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Scientific Basis of Music

BY

Dr. Stone

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THE

SCIENTIFIC BASIS OF MUSIC

BY

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PREFACE.

A Primer should have two objects: the first, to describe, with as little technical complication as possible, the chief outlines of the subject treated; the second, to furnish references for more advanced study. In fulfilment of the latter requisite footnotes have been appended to the text, and a list of standard works thus referred to is added by way of appendix.

W. H. S.

London, *February*, 1878.

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THE SCIENTIFIC BASIS OF MUSIC.

CHAPTER I.

INTRODUCTORY—WAVE-MOTION—LIMITS AND SOURCES OF SOUND

1. MUSIC may be defined as the æsthetic and emotional side of sound. It aims not only at rousing the sensibility of the ear, an organ specially set aside for its appreciation—not only at thus establishing communion between individuals, at warning them of danger, and at enabling them to express their several wants—but, going further and deeper into man's moral nature, it proposes to itself the end and object of affording him pleasure, of soothing him under affliction, and of rousing him to noble and generous actions.*

It is therefore essentially somewhat of an acquirement, an evidence of cultivation, a secondary development in the progress of civilisation, and, in its fullest and grandest form, a very late phenomenon in the history of nations.

Its artistic and traditional side has, however, as a rule, preceded and outstripped the scientific explanation of sensorial and mental effects produced.

Instruments of music, intended originally to charm the ear, have in later times been found to embody important acoustical principles, and have been made to render good service to physical investigation.

A note, a chord, and a scale, besides being looked at as pure or harsh, consonant or dissonant, cheering or melancholy, may therefore be also idealised as mathematical abstractions, as illustrations of the law of number, as convenient and tangible demonstrations of the great modern generalisation of VIBRATION, or WAVE-MOTION: which, commencing in the measured beat of the pendulum, passes on through the aerial oscillation of Sound, and reaches, though with a long interval, to the molecular disturbance of Heat; then, merging insensibly into the æthereal motion of Light, can even be traced beyond the luminous spectrum in the phenomena of Actinism and Photography, and, though

* See primer on "The Elements of the Beautiful in Music," p. 10 *et seq.*

doubtfully as yet, will in all probability one day with certainty embrace the marvellous manifestations of Electricity.

From a pardonable exaggeration of this duplex nature has perhaps sprung an unconscious antagonism between artists and scientific men, which it is the especial function of the present day to reconcile. Much has been in former times instinctively discovered by the keen ear and delicate organisation of the former; but, from the days of Pythagoras to the time of Helmholtz, the observations of Science have followed close upon the creations of Art, and now even the most gifted musical genius can hardly dispense with a general knowledge of theoretical researches.

An attempt will be made in the following pages to sketch broadly the outline of the ground in which Music is conterminous with Physics, and to fill in with somewhat greater detail departments necessarily incomplete in the excellent primer on the "Rudiments of Music," already published in this series.

2. The Wave of Sound emitted by a sonorous body is ill represented by the ordinary conception of a straight line. Like the ray of light, its progress in homogeneous media, from source to organ of sense, is direct: but the wave itself is spherical. A bell when rung in open air, or deep in still water, throws off spherical shells of alternate condensation and rarefaction, expanding equally and simultaneously in all directions until they meet with an obstacle. It is only when these vibrations are confined to some body ot limited dimensions that their free expansion is coerced and caused to follow the readiest path. When spreading uncoerced, again like the subtle waves of light, their force rapidly diminishes, in proportion to the square of the distance travelled; part of the mechanical energy expended in exciting them is lost by friction, another part is converted into heat; and thus they are gradually extinguished, just as the boy's bubble ends by bursting from attenuation of the viscid film which incloses its increasing dimensions. If the conveying medium, which may be solid, liquid, or gaseous, assume a form of less than three dimensions, this extinction occurs far less rapidly, and may be even compensated by an opposite phenomenon which will be noticed further on (see par. 64). Thus, if a source of sound be applied to a plank, which has mainly length and breadth, the wave will cover its superficies with but little loss. If the plank be diminished to a rod, or replaced by a string or wire possessing mainly the one dimension, length, a still further saving will be effected, and its power of travelling will be enormously increased. Even a column of air inclosed in a rigid tube may be made to serve the same purpose, as is daily seen in ordinary speaking-tubes.

