately, this change is in the wrong direction. The older monuments are much more interesting, and are better executed, than the later ones. In other words, the Indians themselves are forgetting their art. This matter is worth illustrating by photographs (figs. 113, 114). Monuments carved within the last 40 years look (usually) rather staring and stiff, compared to the ones executed previously. With the increasing decay of the old landmarks, a unique style of work bids fair to pass as completely out of existence as though it had never been.

This art consists almost solely in the representation of animals. In the second place, the carvings refer almost always to the parts which these animals played as actors in certain interesting old myths. The carving is meaningless, unless one understands the allusions. Personal experiences are sometimes portrayed. This matter, also, can be very simply illustrated. In the third place, in making a representation of an animal the Indian has special stylistic devices. He puts in what he knows should be there (including at times things not visible at all). Finally, he often simplifies and distorts (according to certain definite rules), in the interest of getting in what he regards as important. He actually loves artistic complexity. All of these tendencies prevent us from readily appreciating what is in many cases a genuine artistic masterpiece. These points may well be explained separately.

The significance of the poles can scarcely be understood without taking into consideration the form of society which these Indians had developed. All of the tribes of the Northwest Coast are divided into what are usually called "clans." This word is borrowed from the Scotch, and is a very poor term to describe the social groups of the Northwest Coast Indians, for here each group looks upon itself as related by blood to some particular animal. A tremendous mass of ideas and usages has grown up, involving kinship, rules of marriage, property, religious ceremonies, and descent, all centered about these

FIG. 115.—A late carving, representing a Bear; more realistic than the former, but not half as interesting. (Photograph by Julius Sternberg, for the Smithsonian Institution.)

FIG. 116.—The lower part of an old totem-pole, showing the old style conventionalized way of representing the Bear. The smaller figure is a carving from the corner of the house, representing the killer-whale. (Photograph by Julius Sternberg, for the Smithsonian Institution.)

animal crests. To the Indian of this region, the most important thing in life is his animal crest or "totem." All his ideas and ambitions center about this hereditary animal progenitor and protector, the similitude of which he carves on all his utensils, paints on his house-front, tattoos on his arms and chest, paints on his face, and represents on his memorial column. Curiously enough (from our particular point of view) these people reckon kinship through the mother only. This has some curious consequences. A man (to mention one consequence) sets up a memorial column, not for his father, but for his mother's relatives, particularly her brother. Conversely, if a collector wishes to buy a pole for preservation, he ought logically to arrange matters, not with a dead chief's son, but with the dead chief's nephews; for a son has (according to the native idea) no connection with his father. It is to a maternal uncle that a boy or young man looks for guidance and counsel, and it to his maternal uncle's memory that he owes respect and veneration. It is from this uncle only that he inherits property. A boy's whole position in society, his rank, his outlook, his standing, and his prospect for a wife, all hinge upon the animal crest which he inherits from his mother's brother. It is clear, therefore, that a "totem-pole" will display to the public view all the animal crests which the Indian possesses, and all those with which his family (*i. e.,* his *maternal* relatives) have been associated in the past.

The importance of these animal crests to the Indian, may be illustrated in an interesting way by the matter of personal names. Many of the names used within a group of kindred, refer to the qualities, or traits, or tricks of behavior, of those animals to which the group looks. Sometimes the names are highly figurative. Sometimes they are so pitilessly literal and Homeric in their directness that they almost disconcert us. Some very famous names, which have been used in certain families for generations, appear in the following list:

NAMES IN THE RAVEN CLAN

"*Raven's child.*"

"*Waddling.*" This refers to the raven's gait when he walks on the ground.

"*Treating-each-other-as-dogs.*" This alludes to the fact that when a raven dies, the other ravens pull the body about, dragging it here and there.

"*Big-doings.*" This refers to the fact that young ravens are noisy, in the nest. The native word means literally a celebration, or fiesta of some sort.

"*Stinking-nation.*" This epithet refers to the fact that the raven's nest has a bad odor.

NAMES IN THE EAGLE CLAN

"*Four-eggs,*" an allusion to the eagle's trait of laying always four eggs in the nest.

"*Tail-dragging,*" because the tail of the eagle drags when he walks.

"*Flying-deliberately.*" The eagle, with his great bulk and enormous wings, flies strongly but deliberately, unlike any of the smaller birds.

The next point to be explained is the matter of mythology. The animals whose likenesses appear in the carvings are the heroes of endless mythical tales. It requires a good deal of erudition therefore to explain some of the carvings on the totem-poles. Only the old Indians can do it. In the first place, the animal may be represented either in human or in animal form, for any animal can take either form, as he pleases. A bear, for example, in his own den, takes off his bear-skin and hangs it up. What looks like a lot of stones or branches is in reality the furniture and property in a fine house; and the bear himself appears there as human as you or I. Conversely, when the Indian artist is carving the likeness of a man, he is occasionally so moved by his feeling for that man's totem or crest, that he introduces features of the crest-animal into the carving. The art is therefore a bit abstruse; and the native sculptor seems in some cases to delight in border-line styles of execution.

The carvings on a given pole, where they refer to the great animal heroes, usually allude to some certain episodes in the myth of that particular animal. For example, a certain family of Raven-people living at the town of Kasaan put up the pole shown in figure 117. It represents part of the legend known as "Raven Travelling." At the top is Raven himself, in human form. Below him is his likeness in bird form (and an impish look it has). Below this again is a fish called the sculpin or bull-head—an excessively ugly and repulsive looking fish.

Bull-head used to be a beautiful fish, the prettiest of all that swam in the sea. Raven when walking along the shore saw Bull-head disporting himself, and called out to him, "Come on shore one moment." Bull-head paid no attention. "Come ashore a moment," said Raven, "you look just like my grandfather." "I know you," said Bull-head, "you might as well be still. Future generations also will know what kind of a person you are!" Bull-head was thus too smart to come ashore. "Well then," said Raven, "from this time on your head will be big, and your tail will be skinny, and you will be ugly." That is why Bull-head is so ugly to-day.

FIG. 117.—A totem-pole at Kasaan Village, illustrating the myth of the adventures of Raven. (Photograph by Julius Sternberg, for the Smithsonian Institution.)

An illustration of another kind of crest is supplied by the following picture (fig. 119). The carving at the top represents a man in a stove-pipe hat and a frock coat. An old lady belonging to the house in front of which this pole stood, was the first person in the village to encounter a white man. She went to Sitka with some Indians, and there saw a ship with whites in it. The figure representing what she saw was accordingly put on her pole. Below this white man is a

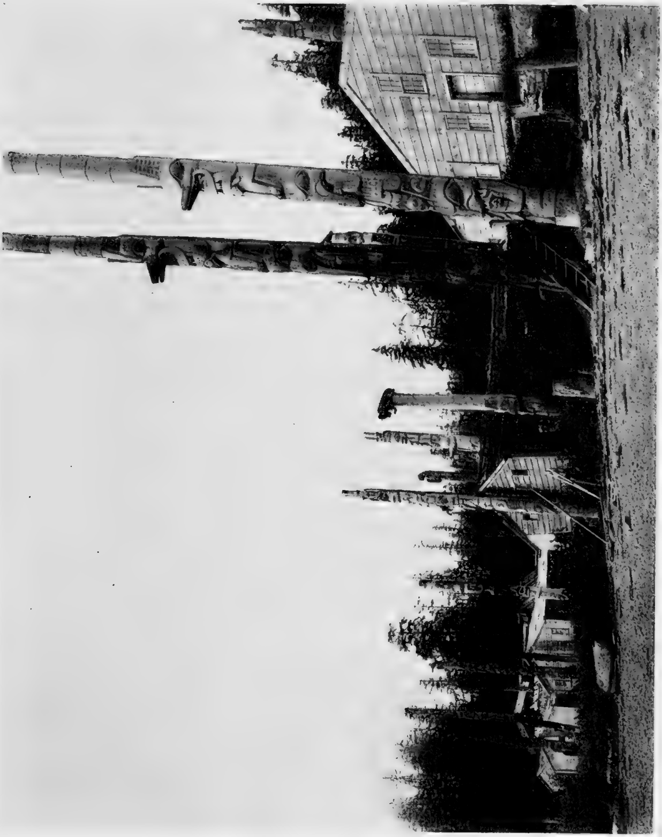


FIG. 118.—A photograph of Kasaan Village made by Lieutenant Emmons, about 1885. The poles in the foreground show the crests of Chief Skowl.

splendid carving of Raven, and below him a figure representing a "*sea-lion rock.*" The supernatural being who lives in the rock is pictured as a great beast, who embraces a sea-lion, the flukes of which are under his chin. Such a rock-being is called "Grandfather-of-the-sea-lions." In this pole, carvings like the carving of the Raven, representing the ancestor of the owner's family, are combined with

FIG. 119.—A pole with a white man as a totem (central pole). An old lady who set up this pole was the first Indian of her group to see the whites, so she took a white man (in a frock coat and a stove-pipe hat) as her crest. (Photograph by Julius Sternberg, for the Smithsonian Institution.)

a carving representing something in the history of the owner's wife, namely, that she was the first person in the village to come in contact with the whites.

A totem-pole represents, really, a certain Indian's claim to fame. His claim may be based either on his own experiences (like a distinguished conduct medal is, with us) ; or it may be founded on his ancestry, as in the case of a title of nobility or a coat of arms.

The idea that a pole always represents descent is therefore not quite accurate. It is more nearly correct to say that the pole represents the Indian's claim to fame, or the claim of his family, whatever that claim may be based on. Examples of both kinds of carvings are plentifully illustrated in the poles.

A quaint example of a recently-acquired crest is shown in the next photograph (fig. 120). This specimen was described to me as "the best totem-pole in Alaska." As a matter of fact, it is not properly speaking an example of totemic art at all. The owner's wife was an Eagle woman, so the Eagle appears at the top of the pole. The owner himself many years ago, prior to the American occupation of Alaska, became converted to Christianity. The three figures on the body of the pole were copied, along with the scroll designs, from a Bible in the Russian church at Sitka. The bottom one represents, it is said, St. Paul. The pole, while it is not a totemic monument as far as the designs on it are concerned, illustrates how an individual's inner experiences give rise to crests. This man gave a great "potlatch" when he raised the pole, and thus endowed himself with title to these carvings, and made them his own. He was the first of his group to become a Christian.

It will be seen that there are a variety of ways in which carvings come to be on poles. In one case I know of, a chief who belonged to the Raven side, gave a great feast to a rival chief, a man of the Killer-whale persuasion at Wrangell, and made him numerous gifts. This latter chief fell upon evil days (he became a drunken loafer, in fact) and was never able to return these gifts, in their equivalent. The first chief therefore put on his totem-pole his own crest, the Raven, represented as biting the dorsal fin of a Killer-whale. The rival chief resented the affront, but he had lost his property so what could he do?

Some of the larger poles are 50 or 60 feet long. The tree is felled and transported to the village-site, often at great labor. Here it is blocked up, and an artist, hired for the purpose, works out the design. To carve an elaborate pole was often the work of several years. The back side of the pole was hollowed out, to lighten, as much as possible, the labor of erecting it. A large concourse of people assembled for the actual erection of the great column, and to partake of the accompanying feast. Tremendous amounts of property were distributed at such times, by the host and by his relatives, and such an occasion has come to be called a "potlatch." The rank of a family

FIG. 120.—A "totem-pole" with figures copied from an old Russian Bible in the church in Sitka. The owner was the first inhabitant of the village to become a Christian. (Photograph by Bergstresser, Alaska.)

was greatly increased by this means. The size of a pole, and the style of the carvings, like the name assumed by the owner, were correlated to a nicety with the cost of the potlatch and the amount of property disbursed. The noble families were very careful of their dignity. Once a young man who was preparing to take a swim,

FIG. 121.—A pole at the village of Howkan, showing (near the top) a representation of the Czar of Russia who sold Alaska to the U. S. A. (Photograph by Julius Sternberg, for the Smithsonian Institution.)

slipped on a treacherous rock and capsized on this beach. His father at once ordered that a slave be killed, so that nobody would laugh at his son. Slave people, who merely represented objects of value, were often dispatched at potlatches, to add lustre to the occasion, and to show that the owner was so rich that the value of a slave was nothing to him.

In later times, after the first contact with civilization, it became difficult to kill slaves. The custom developed, therefore, of manumitting one or more slaves when a pole was set up. A figure representing the slave who went free, was often carved on the pole. A very finely carved pole in Howkan (fig. 121) has an amusing figure on it. It represents the Czar of Russia who sold Alaska. It shows him with his military uniform, with epaulettes. An Indian made this pole soon after the transfer of Alaska to the United States. Concerning the Czar he said as follows: "We have now got rid of this fellow. We have let him go off about his business. Therefore, I will put him on my pole, in memory of the event."

A certain artistic style has become established in this region, which also tends to prevent the carvings from being readily recognized. Two tendencies especially may be recognized. In the first place, many parts of the animal are suppressed entirely, and selected features only are portrayed. In the second place, the Indian artist feels at liberty to *rearrange* the parts of the animal, to make the design fit the available space. Often the animal is reassembled in an entirely new way, the parts appearing in the most unexpected and incongruous way. These two tendencies have been labelled by Boas the tendency toward *symbolism,* and the tendency toward *distortion.*

Some of the important totem animals are symbolized by the following traits. When one or two of these traits are present, the animal may be readily recognized.

Beaver. This animal is usually represented as sitting up, and gnawing at a stick, which he holds in his forepaws. The great incisor teeth of this rodent are always shown very plainly.

Bear. The bear is usually in a sitting posture, usually holds something between his paws, and usually has something protruding from his jaws (if nothing else, then his tongue).

Eagle. The beak of the eagle curves over at the end, and has a characteristic shape.

"Thunderbird." This bird (which does not appear in the natural histories) makes thunder by clapping his wings, and lightning by winking his eyes. He is carved very much like the eagle, but his beak is larger, and he wears a cloud hat.

Hawk. The carving of the hawk may be distinguished by the fact that the beak curves over, and the point of it touches the mouth or chin.

Shark. The characteristics emphasized in the shark-carvings are rather curious. The animal's gill-slits (a row of openings on either side of the animal's neck) are always shown by crescent-shaped markings. When the shark is represented in human form, these marks appear on the cheek. The mouth is invariably *curved downward* at the corners, and is often furnished with sharp triangular teeth. The forehead of the shark always rises into a sort of peak.

The principle of dissection is equally useful to the native artist. It may be illustrated not merely in the case of totem-poles, but with many varieties of objects. We may suppose for example that an Indian's totemic crest happens to be the Killer-whale, and that this man is ornamenting a slate bowl with this family crest. The shape of the bowl is settled in advance; that is, being a bowl or dish, it is round. The nature of the design is also a cut-and-dried matter. The man in the nature of the case wishes to represent the Killer, for that is the crest he has inherited from his forebears. He therefore has to make a killer-whale pattern which will exactly fit into a round field. The Indian's artistic ideal is quite different from our own. He feels (apparently) that certain essential traits (or "symbols") of the animal must go in; and that the design when finished must neatly fill up the available space.

The monuments left in Alaska are often in the last stages of neglect and decay. Worse than that, even, many of them are being deliberately destroyed. The Indians themselves, under the influence of the whites, learn to despise these monuments of their past, as being reminders of their state of unregenerate barbarism. One Indian chap, trained in the white man's ways and "educated" perhaps somewhat beyond his intelligence, cut down with an axe a lot of fine old totem-poles, sawed them into sections, and used them in building a sidewalk. (See fig. 122.)

The fate which has for various reasons overtaken these monuments is best indicated by the accompanying photographs. The ruin and decay which has fallen upon all things simply beggars description. No work could be better than to preserve, somewhere in Alaska, at at least one house, with its totem-poles and carvings complete. This would at least serve to illustrate the kind of architecture which these Indians developed. Some of these native houses were of cyclopean proportions, the great beams being 3 and 4 feet in diameter. The older Indians themselves often have toward the whole matter what seems to be an apathetic attitude, but this is misleading. The real inner feeling seems to be that the old times are gone, and that these monuments of the vanished past should, in the nature of things, be allowed also to decay in peace and to vanish quietly from off the face of the earth. It would not be impossible to interest some of the more alert ones in the preservation of at least some of the ancient glories of

FIG. 122.—Totem-poles sawn into sections to make supports for a sidewalk at the village of Klinkwan. A section of a pole is visible under the sidewalk, to the right. In the background stands an undamaged pole, showing (at the top) Raven carrying the moon. (Photograph by Julius Sternberg, for the Smithsonian Institution.)

FIG. 123.—An outcrop of rock at Howkan, shaped to represent the sea-lion. (Photograph by Julius Sternberg, for the Smithsonian Institution.)

this region. In spite of all that has happened, there is much of great interest left, as the pictures show. No poles worthy of the name have been carved for 30 years, and for 20 years before that the art was degenerating. Some of the old columns are in a marvelous condition of preservation considering their age. The decay begins at the top,

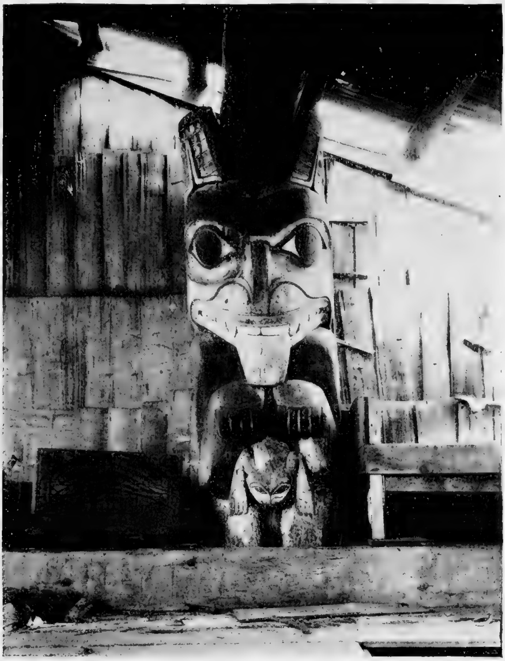


FIG. 124.—Interior of an abandoned native house, showing one of the totemic house-posts, portraying the Bear. (Photograph by Julius Sternberg, for the Smithsonian Institution.)

where seeds also take root and sprout. Often when the top figure is gone, the remainder of the carvings are fairly sound. At the town of Tuxekan an observer in 1916 counted 125 poles standing. In 1922, only 50 were left. The information about the poles, also, is disappearing even more rapidly than the poles themselves, for only the old people know or care.

FIG. 125.—Panorama of Kasaan Village, Alaska, as it was in 1922. (Photograph by Julius Sternberg, for the Smithsonian Institution.) Compare this with a photograph of the same village, made about 1885 (fig. 118, above).

During the time the observer was in the field, a half dozen of the old village-sites were visited. Sketch-maps were prepared, showing the condition of the monuments. Quite extensive notes were taken from native informants, respecting the genealogies of the people who owned the houses, and the symbolism of the poles. A complete list

FIG. 126.—Three Indians of a totem-pole tribe, in native garb.

was made also of the geographical names along the coast from one village to the next. The native geography of extreme southeastern Alaska was therefore rather completely obtained. The number of place-names thus recorded, charted and analyzed, amount to several thousand. There is probably no region in North America where investigations can be carried out with richer results.

ARCHEOLOGICAL INVESTIGATIONS AT PUEBLO BONITO, NEW MEXICO

During the months of May to September, inclusive, Neil M. Judd, curator of American archeology, U. S. National Museum, continued his investigation of prehistoric Pueblo Bonito, in behalf of the National Geographic Society.[1] As in 1921, Mr. Judd's staff consisted of seven trained assistants with about 20 Navaho and Zuñi Indians employed for the actual work of excavation.

FIG. 127.—Mr. R. P. Anderson, a former captain of engineers, A. E. F., at work on a topographic map of Chaco Canyon. This view, taken from above Pueblo Bonito, affords an excellent idea of the surroundings of the great ruin and the height of the canyon wall. Note the horses and one of the expedition's test pits in the right foreground. (Photograph by Neil M. Judd. Courtesy of the National Geographic Society.)

In these recent explorations, attention was directed especially to the eastern part of the great ruin, a section which includes not only the finest masonry in the whole pueblo but which exhibits other evidence of relatively late construction. This entire section, although apparently erected last, was probably abandoned before the remainder of Pueblo Bonito. Because of this general abandonment, cultural evi-

[1] Smithsonian Misc Coll., Vol. 72, Nos. 6 and 15.

dence is largely lacking in the several rooms but the information gathered has been sufficient, nevertheless, to afford accurate comparison with that of other sections. It is now certain that Pueblo Bonito is not the result of a single, continuous period of construction, rather, that it took its final form after much building and rebuilding in which substantial homes were razed to make way for others.

A deep trench was cut in the east refuse mound in order to obtain chronological data for use, with similar information gathered in the

FIG. 128.—Part of the excavated northeast section of Pueblo Bonito at the close of the 1922 season. Most of these rooms had been abandoned prior to the general exodus from the village and were utilized as dumping places for refuse by families which continued to dwell nearby. (Photograph by Neil M. Judd. Courtesy of the National Geographic Society.)

west refuse mound during 1921, in tracing the cultural development of Pueblo Bonito and establishing relative dates, if possible, for the several foreign influxes already apparent. As has been previously noted, clans from the Mesa Verde, in Colorado, and from the valley of the Little Colorado River, in Arizona, and elsewhere, came to dwell at Pueblo Bonito at some time after the establishment of the great community house. The expedition seeks to isolate these outside influences and to determine the effect they exerted upon the distinctive local culture.

In addition to the purely archeological phase of the expedition, geophysical investigations were undertaken in an effort to trace climatic or other changes which may have taken place in Chaco Canyon since the occupancy of prehistoric Pueblo Bonito. Three test pits near the ruin, each more than 12 feet in depth, provided stratigraphic sections of the valley fill in addition to that already available in the arroyo. From the evidence disclosed in these pits, and elsewhere, it now appears that Pueblo Bonito was originally constructed on a slight elevation, superficial indications of which have since been entirely obliterated through building up of the level valley floor by means of blown sand and silty deposits washed in from the sides of the canyon. These deposits vary in depth from 2 to 6 feet and frequently contain scattered objects of human origin.

A pre-Pueblo ruin, the existence of which was disclosed only through caving of the arroyo bank, affords further evidence of the human occupancy of Chaco Canyon at a considerable period prior to the erection of Pueblo Bonito and the other major ruins, a similar structure having been excavated by the National Geographic Society's Reconnaissance Expedition of 1920. This ancient habitation consisted of a circular pit 12 feet 9 inches (3.9 m.) in diameter and about 4 feet (1.2 m.) deep, excavated in the former valley floor; its roof was of reeds and earth supported by small poles which reached from the wall of the excavation to upright posts placed just within an encircling bench. A considerable quantity of potsherds, collected both from the debris which filled the pit and from the masses of adobe which had fallen away from the bank, established the period to which the dwelling belongs as "early black-on-white," a culture well known throughout the San Juan drainage. The fact that the floor of this ancient structure lay 12 feet below the present valley surface is evidence not only of the vast amount of silt which has been deposited since occupancy of the room, but carries the promise, also, that other similar lodges may yet be disclosed by excavation or through the gradual erosion of the valley.

A topographical survey of that part of Chaco Canyon adjacent to Pueblo Bonito, completed by the 1922 expedition, affords the first accurate map of the principal portion of the Chaco Canyon National Monument. This survey correctly locates nine of the major ruins and indicates the relative position of most, but not all, of the smaller structures to be found, especially those along the southern side of the canyon.

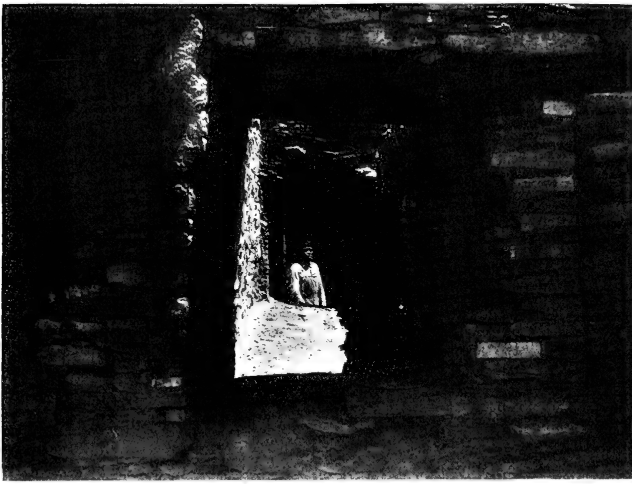


Fig. 129.—A narrow, elevated passage-way constructed through one Pueblo Bonito room to connect the two adjoining chambers. The lintel poles of the nearer doorway are supported, on the right, by a hewn plank which rests upon an upright pine log partially imbedded in the wall. (Photograph by Neil M. Judd. Courtesy of the National Geographic Society.)

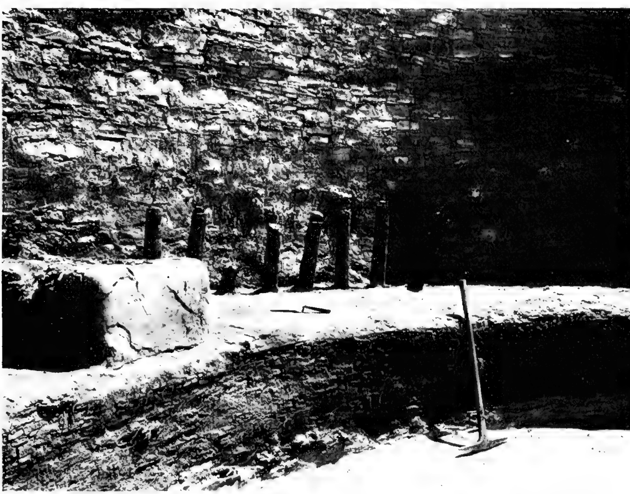


Fig. 130.—The ceremonial rooms which belong with the characteristic Chaco Canyon culture are all very much alike. This view in Kiva G, at Pueblo Bonito, shows a portion of the encircling bench, one of the pilasters or roof supports and several charred posts which originally formed something of a wainscoting behind the lower ceiling logs. (Photograph by Neil M. Judd. Courtesy of the National Geographic Society.)

FIG. 131.—Excavating one of Pueblo Bonito's numerous kivas. Mule-drawn dump cars were used in connection with a portable steel track which could be shifted as the explorations progressed. Owing to the depth of some rooms it was necessary to pass the debris upward from one man to another before it reached the track level. (Photograph by Neil M. Judd. Courtesy of the National Geographic Society.)

FIG. 132.—Many instances of superposition have been disclosed by the excavations at Pueblo Bonito. This particular view shows the disintegrating masonry of a typical Chaco Canyon kiva resting directly upon the partially razed walls of a ceremonial room fundamentally different in construction and representing an entirely distinct culture. (Photograph by Neil M. Judd. Courtesy of the National Geographic Society.)

Altogether, 35 secular rooms and six kivas were excavated in Pueblo Bonito during the past summer. Several of these, following abandonment of the eastern portion of the pueblo, had been utilized as dumping places by the families which still dwelt nearby. Rubbish from wall repairs, floor sweepings containing potsherds and other artifacts, cedar bark and splinters from old wood piles, etc., comprised this debris. The doorways in many of these deserted dwellings had been blocked with stone and mud and the rooms themselves were

FIG. 133.—Part of the excavated area of Pueblo Bonito at the close of the 1922 season, looking southeast across Kiva G (in the foreground). The upper walls in the three kivas shown here have been slightly repaired to prevent rain water from running into the open rooms. (Photograph by Neil M. Judd. Courtesy of the National Geographic Society.)

entirely filled by masonry fallen from the upper stories and by the vast accumulation of blown sand and adobe. Indications of fire were encountered frequently but in most instances the conflagration obviously occurred at a considerable period following the general abandonment inasmuch as blown sand and, sometimes, fallen wall material had accumulated upon the lower floors before the burning of the ceiling structure. From this evidence, it is certain that the fire which destroyed much of the woodwork in the eastern portion of Pueblo Bonito could have contributed in no wise to its desertion. Sections of charred and other beams have been examined to determine the relative date of cutting and in the hope, also, that a means may yet be discovered for connecting the annual rings in these ancient timbers with those in trees still growing upon the northern New Mexico mesas. Inasmuch as the prehistoric Bonitians left no known calendar or other time record, an effort is to be made to correlate their distinctive chronology with that of our own civilization through over-

FIG. 134.—The high cliff behind Pueblo Bonito affords an exceptional vantage point from which to view the ancient ruin. In this photograph, taken at the close of the 1922 season, the relationship of the secular rooms and kivas is at once apparent. Note the cars and track by which debris was conveyed from the ruin for deposition in the arroyo; also the expedition camp in the upper right-hand corner. (Photograph by Neil M. Judd. Courtesy of the National Geographic Society.)

lapping series of growth rings in living trees, old logs and ancient beams.

Investigations pursued beneath the floors of both dwelling rooms and kivas revealed, as in 1921, the remains of razed walls belonging to an earlier period of construction. The later habitations do not necessarily conform to the outline of those preceding; the masonry itself is usually, but not always, different in type thus indicating that people with entirely distinct cultural customs reoccupied this section of the pueblo prior to its final abandonment.

Among the artifacts collected during the past two years are specimens and many fragments of mosaic. These, with the number and

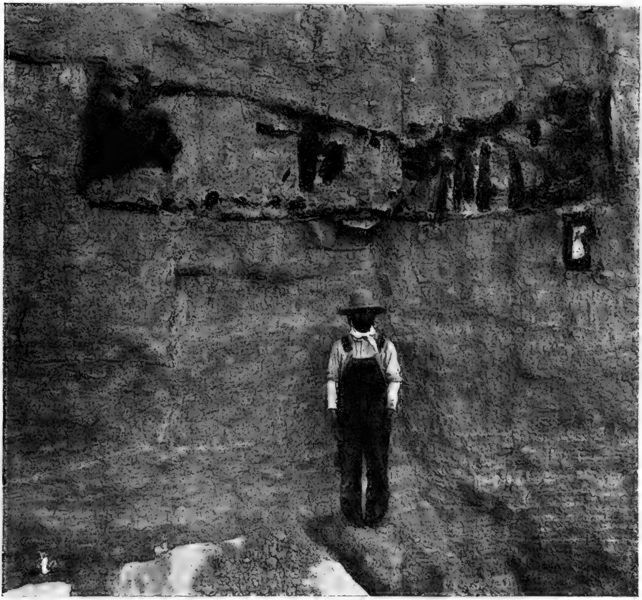


FIG. 135.—A circular pre-Pueblo dwelling, 1 mile east of Pueblo Bonito, was cross sectioned by caving of the arroyo bank. Twelve feet of blown sand and water-deposited silt had accumulated upon the floor of the room whose furnishings included a central fireplace (above the Indian) and a semi-circular bench (at upper left). Charred fragments of roofing poles are plainly seen. (Photograph by Neil M. Judd. Courtesy of the National Geographic Society.)

variety of bracelets, pendants and other objects of personal adornment already recovered, tend to confirm the Navaho and other traditions relating to the great wealth of the ancient Bonitians. Pueblo Bonito is still identified among the Indians of northwestern New Mexico as a village where turquoise and rare shells were abundant. The pottery

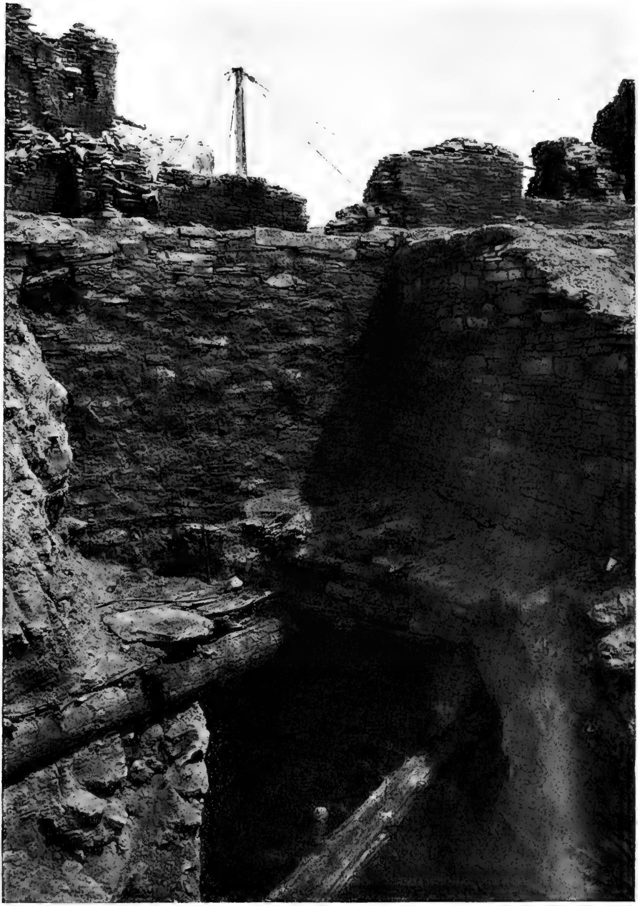


Fig. 136.—Dwellings in Pueblo Bonito were sometimes razed to permit of the construction of ceremonial chambers. The former ceiling beams shown in this illustration are here used both as braces for the curved wall of a kiva and as supports for a second-story room which was subsequently abandoned as its enclosing walls were still further altered. (Photograph by Neil M. Judd. Courtesy of the National Geographic Society.)

of this ancient community is among the finest in the Southwest, no other prehistoric people within the borders of the United States having surpassed the ancient Bonitians in the beauty of form and decoration of their ceramic artifacts.

INVESTIGATION OF PREHISTORIC QUARRIES AND WORKSHOPS IN PENNSYLVANIA

Mr. John L. Baer, acting curator of American archeology in the U. S. National Museum during the absence of Mr. Neil M. Judd, curator, spent a part of April, 1922, and a number of week ends during the summer, along the Susquehanna River, where he investigated a number of prehistoric quarries and workshops for the Bureau of American Ethnology.

On Mount Johnson Island, one mile above Peach Bottom, Lancaster Co., Pa., he has located a workshop where slate banner stones were made in quantity. These prehistoric objects, figures 137, 138, often of finest workmanship, are peculiar to the eastern part of the United States and their use has led to much speculation among archeologists. During the past few years more than 300 broken and unfinished banner stones have been found here, from which a number of series have been assembled showing all stages of development from the split blocks of slate to finished banner stones. The series illustrated herein has been placed on exhibition in the Pennsylvania case in the Archeological Hall of the U. S. National Museum.

This workshop was conveniently located a short distance up the river from a large vein of slate which crosses the Susquehanna. A high cliff of exposed slate extends to within a few yards of the water's edge on either side of the river.

The large number of specimens broken in the early stages of manufacture, found at the island workshop, and the scattered specimens showing more advanced work, picked up on nearby camp sites, indicate that many of the unfinished banner stones were blocked out and partly pecked at the workshop near the source of material and carried to distant camp sites to be completed there. As there was a famous shad battery on Mount Johnson Island, to which Indians from distant points came for supplies of shad and herring, it is probable that many of the slate banner stones scattered through Pennsylvania and Maryland may have been made, or at least started, at this workshop.

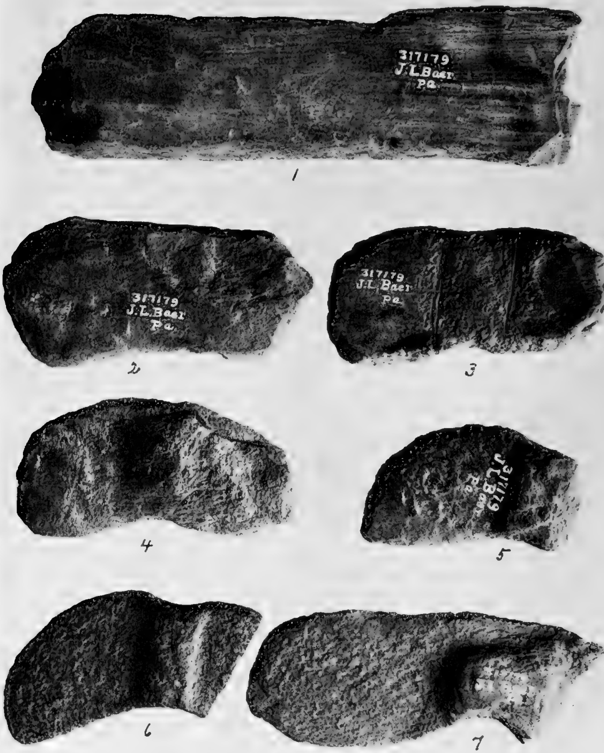


Fig. 137.—A series of unfinished banner stones.

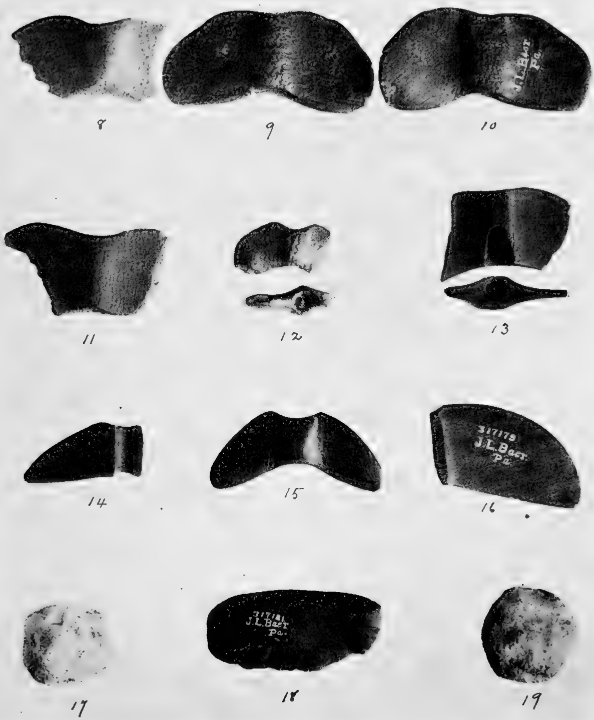


FIG. 138.—Banner stones in series, and shaping tools.

INVESTIGATIONS AMONG THE ALGONQUIAN INDIANS

At the close of May, 1922, Dr. Truman Michelson, of the Bureau of American Ethnology, proceeded to Oklahoma to conduct researches among the Sauk and Kickapoo. The prime object was to secure data on the mortuary customs and beliefs of these tribes. From these data it is now absolutely certain that the mortuary customs and beliefs of not only the Sauk and Kickapoo but also those of the Fox for the

FIG. 139.—Fox winter lodge, at Tama, Iowa.

greater part have been derived from a common source. Towards the end of June, Dr. Michelson went to Tama, Iowa, to renew his work among the Fox Indians. Many texts in the current syllabary were translated, some restored phonetically, fuller data on the mortuary customs and beliefs were obtained as well as new data on the ceremonial attendants and runners.

In August, Dr. Michelson left for Wisconsin, where he spent a week of reconnaissance among the highly conservative Potawatomi, near Arpin. He then visited the Ojibwa near Reserve, Wisconsin, to obtain some first-hand information on them, and afterwards the Ottawa of the lower Michigan peninsula. It appears that their language and folklore survive with full vigor, but their social organization has rather broken down. Dr. Michelson next visited the Delaware and Munsee of Lower Canada. It is clear that the Delaware and Munsee spoken in Canada are not the same as spoken in the United States; so that the term "Delaware" is really nothing but a catch-all designation of a number of distinct though closely related languages. Finally, Dr. Michelson carried on investigations among

FIG. 140.—Fox matting at Tama, Iowa.

the Montagnais, near Pointe Bleue, P. Q., for a few days. He found that although the language is distinctly closely related to Cree, nevertheless it is decidedly more archaic than has been commonly supposed.

FIELD-WORK AMONG THE YUMA, COCOPA, AND YAQUI INDIANS

Miss Frances Densmore, collaborator of the Bureau of American Ethnology, conducted field-work among the Yuma and Cocopa Indians living near the Mexican border in Arizona, and the Yaqui living near Phoenix, Arizona. Songs of the Mohave were recorded by members of the tribe living on the Yuma reservation, and a Mayo song was obtained from a Yaqui Indian.

The Yuma and Cocopa are the most primitive tribes visited by Miss Densmore and are probably as little affected by civilization as any living in the United States. The Yaqui are still citizens of Mexico though they have lived in Arizona for many years, their little settlement being known as Guadalupe Village. They obtain a scanty living by working for neighboring farmers and their chief pleasure is music, which is heard in the village at all hours of the day. They are governed by a chief and several captains, and seem contented and orderly.

The field-work among the Yuma and Cocopa centered at the Fort Yuma Indian agency, situated on the site of Fort Yuma, in California. An opportunity presented itself to observe their custom of cremating the dead. The body of an Indian who had died in an asylum for the insane was brought to the reservation for cremation. When Miss Densmore went to the cremation ground in the morning the body was seen lying on a cot under a "desert shelter." The relatives were crowded around it, sitting close to it and fondling the hands as they wept. The face of the dead man was covered. The wailing had been in progress all the previous night and the people showed signs of weariness. About 100 people were present, many being old men who sat with tears streaming down their faces while others sobbed convulsively. The cremation took place at about two o'clock in the afternoon. The ceremony was witnessed from the time when the body was lifted for removal to the funeral pyre, until the flames had destroyed it. Clothing and other articles of value were placed with the body or thrown into the fire. The ceremony was given in its most elaborate form, the deceased being accorded the honors of a chief because he had, prior to his mental illness, been one of the two leading singers at cremations. The rattle used in the ceremony is said to be about 250 years old. It is made of the "dew-claws" of the deer, one being added for each cremation in early times. It is now impossible to continue this as the deer are not available.

Information concerning this ceremony was surrounded with the secrecy which envelopes this class of material among all Indian tribes. Many of the ceremonial songs were, however, recorded phonographically by the oldest man who has the right to sing them, and an account of the history of the custom was obtained, together with a description of the *Kurok,* or memorial ceremony which is held every summer. In this ceremony there is a public burning of effigies of the more prominent persons who have died during the year. The dead are never mentioned, this custom being rigidly observed. The songs of the Kurok, and several cremation songs of the Mohave, which showed interesting differences from those of the Yuma, were recorded.

Miss Densmore's study included war customs, the songs used in treating the sick, those of the maturity ceremony of young girls, those connected with folk tales, and several long cycles of songs sung at

FIG. 141.—Kachora, a Yuma. His long hair is wound like a turban around his head. (Photograph by Miss Densmore.)

tribal dances, or for pleasure without dancing. These songs are interesting, many of them being pure melody without tonality. The words are exceptionally poetic and concern birds, insects and animals, as well as rivers and mountains. The work among the Yuma was aided by Kachora (fig. 141), a prominent member of the tribe.

A trip was made to a Cocopa village in the extreme southwestern portion of Arizona, near the Colorado River and only a few miles from the Mexican border. In the work of recording songs it was necessary to employ two interpreters, Nelson Rainbow, who translated Cocopa into Yuma, and Luke Homer who translated Yuma into English. In many instances it was necessary for the singer to explain his material to Tehanna (fig. 142) who discussed it with Rain-

FIG. 142.—Frank Tehanna, a Cocopa. (Photograph by Miss Densmore.)

bow, who in turn related it to Homer, after which it was translated into English. Under such conditions it was possible to make only a general study, but much interesting material was obtained. Two of the principal Cocopa singers were Clam and Barley (figs. 143, 144).