3. In any case the wave does not involve the transmission of a material substance. It is not like the flight of a cannon-ball

from point to point. The transmitting body does not move as a whole, but it can be felt by the hand to *thrill*, that is, to vibrate, each particular molecule of which it is composed moving through an infinitely small distance, but giving up to neighbouring molecules its all but undiminished motion, to be thus successively conveyed to the most distant point. In proportion to the elasticity and homogeneousness of the transmitter is the conservation of the impressed motion and the rapidity with which the impulse travels.

4. These alternations of density, of which the sound-wave has been said to consist, possess three properties: they may vary in AMPLITUDE, in LENGTH, in CHARACTER. Their amplitude may be defined as the length of the path which each vibrating particle traverses—the *amount to which it is shaken out of its position of rest;* and upon this depends the LOUDNESS of the sound. Their length depends solely upon the *rapidity with which they follow one another*, and this determines the PITCH of the sound. Their character is given by the *shape of the wave*, which is now found to differ with alteration of its constituent waves, and to this is due the QUALITY, or, as it was formerly called, the *timbre*, of the sound.

5. If the vibrations of which a sound consists follow one another irregularly, and without definite rhythm, the result is what we term noise. If they be regular and periodic, it is musical. The point of transition between the former and the latter is, however, indefinite, since an element of regularity and periodicity is often blended with heterogeneous sound, or can be superinduced upon it. Dr. Haughton* has ingeniously illustrated this fact in the following way: "The granite pavement of London is four inches in width, and cabs driving over this pavement at eight miles an hour cause a succession of noises at the rate of thirty-five in the second, which correspond to a well-known musical note, and one that has been recognised in the silence of the night by many competent observers. Yet nothing can be imagined more purely a noise, or less musical, than the jolt of the rim of a cab-wheel against a projecting stone; yet, if a regularly repeated succession of such jolts takes place, the result is a soft, deep, musical sound that will well bear comparison with notes derived from more sentimental sources." The same coalescence of noises into tones is illustrated by the toothed wheel of Savart, and the "Siren," which will be described in a later paragraph. The superinduction of musical echo can be heard in any closed building of regular form, especially if it consist of many similar parts. In the Crystal Palace, for instance, each

* "Natural Philosophy Popularly Explained," by the Rev. S. Haughton, M.D., F.R.S.

girder of the roof is the counterpart of its neighbour, and stands equidistant from those around it. A falling plank, or even loud clapping of the hands, sends forth an irregular wave of noise, which, being intercepted and reflected back to the ear at similar intervals, gradually becomes periodic and musical. Even more trivial examples of this transition may be noted in the sound of chaff-cutters, lawn-mowers, saw-sharpeners; in the schoolboy's pencil jarring against his slate, or in the purposeless rattling of his hoopstick against area railings.

6. One more limitation is necessary for the full definition of musical sound; that, namely, of the extremes between which the rapidity of the wave-motion must be contained. Both the upper and the lower limits seem to be variable and arbitrary, but for different reasons. The Lower Limit at which a periodic intermittent vibration merges into musical tone has been very differently stated by different observers; indeed, two very different standards for the estimation of musical quality have been unconsciously adopted. Thus much is certain, that the C open diapason pipe of thirty-two feet long in large organs gives 16 vibrations per second; that modern pianofortes have strings sounding A in the same octave with about 27 vibrations; that the double-bass and the double-bassoon in the orchestra can be made to give C of 32 vibrations, and even the B flat intermediate between that C and the A of 27, notes written for the respective instruments by Beethoven, Onslow, and Gounod. The point in debate is rather the musical character of the sounds thus produced than the fact of their production. Helmholtz limits this character to the E of the German double-bass, with about 40 or 41 vibrations. But he requires that the oscillations thus estimated should be simply and purely pendular, without "harmonics," "overtones," or "upper partials." In this statement he may perhaps be right, and certainly it is difficult to controvert, since simple pendular vibrations of this speed are all but impossible to produce. If, however, the note CCCC be taken on a good thirty-two feet metal open pipe, such as that of the organ in the Albert Hall, the 16 vibrations can certainly be separated from their affiliated harmonics by the majority of practised ears. It should, however, be noted that the estimation of very deep tones is a matter of special education, and acquired with considerable difficulty.

7. The Upper Limit varies within a far larger range, for reasons chiefly physiological. The highest notes actually employed on the piano and organ, or in the orchestra, are very far removed from those audible even to the majority of ears. Pianos usually reach A, with 3,520 vibrations, or even C, with 4,224. The orchestral piccolo, or octave flute, has D, with 4,752. But there is good evidence, from the experiments of Despretz, and more recently of Galton, that sounds with as many as 38,000 vibrations

per second can be heard. Sounds actually audible would thus cover rather more than eleven octaves, those used in music from seven to eight.

8. Modes of Producing Sound may be divided into those that are musical, and those that are not. The latter may here be passed over with simple mention; the former require more detailed description. To the latter class belong the shock of two bodies, or their friction with one another—explosion or sudden change of volume, and the disruptive discharge of electricity. Of late the molecular change produced in iron by the passage of a strong galvanic current, which is accompanied by a feeble sound, has also been utilised in some forms of the telephone.

The more strictly musical forms of exciting vibration are best given in tabular shape, as follows :—

VIBRATIONS.

- I. Of Strings
  - 1. Transverse
  - 2. Longitudinal
  - 3. Torsional
  - excited by
    - A. Plucking
    - B. Striking
    - C. Bowing
    - D. Impact of air
  - vary with
    - *a.* Nature of stroke.
    - *b.* Place struck.
    - *c.* Rigidity of string.
- II. Of Rods
  - 1. Transverse
  - 2. Longitudinal
  - 3. Torsional
  - with
    - A. Both ends fixed (approach to those of strings).
    - B. One end fixed (nail fiddle, musical box).
    - C. Centre fixed (tuning-fork).
    - D. Both ends free, nodal points supported (harmonicon).
- III. Of Plates
  - 1. Radial
  - 2. Circular
  - As in Chladni's experiments (gong cymbal).
- IV. Of Bells
  - 1. Spherical
    - A. Excited by blows (clock chimes).
    - B. By tangential or radial friction (musical glasses).
  - 2. Of complex figure (give compound notes with irrelevant harmonics).
- V. Of Membranes
  - 1. Independent (tambourines).
  - 2. With associated air-chamber (kettledrum, resonators).
- VI. Of Reeds
  - 1. Free (as in harmoniums).
  - 2. Beating
    - A. Single (clarinet, organ reed).
    - B. Double (bassoon, oboe).
  - 3. Membranous
    - A. The lips in brass instruments.
    - B. The larynx (human voice).
- VII. Of columns of air
  - 1. Organ pipes
    - A. Open pipes.
    - B. Stopped pipes.
    - C. Half-stopped pipes.
    - D. Pipes with reeds.
    - E. Mixtures and mutation stops.
  - 2. Consonance boxes and vessels.
- VIII. Of flames
  - 1. Chemical harmonicon, pyrophone.
  - 2. Sensitive and singing flames.

9. By far the most ancient investigations in sound are those on STRINGS, which date back to the time of Pythagoras and Euclid. The most important form of these vibrations is the transverse, which alone is utilised for musical purposes, though it is impossible to prevent its being blended with others, both longitudinal and torsional. The longitudinal may, however, be excited by fixing a metallic wire of considerable length between heavy metal clamps, and rubbing it in the direction of its tension with a resined bow or leather. The notes thus produced are considerably higher than those elicited by transverse vibration on the same length of string. The torsional vibrations are occasionally produced in bowing the circumference of a stout string, such as that of a double-bass, with a resined bow, and, being false and unpleasant, are, as well as the preceding, guarded against by players by giving a slight oblique motion to the bow.