The musical instruments of the Yuma and Cocopa are the gourd rattle, the *morache* (rasping sticks), the basket drum beaten with wooden drumming sticks or with bundles of arrow-weed, also a flageo-

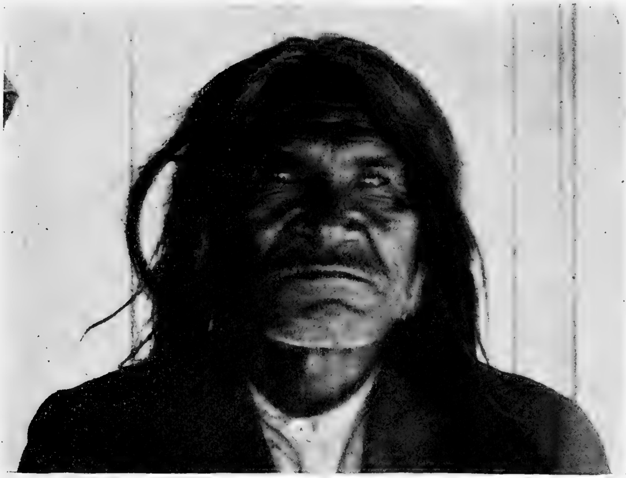


FIG. 143.—Clam, a Cocopa. (Photograph by Miss Densmore.)

FIG. 144.—Barley, a Cocopa. (Photograph by Miss Densmore.)

let and a flute, the latter being the first wind instrument blown across the end which has thus far been obtained. Specimens of all these were secured and the playing of the flageolet and flute were recorded by the phonograph. In addition to her musical work, Miss Densmore made a phonograph record of the numbers from 1 to 30 spoken by an aged woman who knows the "old language."

In April, 1922, Miss Densmore visited the Yaqui at Guadalupe Village, about 10 miles distant from Phoenix. She was present at the observances of the week preceding Easter, including the deer dance which was given on Good Friday. Similar, though more primitive, observances were attended at a Yaqui village near Tucson, in April, 1920. The Yaqui observance of Holy Week is a mixture of Roman Catholic influence and native ideas, customs, and dances. The singing is said to be continuous day and night from Good Friday to Easter. There is an evident fanaticism, and a certain hypnotic effect in Yaqui singing which suggests that, under some conditions, the people could work themselves into an irresponsible state of mind by its use. The melodies connected with the religious observance were less distinctly native than those of the deer dance which was performed on the day before Easter by five men, all scantily clad. The leader of the dancers wore a head dress made of the head of a deer and his leg-wrappings were ornamented with hundreds of tiny pouches made of deer hide containing pebbles, forming a series of rattles. Two of the dancers carried rattles made of a flat piece of wood in which were set several small tin disks which vibrated as the rattles were shaken. In this dance they likewise used four half-gourds, of which one was placed hollow side downward on water in a small tub and another was inverted on the ground. These served as drums. The other two were placed on the ground and used as resonators for rasping sticks. A few days later Miss Densmore recorded the deer dance songs, given by an old man who was the leading singer at all the deer dances. She recorded also a deer dance song of the Mayo, living in Mexico.

It was found there are two kinds of music among the Yaqui, one being the native, exemplified in the deer dance, and the other showing a Mexican influence, though the people stoutly asserted that it is Yaqui and "different from Mexican music." The songs of the deer dance are simple, with some characteristics not previously found in Indian music but appearing to be native concepts. These and similar songs are known to only a few of the old men. Songs of the second kind are sung by the younger men and are very pleasing, joyous melodies, usually accompanied by the guitar.

Instrumental music is highly regarded among the Yaqui, a favorite instrument being a short harp of native manufacture, which is played in an almost horizontal position, its base resting on a box in front of the seated player.

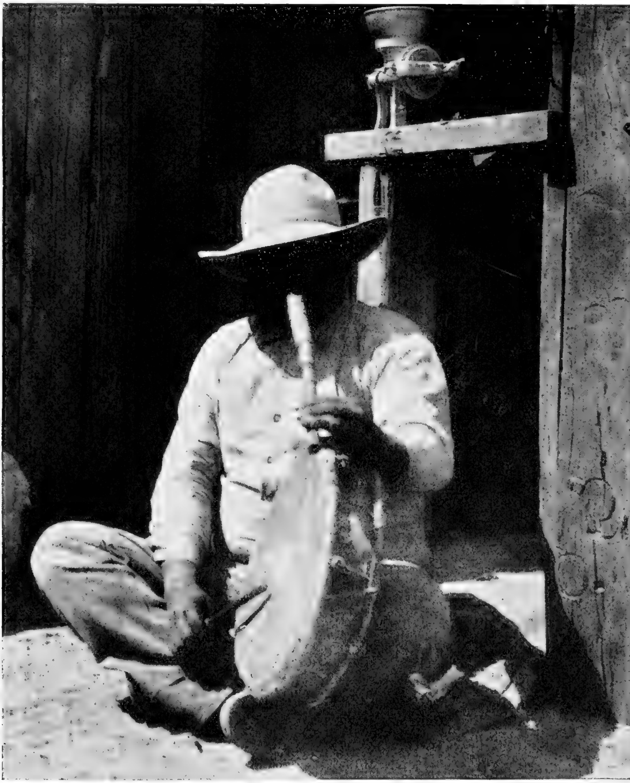


FIG. 145.—Manuel Ayala, a Yaqui, playing on flageolet and drum. (Photograph by Miss Densmore)

Among the musicians at the observance of Good Friday was Manuel Ayala who played the drum and the flageolet at the same time, each having its own rhythm (fig. 145). This flageolet had only two sound holes, and was made in two sections which could be taken apart.

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DESIGNS ON PREHISTORIC POTTERY FROM THE MIMBRES VALLEY, NEW MEXICO

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DESIGNS ON PREHISTORIC POTTERY FROM THE MIMBRES VALLEY, NEW MEXICO

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CHIEF, BUREAU OF AMERICAN ETHNOLOGY

Before the year 1914 little was known of the manners and customs of the prehistoric inhabitants of the valley of the Rio Mimbres in southern New Mexico. Historical references to these people from the time this valley was discovered to its occupation by the United States are few and afford us scanty information on this subject. Evidence now available indicates that the prehistoric occupants had been replaced by a mixed race, the Mimbreños Apache, of somewhat different mode of life. Until a few years ago the numerous archeological indications of a prehistoric population were equally limited. Some of the earlier writers stated that there are no evidences of a prehistoric sedentary population occupying the area between Deming, New Mexico, and the Mexican border.

In his pamphlet on the "Archeology of the Lower Mimbres Valley, New Mexico," published in 1914,[1] the author reviewed the contributions of others on this subject up to that date, and the present paper offers, as a supplement to that preliminary account, descriptions of additional designs on pottery collected by several persons since the publication of the article above mentioned. The writer has laid special stress on the quality of realistic designs on pottery from this region, and has urged the gathering of additional information on their meaning and relationship.

In the author's judgment no Southwestern pottery, ancient or modern, surpasses that of the Mimbres, and its naturalistic figures are unexcelled in any pottery from prehistoric North America. This superiority lies in figures of men and animals, but it is also *facile princeps* in geometric designs. Since the author's discovery of the

[1] Smithsonian Misc. Coll., Vol. 63, No. 10. Supplementary additions were made in the "Explorations and Field-Work of the Smithsonian Institution in 1914," pp. 62-72, Smithsonian Misc. Coll., Vol. 65, No. 6, 1915; and in the American Anthropologist, n. s. Vol. XVIII, pp. 535-545, 1916.

main features of this pottery the Mimbres Valley has come to be recognized as a special ceramic area.

Specimens of this pottery were first called to the attention of the author in 1913 by Mr. H. D. Osborn, of Deming, New Mexico, who excavated a considerable collection of this ware[1] from a village site near his ranch 12 miles south of Deming. Shortly after the discovery the author visited the location where it was found and excavated a small collection. From time to time since the author first announced the discovery of this material, years ago, other specimens of the same type have been described by him. These objects support early conclusions as to the high character and special value of this material in studies of realistic decoration. New designs have been added to available pictographic material which justify these conclusions.

In the past year (1921) Mr. Osborn has continued his excavations and obtained additional painted bowls, thereby enlarging still more our knowledge of the nature of the culture that flourished in the Mimbres before the coming of the whites. These newly discovered specimens are considered in the following pages.[2]

A brief reference to a physical feature of the Mimbres Valley may serve as a background for a study of the culture that once flourished there. The isolation of this valley is exceptional in the Southwest. The site where the Mimbres culture developed is a plateau extending north and south from New Mexico over the border into Mexico. Ranges of mountains on the east side separate it from the drainage of the Gulf of Mexico and high mountains prevent the exit of its rivers on the west. Its drainage does not empty directly into the sea, but after collecting in lakes it sinks into the sands. The lowest point of this isolated plain in which are the so-called lakes, or "sinks," Palomas and Guzman, is just south of the Mexican line. The water of the Mimbres sometimes finds its way into the former, but is generally lost in the sands before it reaches that point. The Casas

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[1] Many of these specimens were purchased by the Bureau of American Ethnology and are now in the U. S. National Museum, but the majority were later sold to Mr. George G. Heye and are now in the Museum of the American Indian, New York.

[2] Several other collectors have furnished me with data on Mimbres ware, among whom Mrs. Edith Latta Watson, and Mrs. Hulbert, of Pinos Altos, New Mexico, should be especially mentioned. On the very threshold of his descriptions the author desires to thank Mr. Osborn, Mrs. Hulbert and Mrs. Watson for permission to describe this new material. He desires also to commend the beautiful copies of photographs of the designs on these bowls, made by the artist, Mrs. George Mullett, of Capitol View, Maryland.

Grandes and tributary streams that lie in the basin south of the national boundary flow northward and finally empty into Lake Guzman. It is characteristic of the upper courses of these streams that they contain abundant water, while lower down they sometimes sink below the surface, but still continue their courses underground unless rock, clay or other formations that the water can not readily penetrate have pushed up their beds to the surface.

Flowing water is constant in the upper Mimbres but lower down the valley it is subterranean, though rising at times to the surface. The river is indicated here and there by rows of trees or a series of ponds. Water is never found in great abundance, but there is always enough for trout and a few other fishes which the early inhabitants, judging from the number of these animals depicted on pottery, admired and greatly esteemed for food.

There is more water in the Casas Grandes River and its tributaries than in the Mimbres, which is smaller and has fewer branches. There is a remarkable natural hot spring in the Mimbres Valley at Faywood, in which a large number of aboriginal implements and other objects were found when this spring was cleaned out several years ago, leading to the belief that it was regarded by the aborigines as a sacred spring.

The forms of pottery found in the Mimbres Valley differ very little from those of the pueblo areas. Food bowls predominate in number, although effigy vases, jars, ladles, dippers, and similar objects are numerous in all collections from this locality. They belong to modified black and white ware, red on white, unglazed, generally two-colored types. There are also specimens of uncolored, corrugated and coiled ware.

As the author has elsewhere indicated,[1] the figures on Mimbres pottery are largely realistic. A reference to an early account of the fauna might be instructive as an indication of the motives of the decoration of this pottery.

" The hills and valleys," writes Bartlett,[2] " abound in wild animals and game of various kinds. The black-tail deer (*Cervus lewisii*) and the ordinary species (*Cervus virginianus*) are very common. On the plains below are antelopes. Bears are more numerous than in any region we have yet been in. The grizzly, black, and brown varieties are all found here; and there was scarcely a day when bear-

[1] Archeology of the Lower Mimbres Valley, New Mexico, Smithsonian Misc. Coll., Vol. 63, No. 10, 1914.

[2] Personal Narrative, 1854.

meat was not served up at some of the messes. The grizzly and brown are the largest, some having been killed which weighed from seven to eight hundred pounds. Turkeys abound in this region, of a very large size. Quails, too, are found here; but they prefer the plains and valleys. While we remained, our men employed in herding the mules and cattle near the Mimbres often brought us fine trout of that stream, so that our fare might be called sumptuous in some respects."

The above mentioned animals and many others are represented on ancient Mimbres pottery. There are a few paintings of flowers but only rarely have natural objects such as sun, moon, mountains, or hills been identified. Of geometrical designs there are zigzags, terraces, circles, rectangles, spirals, and conventionalized heads, beaks, feathers and the like of birds; but food animals are the most abundant, deer, antelope, turkeys, rabbits and the like predominating. We have every reason to suppose from the pictography on the pottery that animal food formed a considerable part of the dietary of the ancient Mimbreños, but there is also abundant evidence that they were agriculturists and fishermen.

As a rule the bowls on which the designs here considered are depicted were mortuary, that is, found buried with the dead under the floors of former houses. These bowls are almost universally punctured or "killed" and are commonly found at the side of the skeleton, although when it is in a sitting posture, as often occurs, the bowl covers the head like a cap.

The Mimbres pottery shows several designs representing composite animals, or those where one half of the picture represents one genus of animal and the other a wholly different one. Similar composite pictures are rarely found in American art, although there are several examples of feathered and bicephalic serpents, winged reptiles, and the like. Probably if we were familiar with the folklore of the vanished race of the Mimbres we would be able to interpret these naturalistic pictures or explain their significance in Indian mythology.

The attention given to structural details in the figures of animals shows that the ancient inhabitants of the Mimbres who painted these designs were good observers, clever artists, and possibly drew these pictures from nature. There are, however, anomalies; profiles of the tails of birds are drawn vertically and not represented horizontally; the feathers that compose them were placed on a plane vertical, not horizontal, to the body. Both eyes were rarely placed on one side of the head as is so often the case with bird figures from the ancient pottery. They are often lozenge shape but generally round. Birds are the most common Mimbres animal paintings and the details of different kinds of feathers are often so carefully worked out that they can be distinguished. Many birds are represented as destitute of wings or have them replaced by geometrical figures of various angular shapes.

The designs here described support the theory already published, that the pottery of the Mimbres is related to that of Casas Grandes in Chihuahua, Mexico, but there are significant differences between the houses of the two areas. The Casas Grandes culture apparently extended northward into New Mexico and penetrated to the sources of the Mimbres River. In this uniquely isolated valley, whose rivers had no outlets in the sea, there developed in prehistoric times one of the most instructive culture areas of the Southwest. The geographical position renders it most important to investigate as it lies midway between the Pueblo and Mexican region, showing affinities with both.

The majority of designs on Casas Grandes pottery are drawn on curved surfaces, as terra cotta vases, jars, and effigies, while those on Mimbres ware are depicted on a flatter surface—the interior of food bowls. For this reason the spaces to be filled on the former are more varied; but the style in the two types is practically the same.

The designs of Mimbres ceramics are painted on the inside surface of clay bowls, the color of which is white, red, brown, or black. While the majority of the designs are depicted on the *inside* of Mimbres food bowls, similar geometric figures occur on the *outside* of Casas Grandes vases, dippers, ladles, cups, and other forms. A food bowl furnishes a plane inner surface but its rounded exterior is the least desirable for realistic figures. In these characters we have one of the important points separating the pottery of the Mimbres from that of Casas Grandes.

Effigy jars and vases, predominating in collections from Casas Grandes, are rare in those from near Deming and on the upper Mimbres. The pottery from at least one village site of the Mimbres resembles that of the upper Gila and its tributaries; but both shards and whole pieces of pottery from the Gila are characteristic and can readily be distinguished from that of the Mimbres-Casas Grandes region. The decoration of Mimbres pottery is distinctive and very different from that on any other prehistoric pueblo ware, evidently little modified by it. Although highly developed and specialized like modern pueblo pottery, it is quite unlike that from ancient pueblos of the Rio Grande region.

We find in this pottery well drawn naturalistic pictures as well as geometric designs, but there is no new evidence that the former were developed forms of the latter. It is more than probable that both geometric and realistic types were made contemporaneously and originated independently. By many students geometric ceramic decorations are supposed to be older than realistic; straight lines, dots, circles, stepped figures and spirals are supposed to precede life figures. Others hold that conventionalized designs follow naturalistic forms. It is sometimes supposed that in the growth of decorative art lines or dots are added to meaningless figures to make them more realistic. For instance, three dots were added to a circle to bring out a fancied human face, or representations of ears, nose, and other organs were annexed to a circle to make a head seem more realistic. Lines are thus believed to be continually added to a geometric meaningless figure to impart to it the life form.

There is a certain parallelism in these figures to drawings made by children to represent animals, whose pictures are often angular designs rather than realistic portrayals of objects with which they are familiar. It may be pointed out that some children in their earliest drawings make naturalistic, others geometric figures.

Naturally, when we contrast the designs on pottery from the Mimbres with that of the Mesa Verde, one great difference outside of the colors is the large number of realistic figures in the former and the paucity of the same or predominance of the geometric type in the latter. If we compare the designs of Sikyatki pottery with those on the Mimbres ware the differences are those of realism and conventionalism. The designs of Sikyatki pottery are mainly conventionalized animals, while those of the Mimbres are realistic. Geometrical designs from Mesa Verde are not conventionalized life forms; neither are they realistic. The pottery of the Little Colorado is midway in type, so far as its decoration goes, between that of Sikyatki and Mesa Verde. It is not as realistic as the Mimbres, not as conventionalized as Sikyatki, nor as geometric as Mesa Verde.

There seems much to support the theory that these three types of design, geometric, conventionalized, and realistic, are of equal age and developed independently. The author inclines to the belief that the primitive artist, having noticed certain resemblances in his geometric designs to life forms, men or animals, helped out the fancied likeness by adding dots or lines for eyes, nose and mouth, wings, legs or tail, to a circular or rectangular figure, and thus made a head of a man or an animal, the result being a crude realistic figure. Subsequent evolution was simply a perfecting of this figure. The theory that the conventional figure was derived from the realistic also appeals to the author; and he further believes that there are many geometric decorations that have no symbolic significance.

The naturalistic designs on pottery of the modern pueblos of Keresan stock resemble somewhat those of the Mimbres, or are closer to them than those of the modern Tewa, Zuñi, or Hopi; while, on the other hand, ancient Tewa, Zuñi, and Hopi wares are closer to Keresan than they are to modern pottery of the same pueblos. Ancient Hopi and Zuñi designs resemble each other more closely than modern, a likeness due in part to their common relationship to the culture of the Little Colorado settlements, the differences being due to the varying admixture of alien elements. In fact, the archaic pottery symbols are simpler than the composite or modern.

Human figures on Mimbres pottery are as a rule cruder than those of animals and in details much inferior to those of birds. They represent men performing ceremonies, playing games, or engaged in secular hunting scenes, and the like.[1] Now and then we find a representation of a masked man or woman in which the face is sometimes decorated with black streaks as if tattooed or painted. Frequently there are representations of feathers or flowers on body, limbs or head. Both full face and profiles of men occur in these figures; even the hair dressing is shown with fidelity. Several styles of clothing are recognizable. Let us now proceed to discuss a series of these figures.

HUMAN FIGURES

Figure 1 represents men engaged in a hunt. A hunter carries in his right hand three nooses attached to sticks; in his left he holds a stick to which feathers or leaves are attached. The hunter's hair is tied down his back; apparently he wears a blanket or loose fitting garment. Five groups of upright sticks support horizontal ones; that at the extreme right has attached to it a noose still set. Three captured birds are seen in the remaining nooses. The double row of dots represents a trail; two birds to the right of the human figure

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[1] Why the figures on Mimbres pottery should be more realistic than those from elsewhere in the Southwest is not apparent, unless the richness of the fauna has some connection with it.

face three sticks. The whole picture represents a method of snaring birds that was in vogue among the Mimbres ancients.

Figure 2 is also instructive. It is evidently a gambling scene representing three men playing the cane dice game, widely distributed among our aborigines. Unfortunately almost a half of the picture is no longer visible, but three cane dice appropriately marked lie in the middle of what remains of a rectangular design on the bottom of a broken jar. As the game requires four cane dice, two are missing. On one side of the figure is what appears to be a basket of arrows, evidently the stakes for which the game is being played. One of the seated human figures holds a bow and three or four arrows, while another has only one arrow. Rows of dots extending across the bowl are visible under the feet of the figure with one arrow.

There are six human figures represented in figure 3, five of which in a row appear to be crawling up a ladder while a sixth, bearing in the left hand a crook, is seated in an enclosure near the end of the ladder. The attitude of the five climbing figures suggests men emerging from the earth; the chamber in which the sixth is seated resembles a ceremonial room or kiva.

In figure 4 we have three human figures, two seated and one lying down. The difference between these figures is not great, but the two seated figures have their hair tied in a knob; the hair of the horizontal figure is straight. The left-hand figure bears a zigzag object in his hand that reminds one of a snake or lightning symbol. The right-hand figure appears to hold in his hand an implement represented by parallel lines and dots surmounted by an imitation of a head with feathers. This object calls to mind the wooden framework used by the Hopi in their ceremonies to imitate the lightning.

In figure 5 there are four figures, all different; two were evidently intended to represent men with human bodies and heads of animals. Each carries a rattle in one hand and a stick to the end of which is attached a feather, or a twig with leaves, in the other.

The exact signification of the group of three figures, two male and one female, shown in figure 6, is not evident. The two men carry sticks with attached flowers, or figures of the sun or a star; the other figure, which represents a woman, has a crook in one hand. The frayed edge of the woven belt she wears hangs from her waist.

The knees of the two human figures shown in figure 7 rest on the back of a nondescript animal. The figures are evidently duplicates, the only difference being in the forms of the geometric figures depicted on the bodies of the animals.

Two nicely balanced human figures shown in figure 8 are represented as resting on a quadrilateral object decorated with zigzag markings, like symbols of lightning.

The heads in figure 9 are human but the body and limbs are more like those of quadrupeds.

The method of drawing the human figure in figure 10 is very characteristic. Here we evidently have a representation of a dancer, whose body is painted black, surrounded by a white border.

The human figures thus far considered are drawn in colors on a white background. Not so those that follow. In figure 11 there are two negative figures, representations of human beings placed diametrically opposite each other, and, similarly arranged, two turkeys painted black on a white oval area, a very good example of the arrangement of double units. The human figures are white and have arms and legs extended. A black band in which are two eyes extends across the forehead. The lips are black; mouth white. This is a good example of one pair of units being negative, the other positive. There are four triangles with hachure in the intervals between the figures.

An analysis of the design in figure 12 shows two human figures drawn opposite each other, with arms extended and legs similar to those of frogs. The complicated geometric figures vary considerably but can be reduced to about three units; but these units are not always repeated twice.

In figure 13 there are two human figures, one seated on the shoulders of the other, who is prostrated and has head severed from body. The former apparently is holding a knife or pipe in his right hand and the hair of the decapitated head in the left. The head and back of this seated figure is covered with what appears to be a helmet mask and animal's pelt. The mask resembles the head of a serpent or some reptilian monster that has a single apical horn on the head and jaws extended. Possibly the disguise represents the Horned Serpent or the same being as figure 41. The body of the man and the lower part of the face is black. The Snake priests at Walpi paint their chins black.

ANIMALS

Quadrupeds.—Many of the animals depicted on the bowls are mammals distinguished by four legs, but often these present strange anomalies in their structure. In several pictures of rabbits and some other quadrupeds the lower fore-legs bend forward, and in one instance, a composite animal, the fore-legs are short and stumpy with no indication of a joint, but the hind-legs are slender, longer than the fore-legs, and apparently belong to a different animal. The majority of all the mammals represented have geometric designs on the body.

Variations in the form of the head and mouth are noticeable and are important in the determination of different genera to which these mammals belong. Figure 14 represents two quadrupeds with heads of lions and two geometric designs irregularly terraced, with white border. The interior is marked with parallel lines. The head is short and calls to mind that of a carnivorous animal; there is a white band about the neck; the tip of the tail is white. The rectangular body marking is lozenge-shaped with dots.

Figure 15 represents an unknown quadruped resembling some carnivorous animal. The tail has a white tip like figure 14; the ears are more prominent and pointed.

In figure 16 two men are dragging an animal by ropes tied to the neck of the captured beast. This is an effective way of leading a dangerous animal and preventing it from attacking either one of them.

The head and fore-legs of figure 17 resemble those of the bison. The head has ears, a horn, and a cluster of five feathers that are grouped fan-shape. The rear end of the body and hind-legs are somewhat like those of a wolf. This is a mythological composite animal or two different animals united.

The animal shown in figure 18 is seated, and has tail and ears like those of a hare or rabbit. The head, however, resembles that of a human being, with two black marks on the white cheeks. The upper part of the head is black. The two marks on each cheek among the Hopi are symbols of the Little War God.

Two exceptional animals with tails flattened like beavers are represented in figure 19. Although the fore-legs bear claws the posterior legs are club-shaped or clavate. The distribution of white and black on the bodies indicates a partly negative and partly positive drawing. The mouth has the form of a snout.

It would seem that figure 20 represents a carnivorous animal like a mountain lion. The tail is coiled, ending in a triangular appendage. Head, ears, and claws like a cat. The checkerboard periphery design is particularly effective.

Figure 21 represents a rabbit or hare whose body is black and without ornament. The joints of the legs bend in an unnatural way. Ears, tail, and labial hairs recall a rabbit.

Figure 22 represents two negative pictures of rabbits with characteristic ears and tails. They are separated by a band composed of parallel lines, somewhat after the style of figure 9. Space between fore- and hind-legs is filled in with white zigzag lines. Two rabbits also appear in figure 23, the forms of ears, tail, and body being somewhat different.

Figure 24 is likewise a rabbit figure which resembles the preceding in color. Most figures of rabbits have black bodies without the decorations on other mammals.

The food bowl illustrated in figure 25 has thirteen clusters of feathers, each cluster composed of four feathers, making an ornamental periphery. These clusters are called feathers because of their resemblance to the feather in a bird's wing depicted in figure 54. Although the two figures have rabbit features, the feet are quite different from those of that animal, the legs ending in sickle-like appendages. The reason for the strange shape of the fore and hind feet of this picture is unknown.

The body of the quadruped shown in figure 26 appears to have been penetrated by four arrows, but the central portion of the bowl has been broken or "killed" and an identification of the figure is impossible. The neck is long, quite unlike that of any animal known in the Mimbres fauna.

The animal represented in figure 27 is probably a bat; in no other representation is a realistic zoic figure so closely related to the geometric design.

Figure 28 resembles a frog, and figure 28*a* suggests two tadpoles crossed over a disk on which are depicted eight small circles. The petal-like bodies radiating from the central disk are ten in number, four of which are primary, four double, and two single. A much better figure of a frog is shown in figure 29.

Reptiles.—Figures 30 and 31 have closer likenesses to turtles than to frogs. The resemblance to a turtle is very striking in figure 31. The tail, which is absent in pictures of frogs, is here well developed, and the eyes and legs differ from those of frogs. The carapace of figure 31 is covered with scales.

Figures of a serpent and a mountain sheep are shown in figure 32. The two animals in figure 33 appear to be lizards outlined in white on a black ground; a kind of negative picture in which the body is filled in with black.

The animal shown in figure 34 is apparently a lizard, but it differs from the other figures of lizards in the bifurcated head, lizards generally being represented with lozenge-shaped heads.

The two reptilian figures shown in figure 35 have all the characteristics of lizards and the picture probably illustrates some myth or folk-tale. The mouths of the two lizards and that of the bird are approximated, which would suggest that the three were talking together.

Fishes.—The representation of a fish (fig. 36) between two birds suggests the aquatic habits of the latter. The form of the fish suggests the garpike, but the tail is more like that of a perch. The markings on the body are probably scales. Trout were formerly common in the Mimbres River, but none of the pictures on pottery from ruins in that valley have the adipose dorsal that distinguishes the trout family. There is a considerable variety in the pictures of fishes and probably more than one genus is represented. In no other ancient Southwestern pottery do we find as many different kinds of fishes represented as in that from the Mimbres.

Figure 37 represents a fish with pectoral, ventral, anal, and a single dorsal fin. The tail is uncommonly large. In figure 38 we have a fish accompanied by two birds; the body shows portions of the skin and also backbone and spines. The birds have long legs and necks, which are the structural features of aquatic birds.

In figure 39 we have one of the best examples of Mimbres negative pictures or white on a black background. These negatives are without outlines, their form being brought out by a black setting. Various anatomical structures are evident, as paired pectoral and ventral fins which are curved on one edge; pointed anal fin, small dorsal, crescentic gill-slit, small eyes, no mouth.

Figure 40 represents a sunfish, the body in profile being oval with long pointed dorsal fins and cross-hatched body.

The form of figure 41 is serpentine with two pairs of fins on the ventral side and a single fin on the dorsal region. The body of this animal ends in a fish tail; the head, which is black, has no gill openings in the neck. There is a horn on top of the head which bends forward and terminates in a bunch of feathers. The eye is surrounded by a ring of white dots; teeth white; tongue black.

The small fish represented in figure 42 has three fins on the ventral and one on the dorsal side. Through the whole length of this fish extends a white band, possibly the digestive organs. The fins of this particular fish have spines represented, whereas in other pictures these fins are solid black.

Figure 43 shows two fishes which closely resemble each other in structure. One, however, is painted black, while the other is covered with a checkerboard design. Each of these has a single ventral, dorsal, and pectoral fin, in which regard they differ from the specimens of fishes thus far known in Mimbres designs which commonly have paired pectoral and ventral fins.

Birds.—From their mysterious power of flight, and other unusual characteristics, birds have always been considered by the pueblos to be important supernatural beings and are ordinarily associated with the sky. We find them often with star symbols and figures of lightning and rain clouds. There is something mysterious in the life of a bird and consequently there must be some intimate connection between it and those great mysteries of climate upon which so largely depends the production of food by an agricultural people.

In Mimbres ware, as is usually true in conventional or naturalistic figures on prehistoric pueblo ware, birds excel in numbers and variety all other animals, following a law that has been pointed out in the consideration of pottery from Sikyatki, a Hopi ruin excavated by the author in 1895.[1]

There is, however, a great difference between the forms of birds, conventional and realistic, from different areas of the Southwest, and nowhere is the contrast greater than in those on the fine ware from Sikyatki and that of the Mimbres. The conventional bird and sky band, so marked a feature in the Hopi ruin, are absent in both the Little Colorado and Mimbres pottery.

The wild turkey, one of the most common birds, associated by the Hopi with the sun and with the rain, is repeatedly figured on ancient pottery from the Mimbres Valley.

Figure 44 shows three birds of a simple form from dorsal or ventral side, the head being turned so as to be shown laterally; but generic identification of these birds is difficult.

Figure 45 represents the head, neck, and wing of a parrot. It is instructive as showing wing feathers with white tips and black dots on the extremities. The triangular geometrical figure near its head has six feathers with black dots near their extremities.

Figure 46, one of the most realistic pictures in the collection, is evidently intended for a parrot and is one of the few representations of birds on Mimbres pottery in which the tail feathers are indicated by parallel lines. The special avian feature of this figure is the shape of the head and upper beak, which corresponds pretty closely with

[1] Seventeenth Annual Report Bureau of American Ethnology, Washington, 1898.

a geometric pattern called the " club design " used as a separate design in Casas Grandes pottery decorations.

The appendages on the head of figure 47 are feathers recalling those of quails; the tail is destitute of feathers.

The two wingless birds represented in figure 48 have a characteristic topknot on the head and a highly exceptional bodily decoration. Identification is doubtful.

The bird (fig. 49), shown from one side, has a vertical conventional wing, long neck and legs adapted for wading.

Although the tail of a bird shown in figure 50 resembles that of a turkey, the head and beak are similar to the same organs in a humming bird. Its beak is inserted into the petals of a flower, evidently for honey. The birds (fig. 51), among the simplest figures in the collection, have angular wings, the feathers being represented by serrations or dentations. There are figures of two birds drawn in a white dumb-bell-shaped area in figure 52.

The bird (fig. 53) has outstretched wings with hanging feathers of exceptional form. Legs are not shown, which leads to the belief that the back of the animal is represented. The tail was obscurely shown in the photograph, which made it impossible to obtain a good drawing of this organ. This is one of the few dorsal representations of a bird, most of the others being shown from one side. The position of the hanging feathers of the wings is exceptional.[1]

The bodies of the four birds represented in figure 54 are oval, without wings or legs. Two of these bear triangular and cross designs, and two have lenticular markings. Between the beaks of each pair of birds there is a rectangular and three triangular designs, all terraced on one side.

The tips of the tails of the birds represented in figure 55 are like that of a turkey but it is hardly possible to prove that this is a proper identification.

The bird figure shown in figure 56 exhibits no wing or tail feathers, but the body is prolonged into a point. The head bears four upright parallel lines indicating feathers. Legs, short and stumpy. The object suspended like a necklace from the neck is not identified.

There are several examples of wingless or tailless birds and a few are destitute of legs. The signification, if any, of this lack of essen-

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[1] On the reredos of the Owakulti altar at Sitcomovi on the East Mesa of the Hopi there is a similar figure with drooping wing feathers. Here it probably represents the Sky god, as there are several stars near it.

tial organs does not appear. Some of the birds have egg-shaped bodies; the heads with long beaks.

Figure 57 probably represents a turkey. The feathers of the tail are turned to a vertical position and the elevated wings have characteristic feathers. The legs end in conventionalized turkey tracks. There is a protuberance above the beak—a well known turkey feature. Figure 58 also represents a turkey, or rather three heads of the same animal with a single body. There are also three wings. The tail is turned vertically instead of horizontally and the claws are four in number—three anterior and one posterior. It has a single breast attachment.

Feather designs.—Among the modern pueblos the feather is one of the most prominent ceremonial objects and the specific variety used in their rites is considered important. Every Hopi priest in early times had a feather box, made of the underground branch of the cottonwood, in which he kept his feathers ready for use. The forms and decorations of Mimbres pottery would seem to indicate that feathers played a conspicuous rôle in the symbolic designs on prehistoric pottery.

The importance of the feather as a decorative motive is somewhat less in Mimbres pottery than in Sikyatki, the symbolism of which is elsewhere[1] considered; but the symbols for feathers in the two areas are different and might very readily be used to distinguish these areas.

The types of the wings and tails of birds here considered were taken from the realistic representations on Mimbres pottery. We often find a dot indicated at the tip of a feather, a feature likewise seen in pottery from Casas Grandes in old Mexico and of wide distribution in aboriginal North America.

In order to be able to demonstrate that a geometrical decoration is a feather in Mimbres designs, the author has taken the representations of the wings and tails of many pictures of birds and brought them together for comparison. A few of these different forms of bird feathers from the Mimbres are shown in the figures (59-92) that immediately follow. The different forms of tail feathers thus obtained are considered first and those from the wings follow. It is interesting to point out that the author's identification of certain linear designs on Southwestern pottery as feathers was not obtained from the surviving Indians but by comparative studies. Starting

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[1] Thirty-third Annual Report Bureau of American Ethnology, Washington, 1919.

with the thought that certain rectangular designs are feathers, we can demonstrate the theory by its application and association with other bird figures.

Several forms of feather designs that appear quite constantly in the decoration of Sikyatki ware are not found on Mimbres ceramics, and *vice versa*. The Mimbres has several geometric feather designs peculiar to that valley. In the Sikyatki ware the relative number of feathers, free from attachment to birds, used in decoration is larger than in the Mimbres ceramics. Tail feathers have as a rule a different form from wing feathers and are more seldom used. Eleven different figures of birds' tails are here given, and there are twenty-two designs that are supposed to represent wings of different birds.

Tail feathers.—One of the simplest forms of birds' tails obtained in the way above mentioned is shown in figure 59, which represents five feathers. This feather type has square ends, each feather differentiated by lines as far as the body attachment. In figure 60 we also have four tail feathers, but the ends are rounded, and in figure 61 there are four feathers having rounded tips; the two outer could better be regarded as incomplete feathers. There are likewise four feathers in figure 62, but, although the tips are rounded, the angles are not filled in with black as in the two preceding specimens. Here the four feathers are united by a broad black band. In figure 63 three whole and two half feathers are represented, united by two broad transverse bands and four narrow parallel lines also transverse; and in figure 64 there are five whole feathers and two half feathers, which are barely indicated, the lines that divide the two members being simply indicated.

It is instructive to note how often this connecting black band appears on bird tails. Figure 65 is a case in point. Thus far also the feathers of birds' tails considered are about equal in length. Here (fig. 65), however, the middle feathers are longer than the outer; the line connecting the tips would be a curved one.

An innovation is introduced in the tail feathers shown in figure 66. Their tips are rounded and there is a slight difference in general form between the three middle and the two outer members. The novel feature is the appearance of semicircular, or triangular black dots at their tips. Whether the existence of these differences means that another kind of feather is depicted or not the author is unable to say.

In figure 67 the four feathers are characterized by black markings throughout almost their whole length. This variation may indicate a special kind of feather or a feather from a different bird.

Wing feathers.—The simplest forms of wing feathers are marginal dentations, serrations, or even parallel lines without broken borders. One of these last mentioned is figured in figure 68, where the wing is sickle-shaped and the feathers short, curved lines. In figure 69 these lines are replaced by dentations, and in figure 70 we have three wings, each with dentations on one edge.

The form of the wing has been somewhat changed in figure 71, but the feathers appear as dentations, while in figure 72 the feathers have become semicircular, each with a black dot. Wing feathers in figure 73 are simple triangles without designs, and in figure 74 they are semicircular figures, black at the base.

Typical forms of wing feathers appear in figures 75-79, which differ somewhat in form but are evidently the same. One of the essential features of these wings, as shown in the four figures mentioned, is their division into two regions distinguished by the forms of feathers in each case. This is not as well marked in figure 75 as in figure 76, where the four primary and three secondary feathers on the same wing are distinctly indicated. The markings on these are similar, but the primary feathers are long and their extremities more pointed. In figure 77 we can readily distinguish primary and secondary feathers in the same wing by the absence of a black marking evident on all the others, and in figure 78 the three secondary feathers are distinguished by dots near their tips; the primary wing feathers are here narrower and longer, the longest terminating in curved lines. Figure 79 represents a wing with seven feathers, of which the four secondary are distinguished by the existence of terminal dots.

Neither figure 80 nor 81 shows distinction of primary and secondary feathers but both have blackened tips. A like marking appears in figures 82 and 83, where it extends along the midrib of four feathers.

Figure 84 represents a right wing of a bird with eight feathers. A similar representation is found on the left side and for comparative purposes a cluster of these designs from a bowl decorated with geometric designs is also introduced (fig. 85).

Three feathers which have markings probably symbolic but different from any previously described are shown in figure 86. These were attached to a staff. Their identification is doubtful, which may likewise be said of figures 87 and 88, the two latter being a very simple form of the feather symbol. The four designs that appear in figures 89-92 are supposed to represent either tails or wings of birds in which individual feathers are not differentiated.

It is sometimes difficult to recognize the feather element in some of these and in others it is very well marked. These designs have been identified as feathers mainly on account of their connection with wings or tails of birds.

Insects.—The people of the ancient Mimbres probably did not recognize a sharp line of demarcation between birds and insects. Both were flying animals and can be distinguished in several figures. Figures 93-95 were evidently intended to represent insects, probably grasshoppers. The animal represented in figure 96 is enigmatical. It apparently represents an insect but has strange anatomical features for a member of this group. The head and antennae resemble those of other insects, but the two sets of leg-like appendages, three in each set, hanging from the ventral region distinctly resemble fins of fishes. We cannot identify this as a naturalistic representation of any known water insect. It is probably some conventionalized mythic animal.

It is impossible to identify with any certainty several pictures that occur in the collection further than to recognize that they represent insects. There are several pictures of the grasshopper or locust, and the bee, dragon-fly, and butterfly can be recognized. The object shown in figure 97 looks like an insect but its structure is not sufficiently marked to definitely determine the family.

The insect shown in figure 98 has the wings and extremity of the abdomen similarly marked and recalls the dragon-fly. The head and legs differ considerably from those in figure 97.

Figure 99 appears to represent a moth or butterfly. No identifications were made of figures 100 and 101. Figure 102 is a representation of an animal with four pairs of legs, possibly the insect known as the "skater." It has a head, thorax, and abdomen like an insect, legs like a grasshopper, and a tail like a bird.

The animals, and more especially the geometric patterns represented on both Mimbres and Casas Grandes pottery, are often similar; but this similarity in the beautiful pottery of the northern and southern regions of the Mimbres-Casas Grandes plateau is even stronger than the resemblances here pointed out would seem to indicate. The pottery of both regions, for comparative purposes,[1] may be regarded as belonging to the same area.

[1] The northern extension of typical Mimbres pottery is doubtful, but certain food bowls from Sapello Creek, a Gila tributary, bear figures that distinctly resemble those found near Deming. Vide: Hulbert and Watson Collections.

COMPOSITE ANIMALS

One unusual feature of life figures on Mimbres pottery is the union of two genera of animals in composition in one picture, probably representing a legendary or mythological animal. The signification of such a union is not known, as the folk tales of the ancient inhabitants of the Mimbres are unrecorded; but it is instructive to note that similar composite animals are not commonly represented on pueblo pottery, ancient or modern, although we have pictures of reptiles and the like with feathers on different parts of their bodies.

It is also instructive to note how many synchronous differences there are between prehistoric pottery and architecture. While there are evidences of interchange of material objects in two areas, we cannot say that the culture of the inhabitants of any two regions was identical until both have been studied. The occurrence of Casas Grandes pottery fragments in the Mimbres ruins or *vice versa* would indicate that the two cultures were synchronous.

GEOMETRIC FIGURES

The geometric designs on Mimbres pottery are as varied and striking as the life figures, and while they show several forms found on the pottery from Casas Grandes, a large majority are different and characteristic. The geometric decorations are confined for the most part to the interior surface of food bowls, but exist also on the outside of effigy jars and other pottery forms. The geometric designs on Mimbres pottery are not ordinarily complex but are made so by a repetition of several unit designs.

The arrangement of geometric figures in unit designs is in twos, threes, and fours. When there are two different units they are found duplicated. There is seldom more than one unit in the arrangement by threes and very seldom an arrangement of units in fives, sixes, or higher numbers. It is instructive to notice *en passant* that while there are several designs on Mimbres food bowls representing stars, these stars generally have four points, but sometimes five.

Great ingenuity was exercised in filling any empty spaces with some intricate geometric decoration. No two bowls out of over a hundred specimens examined bear identically the same pattern painted on their interiors.

One small but important feature in encircling lines should not be passed in silence. There is no break in decorative lines surrounding the bowl. This is characteristic of the northern pueblo or cliff-house area known as the San Juan drainage, but not of pottery from the Gila basin and the Little Colorado area as far north as old Hopi (Sikyatki). Much of the ancient decorated ware in the area between the Mimbres Valley and the Upper San Juan has surrounding lines broken. The broken line does not occur on the black and white type of ware, of which the Mimbres is a highly modified subtype. From the above facts regarding its distribution it appears that the "line of life"[1] on Southwestern pottery can be traced to southern Arizona, and as black and white ware does not have this feature and is ranked as very old, the decorated pottery of Arizona and central New Mexico where it occurs should probably be ascribed to comparatively recent times. The Mimbres ware has no life line decoration and as this valley is only a short distance from the Gila settlements that show the line of life on their pottery the logical conclusion would be that the Mimbres pottery is archaic or probably older than that which has a life line.

There is at least one ruin in the Mimbres in which pottery with the life line occurs. This pottery is so close in other respects to that of the Gila and so different from that of the majority of neighboring ruins in the Mimbres that we may suppose those who settled there came from the Gila valley.

Underlying the pure pueblo or kiva culture of the San Juan and its tributaries is a prepueblo culture which differs in terms of architecture[2] as well as in various types of artifacts.

The unpolished pottery of the prepueblo culture in the Mesa Verde is distinguished by the varieties of corrugated, coiled and rough unpolished ware. One type has the neck and mouth of the jars formed of coiling while the body of the jar is rough without. Unlike food bowls from the Mesa Verde cliff dwellings, the Mimbres pottery is destitute of painted dots continuous or in clusters that are almost constantly found in this more northern area. The great difference, however, between the ancient pottery of these two regions is of course the absence of realistic figures in the northern and their great abundance in the southern prehistoric ruins.

There are many bowls in the Mimbres ware that introduce areas, triangles, rectangles, and other geometrical figures across which

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[1] It does not seem probable that this line break originated independently in different ceramic areas of the Southwest. The pottery on which it occurs is supposed to be later than the Mesa Verde.

[2] As elsewhere pointed out, the character of ancient dwellings in the Mimbres belongs to a more ancient epoch than the pueblos; it looks as if the absence of the life line on pottery supported the same theory, but the other features in decoration appear more highly differentiated and therefore more recent.

extend parallel lines or hachures. When triangles, these figures interlock with the same of solid black, leaving zigzag white designs. This is apparently a rare method of decoration of Mesa Verde pottery by indentations, and occurs at intervals down the San Juan to the great ruins of northern Arizona no less than in ruins at Aztec and in the Chaco.