10. The laws of transverse vibrations in strings are simple and easily demonstrable. It can be shown that the velocity with which they travel along a flexible cord is equal to the square root of the tension applied to it divided by the mass of its unit length. The disturbance of any point in a string causes two pulses to start from this point and run along it in opposite directions. Each of these, on arriving at the end, is reflected from the support to which it is attached, and undergoes reversal as to side. It runs back thus reversed to the other end, and is there again reflected and reversed. When it arrives at the origin of the disturbance it has travelled over twice the length of the string, the other pulse arriving there at the same instant. The period of a complete vibration is therefore that required for a wave to travel over twice its length.

11. From this formula the laws of string-vibration are derived :—

(1) The frequency of vibration varies inversely, the period directly, as the length of the string, if the tension be unaltered.

(2) The frequency of vibration varies directly, the period inversely, as the square root of the tension.

(3) Frequencies of vibration are inversely, periods directly, as the square root of the mass or weight, length and tension remaining the same.

(4) Strings of similar length and density, but of different thickness, have similar vibration periods, if stretched with forces proportional to their sectional areas.

12. For the experimental illustration of these laws an instrument is employed termed the SONOMETER. It consists of a long resonant box, over which one or two strings can be stretched, either by means of wrest-pins or by means of a pulley and a weight. The upper surface of the box below the strings is provided with a graduated scale, usually divided into millimetres.

At each end is a bridge to limit the length of the sounding string, and a movable bridge can be placed at any intermediate point. The sonometer is not only useful for the above purposes, but can be easily made to demonstrate the laws of nodes and harmonics.

13. Harmonics, Overtones, or Upper Partial Tones are notes the vibration frequency of which is an exact multiple of the lowest tone producible on the string. In the latter case the string vibrates in a single segment, whereas in producing the harmonics it divides into several smaller segments, or *loops*, intersected by points of rest, or *nodes*. This result can be brought about at pleasure by lightly touching the point which is to form a node, and bowing or plucking the string nearer to its extremity. If it be touched at its middle, it separates into two loops, and sounds the octave of the original note. If touched at one-third of its length from either end, it gives the twelfth or the fifth above the octave, separating into three loops, with two intervening nodes. Speaking generally, if touched at $\frac{1}{n}$ of its length from either end, it yields a harmonic the vibration frequency of which is n times that of the fundamental tone, the string dividing itself into an equal number of segments. These can often be seen if the string be brilliantly lighted and strongly excited, or can be made more visible at a distance by placing a number of small paper riders astride on it. Those on the nodes will rest unmoved, while those situated on the loops will be forcibly thrown off.

14. The production of harmonics is not limited to the vibration of strings. It has been shown by Helmholtz that it is all but impossible to originate a simple sound unaccompanied by more or less of these affiliated oscillations. If they be of a period not connected by an easy ratio with the foundation or ground tone, the sound is only partially musical ; if, however, they are so connected, a richer and more satisfying character is given to the general compound, which varies according to the particular instrument, and which will be more fully discussed under the heading of Quality.

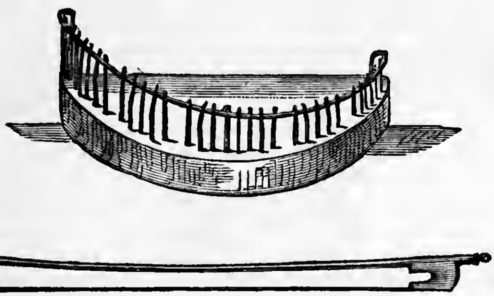
15. If Strings be plucked, as in the harp, guitar, and zither, struck with a hammer, as in the pianoforte, or rubbed with a resined bow, as in the violin, the simple pendular vibration excited is materially complicated with harmonics; the string may be considered as being capable of assuming any given form, because any given form of wave can be compounded out of a number of simple waves. "Hence," says Helmholtz, "every individual partial tone exists in the compound musical tone produced by a single musical instrument, just as truly, and in the same sense, as the different colours of the rainbow exist in the white light proceeding from the sun or any other luminiferous body. Light is only a vibrational motion of a peculiar elastic

medium, the luminiferous ether; just as sound is a vibrational motion of the air. In a beam of white light there is a species of motion which *may* be represented as the sum of many oscillatory motions of various periodic times, each of which corresponds to one particular colour of the solar spectrum. But of course each particle of ether at any given moment has only *one* determinate velocity, and only *one* determinate departure from its mean position, just like each particle of air in a space traversed by many systems of resonant waves. The real motion is of course one and individual, and our theoretical treatment of it as compound is in a certain sense arbitrary."