It seems to indicate an older state of culture as it universally underlies the true black and white or prepueblo culture which is missing in the Mimbres, Gila and Little Colorado regions.

While a knowledge of the distribution of the broken encircling line in pottery from Southwestern ruins is not very extensive, those in which it has survived lie in contiguous areas. This feature is absent in the oldest ruins. In the area where pottery thus decorated occurs there survive few inhabited pueblos. Another point: the decorated pottery of the San Juan drainage, where corrugated ware is most abundant, has no life line; this is true likewise with the Mimbres Valley, where the most realistic decorated figures occur, corrugated ware being comparatively rare. The line of life does not ordinarily occur in black and white ware. Archaic ware, generally speaking, has no line of life, which leads me to suppose that the Mimbres ware is older than the Gila pottery. One of the peculiarities of Mimbres pottery is the use of geometric figures on the bodies of animals. These are practically the same as those used free from zoic forms. Their meaning in this connection is not known but several explanations, none of which are satisfactory, have been suggested to account for their existence on animal bodies. This is not common in the pueblo area but occurs in the region or regions that are peripheral in situation, two of which are the San Juan cliff houses and related ruins and the Mimbres; one north, the other south of the central or northern pueblo zone. The author is led to regard this feature as later in development or more modern. If earlier it would probably have been distributed over the whole area. From a study of houses the author was led to believe that the Mimbres settlements were older than the great highly differentiated cliff dwellings and pueblos.

The geographical distribution of the "life line" is suggestive of its comparatively modern origin. It is found in ruins along the Gila and its great tributary, the Salt, in the ruins along the Little Colorado and its tributaries, at Sikyatki, Zuñi and some of the Rio Grande ruins.

The geometrical decorations on Mimbreños pottery can generally be resolved into certain units repeated two or more times, forming a complex figure. We have, for instance, a single type repeated four times, each unit occupying a quadrant. We have also another unit type repeated three times. In a fourth form we have two unit types, each repeated in opposite hemispheres, all together filling four quadrants. In a fifth method we have three different unit types, each duplicated.

In the design represented in figure 103 we have what appears to be a sun symbol or a circle with checkerboard covering and four projecting appendages that resemble bird-tails arranged in pairs, the markings of the opposite members of each pair being practically identical. The geometrical designs on the periphery of the bowl consist of six units, in each of which pure black and hachure are combined. In figure 104 the design appears as a central circle with four radiating arms of a cross, each with checkerboard decoration. Oval white figures alternate with these arms and in each of these ovals is depicted a compound figure of six triangles. A similar design appears on ancient pottery from the Hopi ruin, Sikyatki, where it has been identified as a complex butterfly symbol, and on that from the cliff dwellings of the Mesa Verde. In Mimbres pottery it sometimes occurs on the body of animal pictures, as the author has shown elsewhere.[1]

In the design (fig. 105) a central circle is absent but it has four arms like a cross with zigzag lines. The design (fig. 106) is made up of four S-shaped figures painted white on a black zone. From the inner ring there arise eight radiating lines which extend toward the center. Each of these radial lines has three parallel extensions at right angles.

Figure 107 is a broad Maltese cross painted white on a black background, one edge of each arm being dentated. This figure may be classed among the negative figures so successfully used by the ancient Mimbreños.

A swastica design represented in figure 108 is so intricate that it is not readily described. In the middle there is a square on the angles of which are extensions that have a dentate margin. The designs placed opposite each other are more elaborate than the other four and are triangular with solid colors and hachures.

Four triangular designs radiate from a common center on a white field in figure 109. Serrate marginal edges are used with good effect in this picture.

[1] See plates 3, 4, Archeology of the Lower Mimbres Valley, New Mexico. Smithsonian Misc. Coll., Vol. 63, No. 10, pp. 1-53, 1914.

There are two pairs of rectangular designs in figure 110 arranged about a central circle with peripheral serration recalling a buzz saw. The combination of designs surrounding it is unique but the elements resolve themselves mostly into zigzag and checkerboard decorative elements.

The extremities of the cross (fig. 111) are rounded; its arms arise from a central inner circle with figures in white on a black background. Two of the arms are ornamented with terraced rims and two have diamond figures separated by parallel zigzag lines forming bands in white on a black background.

Three pairs of designs can be recognized in figure 112, one pair resembling flowers on stalks; the others, also paired, are octagonal in form, recalling flowers seen from above. An eight-pointed rosette forms the center of one, and a cross, white on black, the other. Six triangular designs in which hachures predominate decorate the periphery.

Two pairs of geometric figures cover the interior of the bowl shown in figure 113. One pair is mainly a checkerboard design, the other chevrons on parallel lines. The central figure is surrounded by nine crosses on a white zone. Figure 114 has likewise two pairs of geometric units arranged about a central circular area which is white.

Figure 115 also has two pairs of radically different units, one with two rectangular designs, the other with wavy lines having dentate borders.

There is a trifid arrangement in the decoration of figure 116, consisting of three lozenge-shaped figures with dentate borders and parallel lines set in as many oval white areas. The central figure is a white circle with black border.

Figure 117 is also made up of three unit figures, each of triangular shape with an elaborate border of solid triangles and hachure surrounding figures.

Figure 118 is a very exceptional decoration and may be divided into six units arranged in pairs. There are four triangles, two pairs of which have a decorated border and two have not, but all alternating with a pair of five needle-like solid black pointed extensions reaching from the margin of the bowl inward. The most conspicuous figure is a unit design consisting of bands with two opposite figures united with the margin by a black line, each decorated with four frets.

Figure 119 is an unique decoration made up of a central circle with five claws like birds' beaks, each with an eye. The interior of each is a five-pointed star.

Figure 120 is a central four-terraced symbol from which extend many radiating feather-like designs. A central rosette in figure 121 has eight petaloid divisions; it is white at the extremities, black at the center.

The decoration of figure 122 consists of an intricate meander filling the peripheral space outside a circular central black area.

In figure 123 the more striking parts are the five white circles, one centrally situated, and four equidistantly placed near the periphery. The main portion of the bowl is covered with figures consisting of rectilinear lines and spirals.

The prominent design in figure 124 is a star with eight slender arms and exceptional peripheral decorations.

The centrally placed design depicted in figure 125 is a quadruped with tail curved upward, recalling a conventional mountain lion. The peripheral figures are of two shapes, lozenge or angular, and semicircular with zigzag extensions.

Two birds stand on an unknown object in figure 126, while in figure 127 we have a quadruple arrangement of parts, the same unit being repeated four times. The most striking designs are bundles of conventional feathers, four in each, arranged at intervals. These have been identified as feathers by a comparison of them with the wing feathers of an undoubted bird elsewhere considered.

The designs shown in figures 128 and 129 are four-armed crosses. Between the arms of the last mentioned figure there are white designs on a black ground.

Now and then we find in ancient Mimbres pottery the universal symbol called the swastica. Figures 130 and 131 are geometrical, the latter having three instead of four arms. Figure 132 represents a four-armed swastica in which the extremities of the arms are quite complicated.

One of the most beautiful geometric designs from Mimbres pottery is shown in figure 133, where a combination of curved and linear figures, black, white, and hachure work, all combine to produce the artistic effect. Elsewhere [1] the author has figured a similar design with four S-figures around the periphery of a bowl.

The design on the food bowl shown in figure 134 is very ornate and in a way characteristic of Mimbres ware. We have in its composition solid black, hachure, and white rectangular lines and scrolls

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[1] Archeology of the Lower Mimbres Valley. Smithsonian Misc. Coll., Vol. 63, No. 10, pl. 8.

so combined as to give a striking effect and attractive harmony. Of all geometric figures this appears to the author to be one of the most artistic.

In figure 135 is an artistic combination of a double ring of terraced triangular figures surrounding a central zone in white, and in figure 136 there is a composite decoration composed of a complex of triangular designs. In figure 138 there is a white square in the middle, around which are arranged eight figures of two kinds alternating with each other; four in each type.

The design in figure 137 is simple, consisting of a number of white zigzag figures with intervals filled in with triangles, sometimes black and sometimes crossed by parallel lines.

In figure 138 we have two groups of similar unit designs, four in each group, composed of triangular blocks terraced on one side and crossed by parallel lines. The simple designs on figures 139-140 need no elaborate description.

CONCLUSION

The material here published is extensive enough to permit at least a preliminary estimation of the relation of Mimbres pottery to that of the so-called pueblo area on the north and that of Casas Grandes on the south.

The Mimbres valley is an ideal locality for the development of an autochthonous and characteristic ceramic area. There is not sufficient evidence to prove that decorative elements in any considerable number from the North modified it to any great extent, for we find little likeness to pottery of the Tulerosa and other tributaries of the Gila and Salt. The pottery of the Mimbres had crossed the watershed and reappears in the sources of tributary streams that flow into the Gila. Examples of it have been found on Sapello Creek, which, so far as we know, is the northern extension of the Mimbres culture. The beautiful pottery collected by Mrs. Watson at or near Pinos Altos clearly indicates that Mimbres pottery was not confined to the Mimbres Valley. Limited observations often render it impossible to trace the extreme northern extension of the Mimbres pottery, but it seems to grade into ceramics from the upper Gila and Salt River tributaries. The southern migration of pueblo pottery appears to have been very small, but elements of foreign character worked their way into the Mimbres from the west, as is clearly indicated by shards from the ruin at the base of Black Mountain.[1] The line of demarcation between the two on the west is clearly indicated by specific characters.

The Mimbres pottery most closely resembles that from the Casas Grandes mounds in Mexico, on the south, but whether we may look to the south for the center of its distribution is not apparent. The mounds near Casas Grandes River are situated in the same inland plateau, and although Casas Grandes pottery excels the Mimbres in form and brilliant color, it is inferior to it in the fidelity to nature of its realistic pictures of animals. In this respect the Mimbres has no superiors and few rivals.

We have found no evidence bearing on the antiquity of Mimbres pottery from stratification. It is not known whether it overlies a substratum composed of corrugated, coiled, or black and white ware as commonly occurs in the pueblo and cliff-house regions. Decorative features characteristic of it have been developed independently in this isolated region. A knowledge of the length of time required for its development as compared with that necessitated for the evolution of the Sikyatki designs must await more observations bearing on this subject.

The animal designs were not identified by Indian descendants of those who made them. A determination of what they represent is based solely on morphological evidence. They are as a rule well enough drawn to enable us to tell what animal they represent. Very often the animal is recognizable by comparisons, for we can reconstruct a series reaching from a symbol made with a few lines to a well drawn picture. There is danger in supposing that a series thus constructed may always lead to accurate identifications as comparisons of symbols with decorative designs are often very deceptive.

The break in decorative lines surrounding pueblo food bowls and other forms of pottery is absent in specimens from the Mimbres Valley. This is also true of the cliff house and other pottery of the San Juan Valley.

Pottery from the Gila basin and the intervening area as far north as old Hopi ruins has this life line. Much of the ancient decorated ware found in the area between the Mimbres valley and the upper San Juan also have surrounding lines broken.

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[1] The author has already commented on this infiltration in his Archeology of the Lower Mimbres, *op. cit.* Mimbres and Casas Grandes pottery are readily distinguished.

1

2

3

4

5

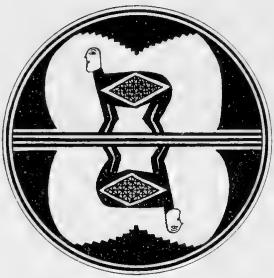
6

OSBORN COLLECTION.

1. Snaring wild birds.
2. Game of chance.
3. Men emerging from the underworld.
4. Man shooting off the lightning.
5. Two men and two animals.
6. Two men and one woman.

7

8



9

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12

OSBORN COLLECTION.

7. Two men kneeling on quadrupeds.
8. Two men lying on table.
9. Two men with bodies and limbs of animals (Hulbert collection).
10. Man dancing.
11. Two men dancing and two turkeys.
12. Two human figures.

13

14

15

16

17

18

OSBORN COLLECTION.

13. Man representing plumed serpent, cutting off head of a victim sacrificed.
14. Two carnivorous animals.
15. Quadruped (probably wolf).
16. Two men dragging a quadruped.
17. Horned composite quadruped with feather head-dress.
18. Man with rabbit ears and body.

19

20

21

22

23

24

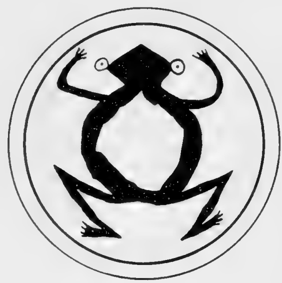
OSBORN COLLECTION.

19. Two animals in white, resembling beavers.
20. Unknown quadruped (mountain lion?).
21. Rabbit.
22. Negative pictures of two rabbits.
23. Two rabbits.
24. Rabbit.

25

26

27



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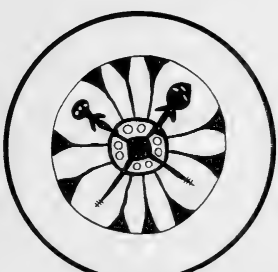

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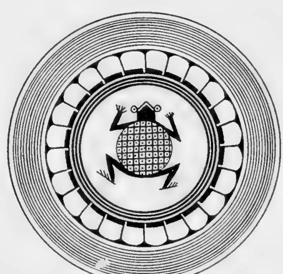

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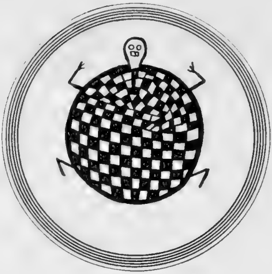
25. Two rabbits surrounded by a zone containing thirteen bundles of feathers (Hulbert collection).
26. Unknown animal (Osborn collection).

27. Bat (Watson collection).
28. Frog (Osborn collection).
28*a*. Tadpoles (Osborn collection).
29. Turtle (Osborn collection).



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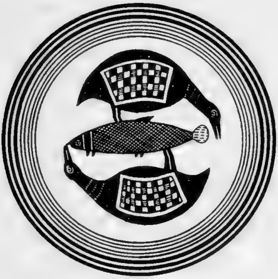
35

30. Turtle (Osborn collection).
31. Turtle (Osborn collection).
32. Snake talking to a mountain sheep (Osborn collection).
33. Two lizards with white outline (Osborn collection).
34. Lizard (Hulbert collection).
35. Two lizards talking to a crane (Osborn collection).



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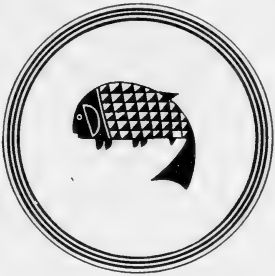

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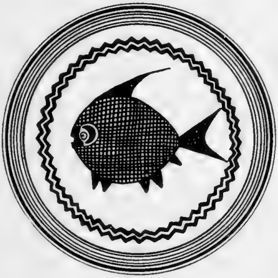

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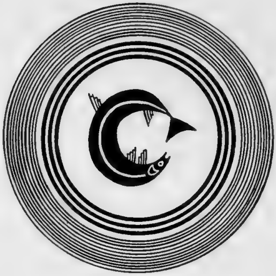
41

OSBORN COLLECTION.

36. Fish with two birds standing on it.
37. Sun fish.
38. Two birds standing on a fish.
39. Two fishes drawn in white on black ground.
40. Sun fish.
41. Serpent-like monster with horn on head.



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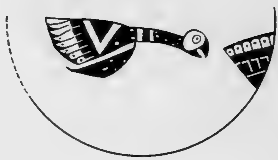

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OSBORN COLLECTION.

42. Coiled fish (Hulbert collection).
43. Two fishes symmetrically arranged.
44. Three birds.
45. Parrot.
46. Well-drawn parrot.
47. Quail.

48

49

50

51

52

53

OSBORN COLLECTION.

48. Two birds on dumb-bell-shaped field.
49. Bird with wings extended.
50. Two birds taking honey from flowers.
51. Three birds.
52. Two birds with triangular tails and wings.
53. Sun bird.

54

55

56

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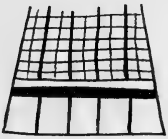
58

OSBORN COLLECTION.

54. Four birds with swollen bodies.
55. Two birds with long necks.
56. Unknown bird.
57. Turkey.
58. Turkey with three heads.



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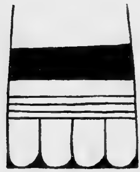

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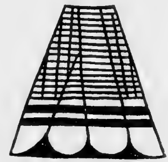

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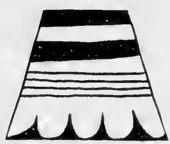

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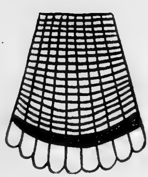

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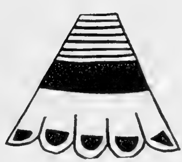

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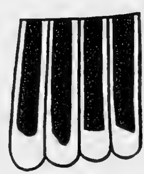

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TAIL FEATHERS.


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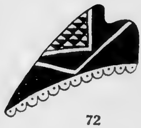
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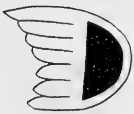
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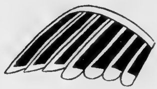
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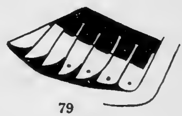
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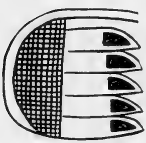
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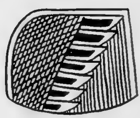
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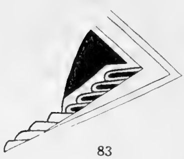
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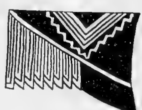
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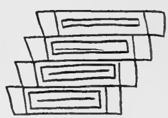
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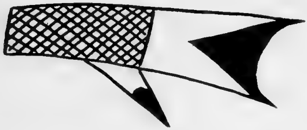
WING FEATHERS.



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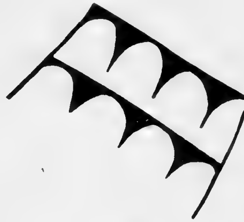

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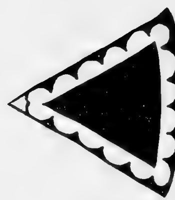

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ABERRANT WINGS AND TAILS OF BIRDS.

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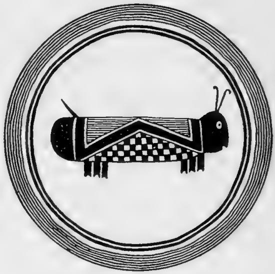

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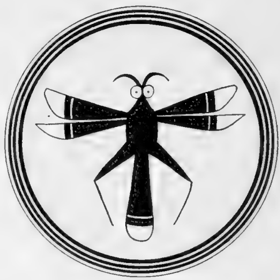


98

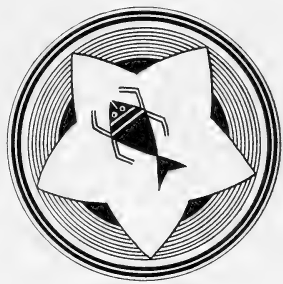
OSBORN COLLECTION.

93. Grasshopper with extended wings.
94. Four grasshoppers with extended wings.
95. Locust.
96. Unknown animal.
97. Unknown animal.
98. Dragon fly.

99

100

101



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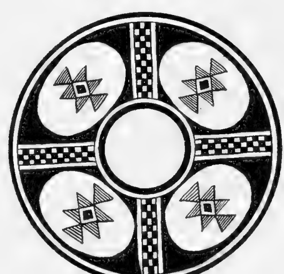

104

99. Butterfly (Hulbert collection).
100. Unknown animal (Osborn collection).
101. Insect with extended wings (Osborn collection).
102. Water bug (Osborn collection).
103. Sun emblem (Osborn collection).
104. Cross with butterfly symbols (Osborn collection).

105

106

107

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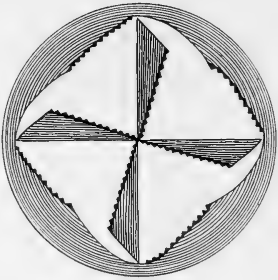

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110

OSBORN COLLECTION.

105. Cross painted white, alternating with four zigzag lines.
106. Geometrical figure with friendship signs (Hulbert collection).
107. Maltese cross, modified.
108. Rectangular figure, modified.
109. Cross.
110. Cross with zigzag modifications.

111

112

113

114

115

116

OSBORN COLLECTION.

111. Cross with rounded arms.
112. Six flowers, two in profile, the remainder from beneath.
113. Geometrical figure.
114. Geometrical figure.
115. Two-armed rectangular figure.
116. Center circle with three rectangular figures with serrated edges.

117

118

119

120

121

122

117. Swastica with three points (Osborn collection).
118. Figure of unknown meaning (Watson collection).
119. Five heads of birds around a central circle (Osborn collection).
120. Radiating feathers (Osborn collection).
121. Radiating pear-shaped objects surrounded by elaborate zone of complicated solid black and parallel lines (Osborn collection).
122. Figure of unknown meaning (Osborn collection).

123

124

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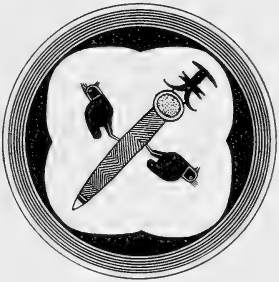


126

127

128

123. Intricate design with five white circles (Hulbert collection).
124. Star with eight rays (Osborn collection).
125. Quadruped surrounded by zigzag lines (E. White collection).
126. Two birds on an unknown weapon (Osborn collection).
127. Cross with four bundles of feathers (*vide* fig. 53) (Osborn collection).
128. Rectangular cross around a circle, with elaborate peripheral design (Osborn collection).