16. If a String be excited by impact of air, as in the Æolian harp, the combination varies from instant to instant, and the result is the weird mingling of high and low sounds which is the characteristic of that singular instrument. In plucked or struck strings it varies much, according to the nature of the blow, being full of high upper partials if the body striking be sharp and hard, as in the "jack" of the old harpsichord and the metal plectrum of the zither; more soft and smooth if the elastic tip of the finger be used, as in the harp or the soft felted hammer of the pianoforte. The makers of the latter instrument have been clearly led by practice to discover certain relations between the elasticity of the hammer and the best tones of the string. The place struck or plucked also influences the tone by causing those upper partials to disappear which have a node at the point excited, those again being strongest which have a maximum displacement at that point. In pianofortes the point struck is about one-seventh to one-ninth the length of the string from its extremity. "The selection," again remarks Helmholtz, "is not due to theory. It results from attempts to meet the requirements of artistically trained ears, and from the technical experience of two centuries." Soft and heavy hammers have, by a similar process, been selected for the lower notes, lighter and harder for the upper octaves. The influence of rigidity is seen best in gut strings, which, being much lighter than metal strings, produce higher partial tones. The difference of their musical quality depends partly on this circumstance, and partly on the inferior elasticity of the gut, which damps the higher partials much more rapidly. The tone of plucked catgut strings, as in the guitar and harp, is therefore much less tinkling than that of metal strings.

17. The motions of bowed strings have been studied by the great observer above named by means of the vibration microscope. It may be sufficient here to note that during the greater part of each vibration the string clings to the bow, and is carried on by it; it then suddenly detaches itself, and rebounds, being again seized by other points in the bow, and again carried forward.

18. The vibrations of Rods, Plates, and Bells, being only of limited application to music proper, may be briefly considered together. Those of rods possess the same three divisions as do strings, the transverse being the most useful. If both ends of a rod be fixed it approximates to a stout string, the harmonics, from its greater rigidity, being considerably modified. If one end only be fixed, another set of conditions prevails. The practical applications of this form are few. The "nail fiddle" to be seen at the South Kensington Museum is an instrument founded on an accidental sound, elicited by hanging a cloak on a metallic nail firmly fixed to the wall. The nails in the completed form are of selected and increasing size, so arranged in a circle as to be bowed on their outer aspect by means of a fiddle bow. The musical snuff-box is a far more advanced development of the same principle, the rods being arranged in a horizontal comb,



NAIL FIDDLE.

weighted with lead for the lower register and plucked by means of steel pins projecting from a barrel, rotated by means of clockwork. Chladni used rods of this character for the construction of a tonometer.

19. Rods fixed at the centre furnish one of the most important acoustical, if not actually musical, implements we possess, namely, the tuning-fork. This may be looked on as an elastic rod bent on itself in the middle, and supported at this point by a projecting stem or handle. The advantage of this arrangement is that the vibrations of the two extremities, which should be symmetrical about the handle, take place in opposite directions, and thus cancel or antagonise one another. A rising and falling motion is moreover communicated to the handle, which is easily transferred to any resonant body on which the tuning-fork is rested, without thereby damping the vibration. From the same causes it is possible to dispense with firm fixture of the fork,

which may be held loosely in the fingers. The chief function of the tuning-fork is as a standard of pitch, for which it is especially fitted, from its purity of tone and its slight liability to variation with heat and atmospheric changes. It will be further adverted to in this respect in a later paragraph. It may here be noted that from the bending of the rod, and the firm attachment of the stem to the central segment, the position of the nodes is brought much closer together than in the simpler form.