129

130

131

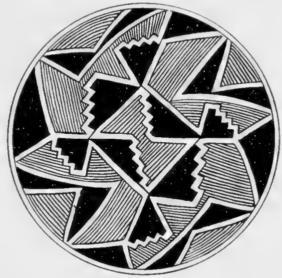
132

133

134

129. Maltese cross (Osborn collection).
130. Cross with arms of two types (Osborn collection).
131. Three-pointed swastica (Osborn collection).
132. Swastica with zigzag extensions (Osborn collection).
133. Combination of rectangular and spiral designs (Osborn collection).
134. Complicated unknown figure (Watson collection).

135



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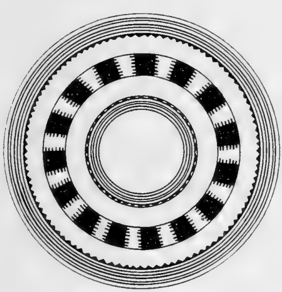

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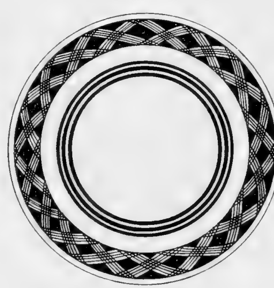

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135. Rings of cerrated symbols surrounding a central white area (Watson collection).

136 to 140. Geometrical ornamentations of unknown meaning (136, 138, Watson collection; 137, 139-140, Osborn collection).

SMITHSONIAN MISCELLANEOUS COLLECTIONS
VOLUME 74, NUMBER 7

THE DISTRIBUTION OF ENERGY IN THE SPECTRA OF THE SUN AND STARS

BY

C. G. ABBOT, F. E. FOWLE, and L. B. ALDRICH

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THE DISTRIBUTION OF ENERGY IN THE SPECTRA OF THE SUN AND STARS

By C. G. ABBOT, F. E. FOWLE and L. B. ALDRICH

Until recently, one could form an estimate of the temperatures prevailing in the sun and other stars only by a determination of the distribution of energy in their spectra and the application of the laws of the perfect radiator or absolutely black body. Although recent advances in the physics of the atom point to a new method of approach to this subject, the form of the energy curve still remains of great theoretical interest.

In the measurement of the solar constant of radiation by the method of Langley, it requires us to determine the ratio of the areas of the energy curve of the sun at the earth's surface and outside the atmosphere, and knowledge of the distribution of intensities of the solar rays is indispensable. To be sure, the values come in merely as a series of weights in forming a pair of sums, one in the numerator, the other in the denominator of the fraction which gives the ratio of the solar energy outside the atmosphere to the solar energy within it. Hence no very high degree of accuracy is needful for this purpose. This is fortunate, for so far as our experiments have gone we have never succeeded in obtaining so high a degree of accuracy as would satisfy us from the workmanlike point of view.

This comes out clearly if one compares the results of our various determinations of the form of the solar energy curve as published in Volumes III and IV of the *Annals of the Astrophysical Observatory*. The divergence in these values is considerable, and when in 1920 the experiments for the determination of the form of the sun's energy curve were repeated, a still wider discrepancy appeared, so great that although these experiments of 1920 were ready at the time of printing of Volume IV of the *Annals* we hesitated to include them until they should be checked by other independent determinations.

These proposed new determinations have been made at Mount Wilson during the summer of 1922, and form the first part of the present communication. The latter part includes the application of them to the spectra of ten of the brightest stars observed with a special bolometric outfit by Messrs. Abbot and Aldrich at Mount Wilson in 1922. The work was done in connection with the 100-inch telescope.

We here return our thanks for the aid and encouragement furnished in the stellar work by Dr. Hale, Dr. Adams, and many of the staff of the Mount Wilson Solar Observatory.

SOLAR SPECTRUM ENERGY CURVE

A statement of the method adopted for the observations may be found in Volume II of the *Annals of the Astrophysical Observatory*, pages 24, 50-57. Briefly, it is this:

At each of a number of wave lengths in the solar spectrum it is required to determine: (1) The intensity of the spectrum observed in the bolometer; (2) the selective transmission of the spectroscope; (3) the selective reflection of the coelostat; (4) the transmission of the atmosphere. The bolograph indicates the first, and the measurements on a series of bolographs taken at different zenith distances of the sun furnish the means of computing the last. The reflection of the coelostat is determined by taking bolographs (*a*) with the ordinary pair of mirrors, (*b*) with a substitute pair of mirrors, (*c*) with a combination of both regular and substitute mirrors. The selective transmission of the spectroscope is determined by first passing the ray through an auxiliary spectroscope, selecting certain wave lengths and observing their intensity, (*d*) as transmitted by the auxiliary spectroscope, (*e*) as transmitted by both spectroscopes.

The observation (*d*) is made by setting the bolometer to occupy the position usually occupied by the slit of the usual spectroscope. In this position a number of settings of the auxiliary spectroscope are made, so as to determine the intensity of its radiation at a sufficient number of wave lengths. Then the slit of the usual spectroscope is restored to its proper position so as to permit nearly monochromatic beams of light to pass through the usual spectroscope after having been sorted out by the auxiliary one. The relative intensities of these nearly monochromatic beams are determined by taking bolographic energy curves of them. The areas included in these bolographic energy curves give the relative amounts of energy remaining in these wave lengths after having suffered absorption in the usual spectroscope. Thus the galvanometer deflections with the bolometer at the slit divided by the areas of the corresponding energy curves formed by the bolometer in its usual position, give numbers inversely proportional to the transmission of the usual spectroscope, and suitable to correct its losses.

It will be noted that the procedure thus outlined takes no account of selective absorption by the bolometer for different wave lengths. If, for example, the bolometer should only absorb 50 per cent of the rays in the ultra-violet while it absorbed 95 per cent of the rays in the infra-red, the form of the energy curve would be quite erroneous. We confess that in even our present experiments the possibilities of error from this cause have not been eliminated, but as will appear we have at least shown that with several different bolometers, some camphor smoked, some painted with lamp-black, some in atmospheric pressure, and some in high vacuum, there is no certain difference beyond the experimental error, and we continue here, as heretofore, tacitly to make the assumption that the bolometer absorbs a uniform proportion of the rays throughout the region of spectrum we are concerned with, namely, from 0.3μ to 3μ. Our position is strengthened by the fact that Ångström, Coblentz, and others estimate the absorption coefficient of blackened surfaces for total solar radiation as high as 97 or 98 per cent. This leaves little room for selective absorption.

Observations of 1920.—The determination of the transmission of the spectroscope was repeated in 1920 with new stellite mirrors, those used in 1917 and 1918 having gone to Chile. There is nothing new in the method employed, but the work was done with all possible care and with independent adjustments on July 16, 17, and 19, and August 18 and 19, 16 determinations in all. Ten points in the spectrum were observed in July and nine others alternating with them in August. The average probable error of the determination of relative spectroscopic transmission at these 19 points was 1.2 per cent. The results run as shown in table 1.

Combining these results with the determination of the reflecting power of the stellite-mirror coelostat made in 1918, and determinations of the form of the energy curve at the earth's surface and of atmospheric transmission accompanying made at Mount Wilson on 10 satisfactory days of 1920, of which five gave high, five low solar constants, we obtained the distribution of solar energy in the spectrum outside our atmosphere. These values will be given below.

Observations of 1922.—All the apparatus used in 1920 having been removed to Mount Harqua Hala, we used an entirely new outfit. The coelostat mirrors were silvered but the main spectroscope had new stellite ones.

In repeating the work, we were well convinced that the principal uncertainty rested on the determination of the absorption of the spectroscope. So many closely agreeing observations have been made in former years of the transmission of the atmosphere, the results of which fall in so well with the theory of Rayleigh on the molecular

TABLE 1.—*Spectroscopic Transmission. Observations of 1920*

Place by counter	193 18	194 00	194 45	195 30	196 15	196 45	197 20
Prismatic deviation from ω_1	224.6′	210.6′	195.6′	180.6′	165.6′	155.6′	144.0′
Wave length μ	.355	.370	.391	.412	.441	.463	.492
Relative transmission	194	243	297	291	314	328	343
Probable error, per cent	3.2	3.0	1.8	0.4	1.4	0.7	0.9

Place by counter	198 00	198 35	199 15	200 12	200 30	201 10	201 45
Prismatic deviation from ω_1	130.6′	119.0′	105.6′	86.6′	80.6′	67.2′	55.6′
Wave length μ	.533	.578	.650	.798	.859	1.040	1.215
Relative transmission	372	378	362	348	335	295	291
Probable error, per cent	1.1	1.1	0.9	1.2	0.3	0.9	0.7

Place by counter	202 00	203 00	203 30	205 00	205 50
Prismatic deviation from ω_1	50.6′	30.6′	20.6′	−9.4′	−26.0′
Wave length μ	1.297	1.594	1.733	2.118	2.310
Relative transmission	324	365	383	351	186
Probable error, per cent	1.0	1.2	0.5	0.4	2.3

scattering, that we could not doubt that the atmospheric transmission coefficients obtained on excellent days were abundantly accurate for the purpose here in view. At least this is true for the wave lengths greater than 0.4μ. In the ultra-violet, we are well aware that there is contamination of the spectrum by stray light from longer wave lengths, so that the atmospheric transmission coefficients determined for that region are too high, and the magnitude of this error increases as the wave length diminishes. If that were the only effect of the stray light, it would tend to diminish the intensities of the solar energy spectrum outside the atmosphere in the region of the ultra-violet rays, but there are also two additional effects of stray light, both of which tend in the other direction.

The first of these is the building up of the bolographic energy curve at the earth's surface in the ultra-violet by these same stray radiations which, as we have just said, tend to raise the atmospheric transmission coefficients. Obviously the effect of this building up tends to make the ultra-violet too high.

The third effect of stray light is in the determination of the transmission of the spectroscope. If the reader will go over the summary of procedure for that purpose, which has just been stated, he will perceive that the auxiliary spectrum which falls at the slit of the main spectroscope will be subject to contamination by the stray light. Monochromatic beams of energy result at the usual position of the bolometer, after the passage of the light through both spectroscopes, in which the stray light will be practically eliminated. Consequently in the ultra-violet the auxiliary spectrum will be relatively too bright, owing to the influence of stray light, while in the final spectrum represented by the little energy curves, the stray light will be eliminated. Hence, the ratios of the bolometric deflections at the focus of the auxiliary spectrum divided by the bolographic areas observed in the usual spectrum will be too large in the ultra-violet, indicating a greater absorption in the spectroscope than actually exists, and this will tend to make the ultra-violet part of the solar spectrum outside the atmosphere too high. We shall recur to this question of stray light a little later, and introduce an estimate of the combined effect of these three different influences.

In considering the best means of assuring a trustworthy result, it seemed to us that great advantage would come from using several different prisms, both in the auxiliary and in the usual spectroscope, so that we could carry through the whole determination of the solar energy curve outside the atmosphere with instruments of very different dispersion characteristics. In order to get these as decisively different as possible and at the same time to use materials of high transmissibility throughout the region of the spectrum we were concerned with, it occurred to us to use prisms of rock salt in substitution for the ultra-violet crown glass prisms we usually employ. Moreover, as the work of 1920 and some previous years had been done with ultra-violet crown glass prisms in both the auxiliary and usual spectro-

TABLE 2.—*Circumstances of the Observations*

1922 Date	Object	Prisms: 1st spectroscope	Prisms: 2d spectroscope	Bolometer	Type of blackening	Spectrum places	No. of tests	Notes
Aug. 28	Spectroscope absorption	Great flint	U. V. Crown.	New vacuum	Lamp-black paint.	First set	2	1. Part of plates melted.
" "	" "	" "	" "	" "	" " "	Second set	2	2. " " " "
" 29	" "	" "	" "	" "	" " "	" "	1	3. Bolometer wiggles.
" "	" "	" "	" "	Old air	Camphor smoke	" "	1	4. Correction for shutter.
" 30	" "	" "	" "	" "	" "	" "	1	5. Shutter changed.
" "	" "	" "	" "	" "	Lamp-black paint.	" "		6. Bolometer wiggles much.
" "	" "	" "	" "	" "	" " "	" "	2	7. Bolometer wiggles much.
" 31	Test of bolometers	" "	None	Old vacuum in air	" " "	" "	2	8. Bolometer of 1916.
" "	" " "	" "	"	Old air	" " "	" "	1	9. Same as Aug. 30.
Sept. 1	" " "	" "	"	Old vacuum exhausted	" " "	" "	2	10. On these days many experiments alternately with and without air.
" "	" " "	" "	"	" " in air	" " "	" "	2	
" 2	" " "	" "	"	" " exhausted	" " "	" "	1	
" "	" " "	" "	"	" " in air	" " "	" "	1	
" "	" " galvanometer scale	None	"	" " " "	" " "	None	1	11. Varied shunt.
" "	" " sectors	"	U. V. Crown.	" " " "	" " "	Selected	1	12. Eye observations.
" "	" " bolometers	Great flint	None	" " " "	" " "	Second set	1	13. First spectroscope re-silvered.
" "	" " "	" "	"	New vacuum repaired	" " "	" "	1	14. Strips resoldered and re-evacuated.
" "	Spectroscope absorption	" "	U. V. Crown.	" " "	" " "	" "	2	15. Excellent conditions.
" 3	" "	" "	" "	" " "	" " "	First set	2	" "
" 5	Solar energy spectrum distribution.	None	" "	" " "	" " "	Bolographs	10	16. Cloudless.
" "	Spectroscope absorption	Great flint	Rock salt	" " "	" " "	Combined set.	1	17. See final discussion.
" 6	Solar energy spectrum distribution.	None	" "	" " "	" " "	Bolographs	10	18. Cloudless, good sky.
" "	Spectroscope absorption	Great flint	" "	" " "	" " "	Combined set.	1	19. Excellent conditions.
" "	Test of bolometers	" "	None	Old vacuum in air	" " "	" "	1	20. Compare Sept. 2.
" 9	Spectroscope absorption	U. V. Crown.	Rock salt	Old air repaired	" " "	" "	1	21. Little value.
" 11	Bolographs great wave-lengths	None	" "	" " "	" " "	Bolographs	4	22. Eye observations also.
" "	Test of sector values	"	" "	" " "	" " "	Selected	3	23. Bolographic.

NOTES.—1, 2, Wash water too hot. Only half plates saved. One of each set. 3, Progressive increase of bolometer disturbance led finally to resoldering of connections and reevacuating the bolometer. 4, No glass being in front of bolometer the shutter gave a deflection due to its difference of temperature from surroundings. Noted magnitude and applied corrections. 5, Shutter moved over in front of slit instead of in front of bolometer. Correction avoided. 6, 7, In painting the bolometer strip it was slightly torn. Hence bad wiggles spoiled this work. Rejected. 8, 9, 10, 20, This bolometer was connected to mercury vapor pump and used alternately with and without vacuum of less than 0.001 mm. mercury on Aug. 31, Sept. 1, 2, and 6. Readings in the auxiliary spectrum by eye observations at galvanometer compared with and without air, and with old air bolometer repainted and with new vacuum bolometer repaired. 11, Observed by eye the galvanometer deflections for increasing bolometer shunt by 1, 2, 3, 4, 5, 6, 7 ohms from 1930 ohms originally. First swings were 31.3, 61.0, 91.0, 122.0, 152, 181, 211 mm. No corrections seem required for inequalities of galvanometer scale. 12, A few trials of deflections at the same spectrum points with different rotating sectors. Better determinations later. 14, The new vacuum bolometer returned from Pasadena resoldered and reevacuated with liquid air trap. 15, Results of highest weight. 16, Atmospheric transmission coefficient and absorption of coelostat mirrors entirely determined. 17, Changed to rock salt prism. Good determination. 18, Same remark as 16. 19, Good determination. 21, The old bolometer No. 20, used for many years at Washington (See *Annals*, Vol. I) had been broken as per note 6. New coarse strips of only 0.7 ohms resistance were now inserted. The purity of the spectrum with these and U. V. prism in first spectroscope insufficient. 22, Used sifting train of salt for eye observations. Observed to 14 microns. 23, Excellent sector determination.

scopes, we determined to substitute in the auxiliary spectroscope a prism of ordinary flint glass which, as is well known, produces a far greater relative dispersion in the ultra-violet than the ultra-violet crown glass.

It seemed to us that when these various modifications of the experiments had been made, namely, the use of bolometers in air, bolometers in vacuum, bolometers painted with lamp-black, and bolometers smoked with camphor smoke; when we had employed several different types of prisms; and when we had independently set up the apparatus with the greatest possible care on several different occasions; then, if the results of all these modifications should agree among themselves and should agree either with the work of 1920 or with the work of the earlier years, as reported in Volumes III and IV of the *Annals of the Astrophysical Observatory,* the final result, supported by such far-reaching agreements, ought to be entitled to confidence.

We now proceed to give in table 2 in abbreviated form the data of the observations and their results.

As noted above, the measurements of the degree of uniformity of the galvanometer scale do not indicate appreciable corrections to be necessary. For though the increase of deflection for successive steps of one ohm diminishes slightly with increasing deflection, yet there should be a small change in this direction depending on the fact that a change of one ohm on a shunt of 1,937 ohms about a Wheatstone's bridge coil of 56 ohms produces less current in the galvanometer than 1 ohm change on 1,930 ohms. With allowance for this, the readings differ by less than their probable error from linear relations.

The deflections are governed by rotating sectors. As determined with automatic recording of deflections in numerous series, the deflections for sectors are as follows:

Sector No.	3	2	1	0
Deflection	1.000	3.159	9.161	26 677
Deflection	0.3748	1.184	3.434	10.000

From this we derive factors of reduction:

To reduce	3 to 0	2 to 0	1 to 0	0 to 0
Factor	26.68	8.445	2.913	1.000
To reduce	3 to 3	2 to 3	1 to 3	0 to 3
Factor	1.000	0.3166	0.1092	0.03748

TABLE 3.—*Ratios of Deflections of Various Bolometers as Reduced to Nearly Equal Scales*

A = old bolometer No. 20 in air, camphor-smoked.
B = old bolometer No. 20 in air, lamp-black-painted.
C = 1916 bolometer in air, lamp-black-painted, glass plate in front.
D = 1916 bolometer in vacuum, lamp-black-painted, glass plate in front.
E = 1922 bolometer in vacuum, lamp-black-painted, glass plate in front.

Spectrum place	Wave length	A/C	B/C	D/C	D/C	D/C	D/C	D/C Mean	E/C
	microns								
06:00	0.37	89	105	107	105	99	103	1.035	94
04:30	0.40	100	91	100	106	103	104	1.032	108
03:15	0.46	100	100	104	101	100	99	1.010	106
02:00	0.53	103	106	95	90*	99	105	.997	102
00:45	0.65	102	100	102	88*	95	100	.992	99
99:50	0.86	110	100	105	100	98	101	1.010	100
98:15	1.22	106	99	108	100	99	101	1.020	100
97:00	1.60	111	109	89*	99	93	95	.970	103
95:00	2.12	110	105	100	102	93	98	.982	100

* Omit.

These figures perhaps show that the camphor-smoked bolometer No. 20 read low in the visible and ultra-violet spectrum as compared with the infra-red, but this result may have been produced by changes of sky between the two series of observations, which in this instance were not made on the same day. In all the other cases we incline to think there is nothing definite shown, and the fluctuations were due to slight differences of wave length between settings, or to changes in sky between observations, as well as to accidental errors of galvanometer readings, which latter were sometimes no doubt more than 1 per cent. The change between air pressure and evacuated condition of the 1916 bolometer seemed to us at one time real, but looking at the individual determinations we now incline to doubt it. In vacuum the 1916 bolometer was about five times as sensitive as in air. The observations in vacuum in each case were taken immediately preceding those in air, and at high sun.

Reduction of the observations of spectroscopic absorption.—As a sample of the work we give the observations and reductions for September 2, first series.

TABLE 4.—*Sample of Spectroscopic Absorption Work*

Place by second spectroscope	Sector-free deflections and times				Sector-free areas and times		Sector-free mean deflection	Spectroscopic absorption. Arbitrary units
	Deflection	Time	Deflection	Time	Mean measures	Time		
	cm.		*cm.*		*cm.*²			
06:00	0.77	$3^h\ 07^m$	0.52	$3^h\ 54^m$	1.97	$3^h\ 29^m$	0.645	327
04:30	5.54		4.95		16.19		5.25	325
03:15	15.10	$3^h\ 09^m$	14.15	$3^h\ 56^m$	48.5	$3^h\ 35^m$	14.62	302
02:00	30.51		28.89		112.1		29.70	265
00:45	56.58		54.89		204.5		55.73	273
99:50	85.29	$3^h\ 11^m$	86.15	$3^h\ 59^m$	323.0	$3^h\ 39^m$	85.72	266
98:15	91.20		90.20		330.5		90.70	275
97:00	60.63		61.16		236.2		60.90	258
95:00	17.61	$3^h\ 14^m$	17.61	$4^h\ 01^m$	51.7	$3^h\ 46^m$	17.61	341

Working along in this way, and reducing all of the ratios, deflection divided by area, proportional to spectroscopic absorption, to the same scale of arbitrary units, we come at length to the following tables:

TABLE 5.—*Collected U.V. Glass Spectroscopic Absorption. First Places*

Place by second spectroscope	Dates of observation			Mean values	Per cent probable error
	Aug. 28	Sept. 3–I	Sept. 3–II		
05:15	518	431	417	455	4.2
03:45	495	480	484	486	0.6
02:40	448	446	437	444	0.4
01:25	403	427	432	421	1.3
99:48	384	409	422	404	1.6
98:30	...	428	425	426	..
98:00	...	437	420	428	..
96:30	416	405	398	406	0.7
94:10	...	703	735	419	..

Similarly for the other set of spectrum places we obtained:

TABLE 6.—*Collected U. V. Glass Spectroscopic Absorption. Second Places*

Place by second spectroscope	Dates of observation						Mean values	Per cent probable error
	August 28	August 29–I	August 29–II	August 30	Sept. 2–I	Sept. 2–II		
06:00	500	541	507	496	515	544	517	1.0
04:30	508	458	495	368	507	547	480	3.0
03:15	466	461	452	400	471	473	454	1.3
02:00	410	433	426	397	412	440	420	1.0
00:45	490	445	450	436	426	421	445	1.2
99:50	408	413	400	428	413	385	408	0.8
98:15	433	428	419	422	426	436	427	0.3
97:00	...	377	370	481	402	398	406	2.5
95:00	...	553	591	630	532	569	575	1.7

In the same manner we arrived at the following results for the spectroscopic absorption values in arbitrary units applicable to the case of the rock salt prism replacing the U. V. crown glass prism in the

TABLE 7.—*Collected Rock Salt Spectroscopic Absorption*

Place by U. V. spectroscope	Dates of observation			Mean values	Per cent probable error
	Sept. 5	Sept. 6	Sept. 9		
06:00	699	644	693	679	1.5
05:15	582	567	513	554	2.1
04:30	522	539	476	512	1.6
03:15	451	438	412	434	1.6
02:00	411	391	384	395	1.2
00:45	349	352	368	356	1.0
99:50	313	305	327	315	1.2
98:15	264	271	281	272	1.0
97:00	239	260	270	256	2.1
95:00	215	227	223	222	0.9
94:10	203	208	...	210	..

second spectroscope. As we had no reason to expect absorption bands introduced by rock salt it was unnecessary to investigate so many places in the spectrum as were used for the U. V. crown glass prism which has several such bands. Eleven places were chosen including all the wave lengths of the "Second Places" above and in addition two others from the "First Places." For clearness we give the spectrum settings which the U. V. crown glass prism would have required at these wave lengths, so as to compare with those in the preceding tables.

These determinations of spectroscopic absorption for the U. V. glass and for the rock salt spectroscopes were plotted on a large scale and smooth curves drawn to fix the best values to use for the absorption coefficients at the wave lengths where bolographic ordinates are measured. These results will appear in a later table.

Reductions of observations of coelostat absorption.—On September 5, and again on September 6, bolographs were taken to determine coelostat absorption. Thus, for instance, on September 5, after a series of four bolographs beginning at $6^h\ 36^m$ and finishing with the bolograph at $8^h\ 13^m$ taken to determine atmospheric transmission coefficients, two additional silvered mirrors were employed in connection with the bolographs as follows:

Time of observation	$9^h 45^m$	$10^h 01^m$	$10^h 20^m$	$10^h 39^m$	$10^h 49^m$	$11^h 03^m$
Mirror arrangement	4 mirrors	Usual	4 mirrors	2 substitutes	2 substitutes	Usual

These bolographs of the solar spectrum having been marked with smoothed curves as usual, were measured in ordinates at the usual places as in solar-constant determinations. The results were then combined in the following manner:

From the usual bolographs taken at $8^h\ 13^m$, $10^h\ 01^m$, and $11^h\ 03^m$, it was determined what would have been the usual ordinates at the various times when four mirrors and two substitute mirrors were employed, and thus the whole body of data could be brought to a common time and air mass. Mean values of ordinates for the four mirrors and for two substitutes were determined. Let A, B, and C be directly comparable ordinates at a certain wave length with usual, substitute, and four mirrors, respectively, then the correcting factor for the combined absorptions of the usual mirrors at this wave length is B/C. If that for the substitute mirrors was desired, it would be A/C.

Proceeding thus in effect, we obtained the correcting factors for the absorption of the usual mirrors over the whole spectrum for both September 5 and September 6. The latter day's values were obtained for slightly different wave lengths as observed with the rock salt prism. But the values were readily convertible to a comparable basis, and were thus compared by plotting on a large scale. The two sets of data were in satisfactory accord throughout, but were mutually helpful in smoothing out accidental errors. This being done, smoothed curves were drawn for each day separately and applied independently in the final computations of the energy curves of the two days. From inspection of the results it is believed that the determinations of coelostat reflection are surely correct to within 1 per cent, except as far as they may be affected systematically in the violet by stray light as already referred to above.

TABLE 8.—*The Solar Energy Curve. U. V. Glass Prism. September 5, 1922*

Prismatic deviation from ω_1	Wave length μ	Dispersion coefficient	Coelostat reflection	Spectroscope coefficient	Prismatic energy curve outside atmosphere	Normal energy curve outside atmosphere
230′	0.3504	1104	0.545	632	394	435
220	0.3600	990	0.616	580	506	501
210	0.3709	887	0.667	530	615	546
200	0.3853	788	0.705	490	825	650
190	0.3974	692	0.734	480	980	678
180	0.4127	605	0.760	480	1445	875
170	0.4307	529	0.784	487	1820	963
160	0.4516	460	0.807	470	2350	1081
150	0.4753	397	0.829	450	2960	1175
140	0.5026	338	0.850	436	3390	1146
130	0.5348	282	0.870	420	3806	1073
120	0.5742	230	0.890	420	4500	1035
115	0.5980	206	0.899	428	5002	1030
110	0.6238	183	0.907	440	5650	1034
105	0.6530	162	0.915	444	6000	972
100	0.6858	144	0.923	435	6400	922
95	0.7222	127	0.930	420	6380	810
90	0.7644	112	0.936	410	6270	702
85	0.8120	98.8	0.941	407	6250	618
80	0.8634	86.5	0.945	410	6165	533
75	0.9220	76.8	0.949	413	5910	454
70	0.9861	71.5	0.953	418	5620	402
65	1.062	68.0	0.957	422	5248	357
60	1.146	66.0	0.960	426	4760	314
55	1.225	66.0	0.963	429	4400	290
50	1.302	66.0	0.966	428	3850	254
45	1.377	66.0	0.970	424	3312	218
40	1.452	66.0	0.973	418	2880	190
35	1.528	66.4	0.975	411	2460	163
30	1.603	67.3	0.977	406	2164	146
25	1.670	68.1	0.978	405	2013	137
20	1.739	69.6	0.979	408	1774	123
10	1.870	72.3	0.979	430	1390	100
0	2.000	76.8	0.980	495	1088	84
—10	2.123	83.0	0.980	574	662	55
—20	2.242	90.5	0.981	660	378	34

TABLE 9.—*The Solar Energy Curve. Rock Salt Prism. September 6, 1922*

Prismatic deviation from *A*	Wave length μ	Dispersion coefficient	Coelostat reflection	Spectro-scope coefficient	Prismatic energy curve outside atmosphere	Normal energy curve outside atmosphere
200′	0.3749	1585	0.676	630	199	313
190	0.3820	1484	0.699	592	193	286
180	0.3881	1384	0.717	562	231	321
170	0.3975	1280	0.735	543	335	429
160	0.4057	1193	0.751	526	420	500
150	0.4145	1113	0.766	508	447	496
140	0.4242	1036	0.781	492	461	477
130	0.4350	958	0.796	476	524	502
120	0.4463	886	0.811	463	620	549
110	0.4590	817	0.825	450	672	549
105	0.4652	785	0.831	443	676	530
100	0.4720	750	0.839	436	745	558
95	0.4790	714	0.845	430	826	590
90	0 4860	679	0.852	424	867	589
85	0.4937	642	0.858	419	880	565
80	0.5017	607	0.865	414	917	555
75	0.5105	571	0.871	408	951	544
70	0.5199	534	0.877	402	974	521
65	0.5290	500	0.882	396	1020	510
60	0.5400	466	0.888	392	1088	507
55	0.5513	434	0 893	388	1165	506
50	0.5638	404	0.898	384	1228	496
45	0.5767	377	0.902	379	1307	493
40	0.5905	351	0.907	374	1426	501
35	0.6052	323	0.910	368	1436	464
30	0.6212	294	0.914	362	1482	435
25	0.6380	267	0.917	355	1517	404
20	0.6557	243	0.920	348	1648	400
15	0.6784	222	0.923	341	1743	386
10	0.7037	199	0.927	334	1843	366
5	0.7302	174	0.930	326	1965	342
0	0.7604	152	0.933	318	2087	317
—5	0.7957	135	0.935	307	2170	293
—10	0.8321	117	0.937	298	2261	265
—15	0.8788	975	0 939	290	2396	234
—20	0.9322	820	0.941	282	2514	206
—25	0.9970	670	0.943	272	2676	179
—30	1.093	527	0.945	262	2831	149
—35	1.202	402	0.947	250	2897	117
—40	1.332	300	0.949	242	2961	89
—45	1.500	245	0.951	232	2947	72
—50	1.751	216	0.953	222	2821	61
—55	2.070	208	0.954	212	1657	35

In further reduction we now include the mean result of 1920, the U. V. glass prism result of 1922, and the rock salt prism result of 1922, with the object of comparing these several determinations, getting from them the best general representative values, and finally comparing these with the earlier results of 1903 to 1910, and 1916 to 1918, respectively, given in Table 58 of Volume IV, *Annals Astrophysical Observatory*. In order to do this we first reduced the results of 1922 to the scale of those of 1920. In the following table we do not retain the individual wave lengths observed for rock salt, but have read off from a large scale plot the values which the rock salt work would indicate for the wave length places used in U. V. glass work.

We give in figure 1 the individual values found for the different wave lengths for the work of 1920 and the U. V. glass and rock salt prisms in 1922. As will be seen by inspection of the plot, when we consider all circumstances, particularly the wide differences in dispersion characteristics, the agreement of the rock salt work of 1922 with the U. V. glass work of 1920 is little less than remarkable over the whole extent of spectrum covered. Agreement even descends to the details in the solar bands near wave lengths 0.386, 0.425, and 0.535 micron. There are moderate divergences central at wave lengths 0.65 and 1.3 microns. The discrepancy beyond 1.7 microns is not surprising in view of the difficulty introduced by the water-vapor bands, and the approaching opacity of U. V. crown glass.

Turning to the U. V. glass work of 1922, its agreement with 1920 between wave lengths 0.5 and 1.7 microns is nearly perfect. At greater wave lengths than 1.7 it lies between the 1920 work and the rock salt work. For wave lengths less than 0.5 micron there is a pretty wide divergence, the 1922 U. V. glass work running smaller. The departure does not much exceed 10 per cent until the wave length is less than 0.40 micron.

We incline to attribute this ultra-violet discrepancy to the inferiority of the day, September 5, 1922, as indicated by the logarithmic plots of atmospheric extrapolation. These indicate that the sky was growing less transparent towards noon, for the computed coefficients of atmospheric transmission in the infra-red are all closer to unity than they ought to be. This mediocre character, and the excessively high transmission coefficients, would scarcely affect the form of the energy curve for wave lengths greater than 0.6 micron, because here the atmospheric transmission is always above 90 per cent, so that changes of it affect the form of curve only slightly. But supposing the sky

TABLE 10.—*Comparison of Normal Solar Energy Curves*

Wave length ω_1	U. V. glass deviation from μ	Energy curves outside the atmosphere						
		1920	1922 U. V.	1922 R. S.	1903-10	1903-10 omitting quartz work	1916-18	Weighted mean, 1920-22
0.3415	240′	262	...	...	226	...	263	262
0.3504	230	307	200	...	272	...	304	281
0.3600	220	330	230	...	310	...	330	297
0.3709	210	340	251	325	342	...	353	318
0.3853	200	304	299	300	344	...	385	301
0.3974	190	343	312	350	413	...	411	340
0.4127	180	484	403	513	506	500	567	480
0.4307	170	482	443	495	535	506	518	479
0.4516	160	569	497	548	610	567	580	548
0.4753	150	570	540	575	625	569	622	566
0.5026	140	558	527	553	604	548	566	546
0.5348	130	515	493	509	578	515	530	506
0.5742	120	498	476	493	538	484	508	489
0.5980	115	487	474	493	505	464	482	485
0.6238	110	466	475	430	472	434	450	457
0.6530	105	446	447	400	424	400	423	431
0.6858	100	419	424	384	384	370	391	409
0.7222	95	373	373	350	333	340	351	366
0.7644	90	332	323	315	293	310	313	323
0.8120	85	287	284	279	256	275	278	283
0.8634	80	244	245	244	227	245	247	244
0.9220	75	212	209	211	198	220	212	211
0.9861	70	191	185	191	172	200	187	189
1.062	65	182	164	162	144	180	165	169
1.146	60	150	144	135	119	153	135	143
1.225	55	133	133	113	102	125	118	126
1.302	50	113	117	96	89	96	101	109
1.377	45	97	100	84	78	85	87	94
1.452	40	87	87	76	68	75	75	83
1.528	35	77	74	72	59	67	65	74
1.603	30	68	67	68	52	57	57	68
1.670	25	60	63	63	45	51	50	62
1.738	20	53	57	61	42	46	45	57
1.870	10	40	46	51	33	38	31	46
2.000	00	28	39	42	25	26	23	36
2.123	—10	18	25	32	18	...	15	25
2.242	—20	16	16	...	14	...	12	16
2.348	—30	20	...	...	12	...	10	20

was actually growing worse, the effect on the wave lengths less than 0.6 micron would be more and more serious, as indeed the energy curves of figure 1 indicate.

The second day, September 6, is not subject to this criticism. The work of 1920 rests on many good days of observation. Accordingly we decided to give the 1920 work and the 1922 rock salt work each double weight for wave lengths less than 0.5 micron, and all three curves equal weight for greater wave lengths. With this convention we compute the weighted mean of table 10 as plotted in heavy full line in figure 1.

This new result, namely the weighted mean of the 1920 and 1922 observations, given in table 10 and in the heavy full line of figure 1, we regard as our best determination of the form of the solar energy curve outside the atmosphere.

It rests principally on our very careful work of 1920, which, however, on account of its divergence from our previously published work of 1903 to 1910 we had hesitated to publish until further tested. Now it is confirmed beautifully by the rock salt work of 1922, a determination as absolutely different as possible. The principal differences are: Silver in place of stellite at the coelostat; new stellite mirrors in the usual spectroscope; a flint glass prism of high dispersion in place of the low dispersion U. V. crown prism in the auxiliary spectroscope; a rock salt prism of excessively different dispersion in place of the U. V. crown glass prism in the usual spectroscope; a new bolometer and new galvanometer. Also the U. V. crown glass work of 1922 is in almost perfect agreement over the whole range of longer wave lengths, and where it differs in the visible and ultraviolet it differs in the opposite sense to the 1903 to 1910 work.

We place little confidence in our work of 1916 to 1918 on the form of the energy curve, for a reason already explained in Volume IV of the *Annals*. To avoid confusion we have not plotted it, although its mean result is given in table 10. The mean value of 1903 to 1910 is given there and plotted in figure 1. As it rests on a great number of observations at different stations, and as these individual determinations differ widely among themselves, as given in the *Annals*, Volume III, table 62, it is interesting to examine them separately and see if any class of the individual determinations would have tended to agree better with the new work. We are at once struck by the fact that it is the quartz prism work at Mt. Wilson and Mt. Whitney which has given most of the divergence, excepting of course the three short-wave values at the top of column 4 of the above cited

Table 62 of *Annals,* Volume III. These are very likely vitiated by stray light. The quartz prism was very imperfect, being greatly blemished by interior striae and a tinge of smokiness, and its definition was so abominable that hardly any lines could be distinguished in its solar spectrum. Very possibly the determinations with quartz ought therefore to be rejected.

If we should reject all of them, there would result the following modification of Table 62 of *Annals,* Volume III:

Wave length	0.42	0.43	0.45	0.47	0.50	0.55	0.60
Percentage correction by determinations 1, 2, 3, 4	−3.7	−4.8	−6.1	−8.7	−9.3	−10.5	−10.1
Corrected intensities	506	506	566	570	550	503	453

Wave length	0.70	0.80	1.00	1.30	1.60	2.00
Percentage correction by determinations 1, 2, 3, 4	−1.6	+5.4	+2.8	+0.9	+6.2	+3.2
Corrected intensities	358	280	171	90.6	56.5	25.5

These corrected values are given in table 10 and are much closer to the new determination, indeed they are mainly in very good agreement. We therefore are the more confirmed in our view that the new values, the weighted mean of 1920 and 1922, are good, and that the old ones called " Mean 1903 to 1910 " were vitiated by the inclusion of the numerous quartz prism determinations.

In figure 1 we have given in dot and dash lines the distribution of energy in the spectrum of the perfect radiator or " black body " at 6,000° absolute centigrade. It is apparent that closer agreement exists between this and the new curve of 1920 and 1922 than exists between it and the old one of 1903 to 1910. But still the observed solar energy curve is far from being of the " black body " form. In order to match the two from 0.6 to 2.0 microns, a higher " black body " temperature than 6,000° would be required, and then the visible and ultra-violet parts of the observed curve would lie far beneath the computed one.

We have explained this kind of phenomenon by a double hypothesis. First, because we see deeper into the sun the longer the wave length, because long-wave rays are less scattered. Hence the infra-red region is supplied by a hotter, because deeper lying, layer. Secondly,

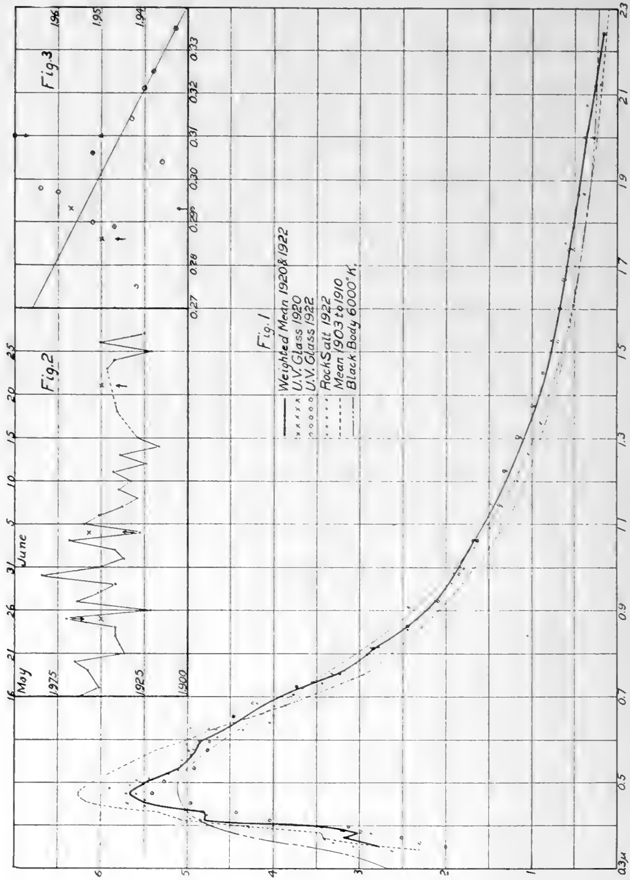
Fig. 1
Weighted Mean 1920 & 1922
U.V. Glass 1920
U.V. Glass 1922
Rock Salt 1922
Mean 1903 to 1910
Black Body 6000° K.
Fig. 2
May
June
Fig. 3

FIGS. 1, 2, AND 3.

the profusion of Fraunhofer lines in the visible, and still more in the ultra-violet solar spectrum, must cut this part down very greatly. The purity of our spectrum does not suffice to enable us to restrict our measurements to spaces between the lines, as was done by Fabry and Buisson in their beautiful studies of the ultra-violet.[1] They find even for the ultra-violet solar spectrum between wave lengths 0.394 and 0.292 micron, the corresponding "black-body" temperatures between 6,020° and 5,970° K. These measurements, however, relate to the center of the solar image, while ours include the rays as mixed in ordinary sunlight and coming from all parts of the sun's image. Ours is therefore a cooler source than theirs.

Fabry and Buisson draw attention to our over-estimate of the transparency of the earth's atmosphere for rays in this region, which indeed we have already admitted. As they point out, it is impossible to determine the atmospheric transmission correctly in this region without screening out stray light arising in the more intense spectrum regions.

We may remark, however, that the high altitudes of our observing stations, as they tend strongly to build up the ultra-violet compared to other parts of the spectrum, are favorable to diminishing this source of error below what might appear from a mere inspection of Fabry and Buisson's sea-level atmospheric transmission coefficients.

As we have stated at the beginning, we have tried to estimate the effects of the three kinds of errors stray light produces in our work on the form of the ultra-violet solar energy curve outside the atmosphere. Two of these tend to make our values in the ultra-violet too high, and the third acts oppositely. Assuming for the moment that the spectroscopic correction factor is right, suppose the true ordinate of the energy curve outside the atmosphere for a wave length λ in the ultra-violet should be e_t, but that in the ordinary bolographic work we determine this ordinate from observations as e_c. The discrepancy is caused by stray light coming from another part of the spectrum, which increases the intensity observed at the wave length λ, and also increases the apparent atmospheric transmission coefficient because the stray light being of longer wave length is of higher real transmission coefficient than the ray in question. Let e_s be the intensity of the stray light outside the atmosphere, and a_s, a_c, and a_t be the true atmospheric transmission coefficient for stray light, the falsified computed one, and the true one for the wave length λ.

[1] *Astrophysical Journal,* December, 1921, and *Comptes rendus t.* 175, p. 156, 1922.

Then for air masses 2 and 1, respectively, the observed intensities will be:

$$\left\{ e_t a_t^2 + e_s a_s^2 \right\} \text{ and } \left\{ e_t a_t + e_s a_s \right\}.$$

Therefore $$\frac{e_t a_t^2 + a_s a_s^2}{e_t a_t + e_s a_s} = a_c \text{ and } e_c a_c = e_t a_t + e_s a_s.$$

Whence $$\frac{e_t}{e_c} = \frac{a_c}{a_t} \left\{ \frac{a_s - a_c}{a_s - a_t} \right\}.$$

Judging from the visible appearance in the eyepiece of the bolometer, when the spectroscope is set for infra-red rays, where there is properly no visible light, the stray radiation there, and presumably in the ultra-violet region as well, represents impartially the whole spectrum, for it appears in the infra-red as white light. If so, we may reasonably assign for a_s the value 0.90. Other lesser values, 0.80, 0.70, may also be used for illustrative purposes.

Take now a wave length in the ultra-violet for which a_c is 0.60. This in ordinary Mt. Wilson observing is about $\lambda = 0.35\mu$. In the following table we give values of the expression $\frac{e_t}{e_c}$ corresponding to assumed values of a_s and a_t, a_c being 0.60 in all cases.

TABLE II.—*Comparison of True and Measured Radiation Outside Atmosphere. Specimens of ratio* $\frac{e_t}{e_c}$.