20. Rods with both ends free give longitudinal vibrations, which follow the same laws as both the longitudinal and transverse vibrations of strings. There is a complete series of harmonics of the ground tone, and the vibration period is that of a pulse travelling twice over the length of the rod; the modulus of elasticity, named after Young, being substituted for the stretching force (see par. 10). The nodes are also distributed exactly as those of an open organ-pipe (see par. 30).

When struck transversely, and supported on the two nodal points, which are situated at a distance from the ends about one-fourth of that between them, rods give a tone relatively higher than when fixed at one end, and the harmonics follow a series resembling that of the stopped organ-pipe. They have, however, been but little used in music of a classical character. In the South Kensington Museum is shown a curious instrument of the kind, termed the *Marimba*, brought from Africa, in which the vibrating bars are formed of the outer hard siliceous bark of the bamboo, supported by twisted thongs, and reinforced in tone by ingenious resonators made of a gourd shell, the orifice of which is closed by a vibrating membrane. The same contrivance has been used in hard stone, glass, metal, or even wood, under the names of the rock-metal or glass harmonicon, and latterly of the "xylophone." It is used in Mozart's opera "Il Flauto Magico" to imitate the sistrum with which Papageno is gifted.

21. The vibrations of PLATES were minutely investigated by Chladni, in 1785, by the beautiful method of strewing sand on them, and noting the lines of quiescence along which it heaped itself up. The problem has been more recently followed up by Wheatstone. Strehlke and Faraday afterwards added a light powder to the heavy sand. In these ways graceful symmetrical figures have been produced, which are of the highest interest in a physical point of view, but which can hardly be said to belong to music.* Helmholtz shows that many proper tones of nearly the same pitch are produced by a plate of this kind. "A disc gives a tolerably good musical tone; whereas plates in general produce sounds composed of many inharmonic proper tones of nearly the same pitch, giving an empty tin-kettle quality, which cannot

* For further details see Tyndall "On Sound," p. 138 *et seq.*

be used in music." This description applies accurately to the cymbals, which are, however, used in military bands to mark time and to reinforce the accent. It applies partially to the gong, which elicits a complex sound of more definite constitution, thus approximating to that of a bell. Both are made of highly hammered metal, and, if free from cracks, are of considerable value

MARIMBA.

22. Bells vibrate essentially in the same mode as do plates. In sounding their deepest note they divide into four segments, separated by intermediate nodal lines. The point at which the hammer strikes is always a loop, and there are three similar points at right angles to one another in the circumference, these angles being each bisected by nodal points of comparative quiescence. The bell, viewed from below, would therefore assume

elliptical forms, the long and short axes of which successively replace each other. The vibration period varies directly as the thickness and inversely as the square of the diameter.

The bell may, however, also divide itself into any *even* number of segments, the notes of which follow the ratio of their successive squares. In thin bells this tendency to subdivision is so great that it is all but impossible to bring out a pure fundamental tone.* In consequence of this continued subdivision there are no points of absolute rest, though Tyndall has found that in the Great Bell of Westminster an ivory ball was driven away five inches at a loop, and only two and three-quarters at an approximate node. Other irregularities occur from the impossibility of casting a bell perfectly homogeneous or symmetrical. The tone produced is therefore accompanied by inharmonic secondary tones, further apart from one another than those of flat plates.

The form of bells is various, and to a great degree empirical. The simplest is a segment of a sphere, a shape which is commonly employed in clock chimes and carillons. A shallow bell appears to give a thin note; and, on the other hand, one too cylindrical in outline, like most of the Chinese and Russian bells, is too hollow, and less easily heard in a horizontal direction.†

The more elastic the material of which a bell is composed, the higher will be its note.‡ The necessary size and weight to elicit a given note are mainly matters of trial and experience, in consequence of which most of the older peals of bells are grossly out of tune. A little tuning can be done, at the expense of quality, by chipping away the thickened rim, usually termed the *sound-bow*, against which the clapper strikes. The common shape of church bells is that of a truncated conoid or paraboloid, closed at the apical end by a dome-shaped roof, to which the suspending luggs are attached. Assuming the diameter at the base as 15, and the height as 12, with a curvature below, in section, of radius 8 for the lower half, and for the upper of radius 30, Dr. Haughton has given a table of weights and pitch. One octave of these deserve quotation, in the hope that they may some day be constructed.