Stray light transmission	True transmission coefficient		
	0.55	0.50	0.40
0.90	0.93	0.90	0.90
0.80	0.87	0.80	0.75
0.70	0.73	0.60	0.50

These illustrations indicate that for the more probable conditions the ratio of real to bolographically determined radiation outside the atmosphere, so far as this depends on daily observations, is between 0.8 and unity. It is of course easy to see why the ratio falls rapidly when the stray light is assumed to have nearly the same transmission coefficient as that observed, for it must then require a far greater dilution with the stray light to change equally the transmission coefficient of the combination.

Returning now to its influence on the spectroscopic correction factors, we have already pointed out that it tends to make this correction factor too large, but just how much we cannot tell. However, as it works in the same sense as the combined effects just tabulated, we can finally say that the complete tendency of stray light is to cause the ultra-violet region of our spectrum energy curve to be too high. The real values would be such as to give smaller intensities in the ultra-violet than our curve indicates. In other words, the real curve would deviate still further below the "black-body" curve in the ultra-violet than figure 1 indicates.

That the error is not so large as the figures of table 11 indicate, or as readers of Fabry and Buisson's paper might suppose, seems apparent from computations by Fowle of the Rayleigh atmospheric transmission coefficients based on the number of molecules of air above Mt. Wilson. For comparison we give observed transmission coefficients of a good day, September 20, 1914, when we observed from sunrise until noon and also the mean of many good days of the years 1909 to 1912.[1]

TABLE 12.—*Atmospheric Transmission Coefficients. Mt. Wilson*

Wave-length in microns	0.342	0.350	0.360	0.371	0.384	0.397	0.413
Computed	——	0.617	0.650	0.684	0.719	0.751	0.784
Observed Sept. 20, 1914	0.615	0.600	0.618	0.681	0.681	0.743	0.764
Observed mean of many days	0.604	0.605	0.635	0.656	0.686	0.726	0.741

Wave-length in microns	0.431	0.452	0.475	0.503	0.535	0.574
Computed	0.815	0.845	0.872	0.897	0.919	0.939
Observed Sept. 20, 1914	0.794	0.820	0.859	0.881	0.893	0.889
Observed mean of many days	0.784	0.812	0.841	0.865	0.882	0.887

Our observed transmission coefficients actually fall below the computed values for all wave lengths given in the table, which shows that even with the blue skies of excellent days on Mt. Wilson there is still some effect of haziness additional to molecular scattering. But we do not see that it is necessary to suppose that our observed values are greatly erroneous, at least for wave lengths above 0.350 micron.

[1] See *Annals Astrophysical Observatory,* Vol. IV, p. 243, and Vol. III, p. 138.

Before leaving the subject of our solar work and its relations to the ultra-violet solar observations of Fabry and Buisson, we give in the following table 13 Fabry and Buisson's determinations of atmospheric ozone for 14 days of the year 1920, and corresponding solar-constant values as determined by Smithsonian observers at Calama, Chile. In giving the solar-constant observations we add for three days corrected values. They are determined by drawing, in figure 2, a smoothed curve following the run of the numbers from day to day. In figure 3 we plot Fabry and Buisson's ozone values as abscissae, with solar-constant numbers as ordinates. The observed values are given

TABLE 13.—*Ozone and the Solar Constant*

Date 1920	Ozone value Fabry and Buisson	Solar constant, Calama	
		Observed	Smooth curve
	cm.	*cal.*	
May 21	0.304	1.936	
25	0.310	1.970	1.950
27	0.298	1.964	
28	0.290	1.952	
29	0.275	1.942	
31	0.306	1.952	
June 4	0.293	1.929	1.957
5	0.297	1.960	
7	0 325	1.938	
9	0.321	1.940	
10	0.335	1.933	
11	0.314	1.943	
21	0.286	....	1.950
23	0.289	1.947	

as circles, the corrected values as crosses. We believe readers who examine figure 2 will scarcely hesitate to think the three corrected values (the crosses) are probable ones. If that is admitted, we think the run of observations in figure 3 gives some indication that increasing values of the solar constant are associated with decreasing quantities of atmospheric ozone.

If this is so, the important infra-red ozone band[1] at a wave length of about 10.4 microns, falling exactly in the region where terrestrial radiation is otherwise most freely transmitted by the atmosphere, very likely changes greatly its absorbing power for outgoing earth rays along with changes in the solar radiation, but in the sense to

[1] See figure 41, *Annals Astrophysical Observatory*, Vol. IV, p. 285.

diminish terrestrial temperatures as solar radiation increases. This, if true, must be an important meteorological consideration. We hope soon to make an investigation of this ozone problem.

STELLAR SPECTRUM ENERGY CURVES

By invitation of Dr. Hale, given in the year 1916, we devised a spectro-bolographic outfit for obtaining spectrum energy curves of images of the brighter stars focused by the 100-inch telescope of the Mount Wilson Solar Observatory. The experiments were unavoidably postponed until the summer of 1922. We do not give here an extended account of them because we hope to repeat them with improvements in sensitiveness and accuracy. We are convinced that though we succeeded in making a vacuum galvanometer of 11 ohms resistance with which we measured 5×10^{-12} amperes, and though in combination with the vacuum bolometer we measured with it a change of temperature of 1×10^{-8} degrees Centigrade, satisfactory stellar spectrum energy observations demand at least tenfold more sensitiveness with fivefold less disturbance than we could achieve in this way. Hence, although we observed roughly the distribution of energy in the spectra of 10 of the brighter stars, including nearly all of the principal Harvard classes, we propose to employ new devices in further experiments.

Without the aid furnished by Dr. Stratton and the Bureau of Standards, Dr. Thomson and the General Electric Laboratory, at Lynn, Dr. Nichols and the Nela Research Laboratory, and especially Dr. Hale, Dr. Adams, and the staff of the Mount Wilson Solar Observatory, we could not have obtained these preliminary results.

Figure 4 gives a general view of the arrangement of apparatus successfully employed after a failure of preliminary experiments at the Newtonian focus of the great telescope, due to electrical and temperature disturbances. The rays *ab* coming from the star were reflected from *b* backwards towards the focus of the 100-inch mirror and were reflected a second time at *c* by a convex mirror whose property it was to increase the focal length from 40 to 250 feet. There was a third reflection by a plane mirror at *d*, so that the rays came at length to the so-called Coudé focus at *e*, in the southern prolongation of the equatorial axis of the telescope.

Here the rays entered the nearly constant temperature room *q*, whose roof, walls, floors, and piers are so massively built of cement as almost to remind one of Egyptian pyramids. The star rays diverged to the concave mirror *f* (at 6 meters distance beyond the

Coudé focus) which brought them a second time to focus over a meter distant at the slit *g*. Thence they diverged to the collimating mirror *h*, of 45 centimeters focus, proceeded parallel to the 18°

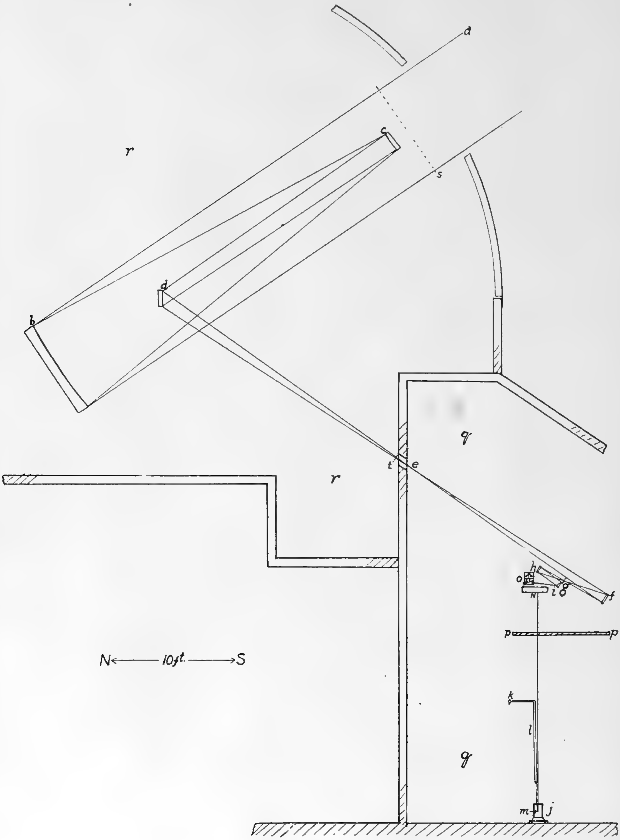

Fig. 4.

ultra-violet crown glass prism *i*, and were returned nearly over the same path by a reflecting coat of silver on the back of the prism so that they came at last to focus on the special vacuum bolometer close to the slit *g*.

Electrical connections led from the spectrobolometer situated 6 meters above the floor (but conveniently adjustable from the platform *p, p*) to the special magnetically shielded galvanometer *j*, whose tiny platinized mirror, *m*, reflected a beam of light from the brilliant special incandescent lamp *k* up to the photographic plate carrier *n*, where bolographs of the stellar spectra were to be taken. The astronomical clock *o* was connected so as to move the prism and photographic plate simultaneously for this purpose.

In practise we found that owing (1) to a slow but persistent drift of the galvanometer due to temperature changes, and (2) to a continual oscillation of the galvanometer light spot over a range of from 1 to 5 millimeters, occasioned apparently by electrical oscillations induced by power and light circuits, it was inadvisable to use the photographic recorder. All of our results were obtained by eye observing upon a ground glass scale drawn with luminous paint, and resting on the platform *p, p*, at 5 meters from the galvanometer.

The procedure of observing was as follows: A selected star having been brought into focus at *e* by the night assistant at the telescope in the dome, *r, r*, the mirror, *f*, was adjusted so as to form its image centrally within the slit at *g*. The prism, previously set by means of a sodium flame exposed at *e* so that the *D* line fell upon the bolometer, was then rotated by turning the driving shaft which connected to the clock *o* through a certain number of turns sufficient to go beyond the region of spectrum where sensible heat could be observed. Then one observer (Mr. Aldrich) made successive settings of whole turns down through the star spectrum, and recorded the other observer's (Mr. Abbot's) galvanometer readings at these settings. Arrived at the other end of the spectrum region where sensible deflections were observed, a return series of settings was made at places half-way between those of the first series. Exposures in the spectrum were made by pulling a cord which lifted a shutter at *t* near the Coudé focus. Frequently the slit *g* was inspected from a distance by a telescope so as to correct if necessary the position of the star image within its jaws.

All of the observations of stellar spectra were made when the stars observed were within less than 50° of the zenith, so that the air-mass never exceeded 1.5. For the purpose of eliminating in one operation the selective losses in the atmosphere, the telescope, and the spectroscope, so far as necessary for such rough measures, it was contrived to observe near midday with the same apparatus an image of the sun whose energy spectrum is known. For this purpose a screen, *s*, with eight symmetrically distributed quarter-inch holes was placed over the top of the telescope tube, and a diaphragm of $\frac{1}{8}$-inch aperture inserted at *t*. These reductions of the solar intensity sufficed, with a little series resistance added in the galvanometer circuit, to permit the solar spectrum to be observed on nearly equal terms with those of the stars. The factor of reduction to bring the sun down to about the intensity of Capella proved to be as expected a little more than 26 magnitudes.

Employing these solar comparisons together with the 1920 determination of the forms of the sun's energy curve outside the atmosphere both for the prismatic and the normal spectra, we have eliminated selective effects of absorption from the stellar spectra which follow.

On various accounts we are unable to claim much accuracy for our results. They are to be regarded merely as a preliminary feeling-out of the problem. Better knowledge of the distribution of these stellar spectra has, we believe, already been obtained by Coblentz with his method of absorbing screens, also being employed by Pettit and Nicholson. But of course if the employment of a prism could be made satisfactorily, its results would be far preferable to those of absorption methods. Our experiments show us just what must be done to bring this about, and we now have great hope of succeeding in new experiments with modified instruments.

In our experiments of 1922 the principal defects are these:

1. Insufficient sensitiveness. It was impossible to measure the radiation, as weakened by increasing prismatic dispersion and increasing atmospheric and instrumental absorption, far enough towards the violet to follow with any accuracy the normal spectra of stars of types *G, F, A,* and *B* to their maxima.

2. Insufficient accuracy of wave length. With the moderate dispersion of what was practically a 36° crown glass prism, the wanderings of the star image in the wide slit of the spectroscope were sufficient to produce uncertainties of wave length amounting roughly to as much as the distance from D to B in the orange-red of the spectrum. This defect could have been reduced greatly had we been able to continue the experiments one or two more nights, and will easily be made small hereafter by better following devices.

3. Insufficient accuracy of intensity measures. Owing to bad following the image wandered sometimes partly onto the slit jaw before it was corrected. This would, of course, have been prevented had the work gone on. But more serious, because incessant, were the oscillations of the galvanometer light-spot on the scale, through amounts which, for some stars, were nearly as great as the observed maximum deflection in the spectrum. Though every deflection re-

TABLE 14.—*Original Observations of Intensities in Stellar Spectra*

Galvanometer deflections in millimeters

Spectrum place		Name of star observed, its magnitude and spectrum class													
Shaft turns from *D*	Wave length	ε Orionis 1.8, *Bo* (2)	β Orionis 0.3, *B8p* (2)	α Lyræ 0.1, *Ao* (3)	α Can. Maj. -1.6, *Ao* (3)	α Aquilæ 0.9, *A5* (3)	α Aurigæ 0.2, *Go* (2)	(3)	Sun -26.5, *Ga* (1)	α Tauri 1.1, *K5* (2)	(3)	β Pegasi Var., *Ma* (2)	α Herculis Var., *Mb* (2)	α Orionis Var., *Ma* (1)	(3)
—3.0	0.477	0	...	...	...	...	0	1	...	..	..	...	...	..	..
—2.5	0.465	...	...	...	...	0	1	..	3	..	..	...	...	..	..
—2.0	0.484	0	0	...	1	...	2	1.5	...	..	1.5	...	...	..	..
—1.5	0.505	0	0	...	...	2.5	3	..	13	0	5	...	...	..	..
—1.0	0.529	0.5	1.5	...	10	...	3	4	...	..	3	...	0	..	1
—0.5	0.557	4	6	0	9	2	7	..	20	2	7	...	...	..	..
0 0	0.589	4.5	2	6	15	...	5	7	37	3	7	...	0.5	0.5	9
+0.5	0.628	5.5	1	1.5	13	6	4	..	34	3	10	...	...	1.5	0
1.0	0.674	1	5	4	11	5	7	10	43	5	13	0	5	3	16
1.5	0.729	...	0	5	17	5	6	..	45	4	14	...	...	6.5	11
2.0	0.797	...	0	4	6	2	6	14	45	9	17	4 ?	9	9	18
2.5	0.874	...	...	6	...	1.5	6	..	45	4	15	...	...	12.5	26
3.0	0.966	...	...	2.5	1	...	5	15	36	12	15	5 ?	7	9	33
3.5	1.088	...	...	3	...	...	1	8.5	41	7	..	...	...	6	30
4.0	1.204	...	...	0	...	...	1	7	30	10	13.5	0.5 ?	7	3	23
4.5	1.320	...	...	...	...	...	..	6	30	10	..	...	...	2.5	29
5.0	1.434	....	...	...	...	...	..	2	18	10	14	0	5	2	16
5.5	1.544	...	...	...	...	...	..	..	13	4	..	...	...	2	20
6.0	1.652	...	...	...	...	...	..	..	15	0	3.5	0	1	1	28
6.5	1.755	...	...	...	...	...	..	..	11	0	..	...	...	..	11
7.0	1.855	...	...	...	...	...	..	..	4	0	0	0	0	..	7
7.5	1.954	...	...	...	...	...	..	..	...	..	..	...	...	..	5
8.0	2.048	...	...	...	...	...	..	..	...	..	..	...	...	..	12
8.5	2.141	...	...	...	...	...	..	..	...	..	..	...	...	..	0
9.0	2.230	...	...	...	...	...	..	..	...	..	..	...	...	..	0.5

(1) Observations of August 19, 1922. (2) Observations of September 13, 1922. (3) Observations of September 14, 1922.

corded is the mean of several trials, it cannot be hoped that these relatively large disturbances are eliminated satisfactorily. Moreover, the uncertainties of wave-length settings mentioned above aggravate the errors of intensities, because the deflections, even if true, might have related to wave lengths somewhat different from those supposed. If the experiments on each star had been repeated several times on later nights very much greater accuracy could doubtless have been had in the final means. But, after all, the sensitiveness available was not adequate ever to give satisfactory results, and it would have been a waste of time to go on with the apparatus as it was in 1922. With these remarks we give the observations. We have arranged the stars in order of the Harvard spectrum classification, although the order of observing followed approximately the order of their right ascensions.

The scale of galvanometer deflections differs on the three nights of observation and even at different hours of the same night according to the time of swing which was practicable at the time. Wherever there are two observations on one star we have reduced the smaller deflection data to the scale of the larger approximately and have given the observations of larger deflection greater weight in drawing smoothed curves. In view of what has been said of the sources of error always present, readers will not be surprised at the irregularities which the data present.

As the work is altogether rough and preliminary we shall not take space to detail what steps were necessary to reduce the direct observations for the selective losses in the atmosphere and the apparatus, merely repeating that these reductions depended on the solar-spectrum observations of 1920 taken together with those made on August 19, 1922, with the great telescope and stellar spectro-bolometric outfit.

In figure 5 we have given in smooth curves as well as we can the stellar distribution outside the atmosphere on the scale of the 36° ultra-violet crown glass prism, and in figure 6 the corresponding curves reduced to the normal or wave-length scale. In drawing the normal curves we were immediately made conscious that for the stars of types *B, A, F, G,* the original very small deflections in the shorter wave lengths lacked a sufficient degree of accuracy to warrant multiplying them by the very large prismatic dispersion factors. Such results would have had no meaning and would have been apt to mislead. Accordingly we cut off all of these normal curves beyond wave length 0.5 micron, and omitted four stars of types *B* and *A* for which the observed deflections at maximum ordinate in the prismatic spectrum did not exceed 5 millimeters.

Obviously in order to determine at all satisfactorily by heat methods the spectrum distribution for stars of types *B, A* and *F*, it will be necessary to use apparatus of a decidely higher order of sensitiveness than ours.

On the whole the positions of maximum ordinates in the prismatic spectra shift with spectrum type much as we should have expected.

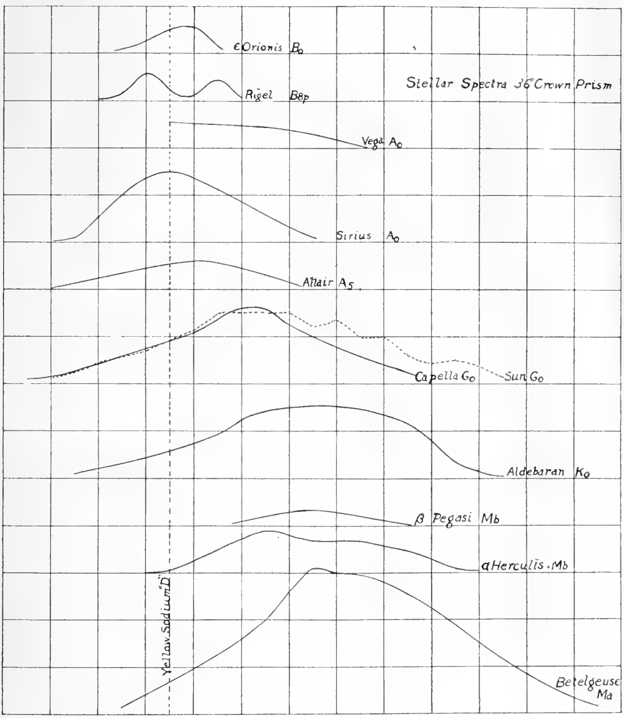

FIG. 5.

It is satisfactory that the curves for the sun and Capella agree so well. The several depressions in the infra-red of the solar curve are most likely real, as they coincide closely with great infra-red water vapor bands. The stellar curves would doubtless have shown them too if there had been enough energy so that they had been equally as accurate.

We attribute little weight to the circumstance that the maximum in the normal spectrum curve of α Herculis falls to the violet of that of α Orionis. That Aldebaran gives its maximum at shorter wave lengths than either, we think is real, but we do not feel confidence in the exact places for any one of the three. Greater accuracy is essential if real deductions as to star temperatures and their approach to "black body" conditions are to be made.

Though we have not concealed the shortcomings of these stellar observations, they cost a great deal of effort. Fatalities seemed to lurk about the work to surprise us so that we were almost ashamed to meet

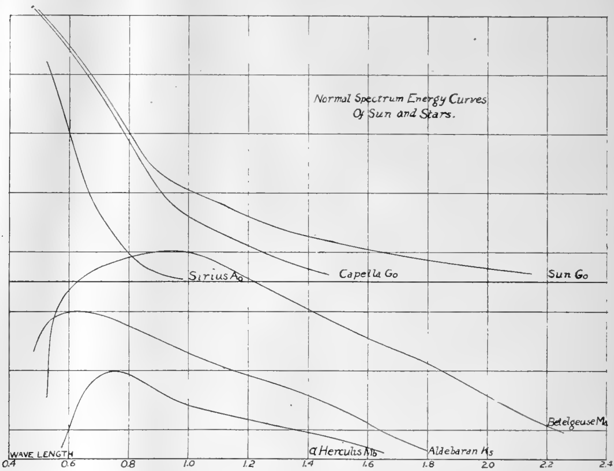

FIG. 6.

any one on Mount Wilson lest he should ask what new things had gone wrong that day. We made a list of all the serious mishaps, and they numbered nearly 30, some requiring a whole week to repair. But we feel after all that a decided step was made to have gotten from 10 to 30 millimeters deflection in the fairly extended spectra of four of the brightest stars. For it was not many years ago that Boys failed to recognize stellar heat, and Nichols observed but one or two millimeters in the total radiation of such stars. Naturally our success, such as it was, depended largely on the great size of the Mount Wilson telescope, but besides that it indicates a large gain in sensitiveness of apparatus. Furthermore, the experience gained clarifies the problem so exactly that plans for future experiments may now be laid with great certainty.