* Tyndall "On Sound," p. 150.

† Dr. Haughton, *op cit.* p. 195.

‡ The common composition is of copper and tin, hence termed "bell-" or "gun-metal," in the approximate proportions of six atoms of the former to one of the latter. This is equivalent to a percentage by weight of copper 76·5, and tin 23·5. The exact atomic ratio seems to produce too hard and brittle an alloy, which defect can be reduced by slightly increasing the quantity of copper. A common mixture is 13 copper by weight to 4 tin, or by an admixture of zinc, and possibly of silver, although the traditionary stories as to the effect of the latter metal seem to a great extent imaginary.

Note	Diameter	Sound-bow	Weight	Clapper
	Inches	Thickness	lbs.	lbs.
CCCC	128·0	8·53	40,960	1,029
DDD	113·8	7·58	28,767	725
EEE	102·4	6·83	20,971	529
FFF	96·0	6·40	17,280	437
GGG	85·3	5·69	12,136	308
AAA	76·8	5·12	8,847	226
BBB	68·3	4·55	6,214	161

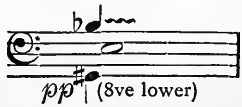
Helmholtz states that the tones vary with the greater or less thickness of the wall of the bell towards the margin, and that it appears to be an essential point in the art of casting bells to make the deeper proper tones mutually harmonic by giving a certain empirical form. Gleitz, the organist, in his "Historical Notes on the Great Bell and the other Bells in Erfurt Cathedral," states that the first named gives the following series of notes: *e*, *g*♯, *b*, *e'*, *g'*♯, *b'*, *c''*♯. It was cast in 1477. Hemony of Zutphen, in the seventeenth century, required a good bell to have three octaves, two fifths, one major and one minor third. By the kindness of Sir F. G. Ouseley and Dr. Stainer, the writer is enabled to reproduce, in musical notation, the compound notes of several well-known bells. When played on the pianoforte the dampers should be raised.

Hereford Cathedral {Hour Bell. Tenor Bell

Great Tom of Oxford.

St. Paul's.—Large Hour Bell.

Big Ben of Westminster.



In these notations, which can only be considered approximate, minims are employed for loud sounds and crochets for those which are less prominent. All the notes should be struck simultaneously, but the minims louder than the crotchets.

In the large hour bell of St. Paul's, the upper note is much louder than the A-flat, which ought to be the true note of the bell. The wavy line is to show that the pitch of the upper note does not remain stationary. In Big Ben the E is not a pure note, but is combined with so many sounds that it is impossible to give a nearer analysis of the tone of the bell.

It is found that the number of vibrations made in a given time is proportional to the square of the number of segments into which the bell divides itself. Thus, if $2m$ be the number of vibrating segments, we find, since n varies as m^2, by making m successively equal to 2, 3, 4

4	9	16	25	36	&c.	m^2
1	$\frac{9}{4}$	4	$\frac{25}{4}$	9		
C_1	D_2	C_3	$G\sharp_4$	D_4		

corresponding to its division into the following segments :—

4	6	8	10	12	&c.	$2m$

None of these secondary notes are harmonics to C, except C_3. They are, however, very variously audible in different bells.

23. The vibrations of membranes have been of late studied theoretically by Lord Rayleigh.* He shows that, in a circular membrane, the tones corresponding to the various fundamental modes do not belong to a harmonic scale, but that there are one or two approximately harmonic relations, such that the four gravest modes with nodal diameters would give a consonant chord.

The membranes actually employed in music may be divided into those which are free, such as tambourines, what are termed "gong drums," standing vertically, and the modern sidedrum. These all appear to give a very indefinite note, and are not even approximately tuned. They serve to mark rhythm, and to excite the tympanic membrane of the ear to a more acute appreciation of other sounds. Kettledrums, on the other hand, possess an associated air cavity, evidently intended to reinforce certain notes in the harmonic series to the exclusion of others. These are tuned by altering the tension of the head or vibrating membrane. They can be made to vary in pitch by this means through the interval of a fifth. Two or (far better) three of different sizes are usually employed, though Berlioz, in his "Requiem," has scored for a chromatic scale of twelve. Their principal function seems to the writer to be to strengthen one or two important notes of the sixteen-foot octave, such as the dominant and tonic, this register being unaccountably neglected in orchestral music. Occasionally, however, they are used as melodic instruments to give out a simple subject, and may then be of eight-foot tone.

* "Theory of Sound," p. 250.

The resonators employed by Helmholtz in the analysis of musical sound were originally made with tense membranes, but he afterwards found that the natural tympanic membrane of the ear was competent to the function, as will be shown further on. Exactly similar contrivances already existed in the African *marimba* named above.

24. The REED is a source of sound which has many varieties. In the simple form implied by the name it has furnished some of the most ancient instruments with which we are acquainted. Mr. W. Chappell has shown that the pieces of straw found beside pipes in the Egyptian tombs have evidently been intended for the manufacture of reeds.* The form of these has probably been that still fabricated by children in the fields out of a joint of oats or tall hollow grass. The tubular stem is cut at a knot, so as to form a stopped tube, and below the knot a lateral flap is cut from the side, which, springing outwards by its natural elasticity, acts as an intermittent obstacle to air blown through it from without. A peculiar and unpleasant note is thus elicited; but if such a reed be adapted to the end of one of the Egyptian pipes named above, a distinct scale, usually tetrachordal, can be originated. Copies of the pipes fitted in this manner were exhibited and played on by Mr. Chappell and the writer in the Loan Exhibition at South Kensington.

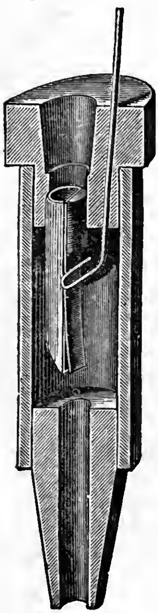
25. The simplest form of REED is that termed FREE. The use of it as a producer of sound is comparatively modern. A longitudinal slot is formed in a flat metal plate from ten to twelve times greater in length than in width. On the upper surface of the plate lies a thin tongue of some elastic material, such as lancewood, brass, German silver, or steel. At one end this is screwed or riveted firmly to the plate; at the other it is thinned away to a feather-edge for high notes, or loaded with weight for grave sounds. In shape it is exactly the counterpart of the orifice, but just so much smaller as to pass "freely" through it. The unattached end is easily set in vibration, either by striking the reed on a table, like a tuning-fork; by a blow with a small felted hammer, as in the "percussion" harmonium, in which cases it utters a feeble musical sound; or by forcing air through the partially closed opening in a direction from the tongue towards the plate, in which case it originates a powerful though somewhat harsh continuous note. The first step in the process is obviously the pressing of the tongue into the slot, thus all but cutting off the stream of wind; the second, its elastic rebound, which permits freer passage. Two plans have been adopted for producing the necessary wind-pressure: first the use of ordinary compressing bellows, like those of an organ, in which case the reed is fixed downwards.

* "History of Music," vol. i. p. 261.

or towards the wind-chest; secondly the employment of a bellows specially fabricated to exhaust its own cavity, and thus, by lessening the internal density, tending to draw in air at the atmospheric pressure, in which case the reed is fitted with its tongue outward, so as to meet the inrush of air into the partial vacuum thus produced. The former plan is that of the seraphine, concertina, melodeum, and harmonium ; the latter that of the so-called "American organ."

The weak point of both forms is the complete independence of the reed. It has no consonant tube to reinforce its regular and to damp its aberrant oscillations. The harmonium in this respect is worse than the American organ: first because the outward stream of wind carries directly to the ear all harshness, from whatever cause arising; secondly because the closed bag of the exhausting bellows in the American organ furnishes a partial but still appreciable substitute for the consonant bell of the organ reed. On the other hand the harmonium retains the power of "expression," namely, the ability to alter the amplitude of vibrations, and the consequent loudness, which is all but lost in the American organ

26. The beating organ reed is of more complex structure than that just given, and is a far more ancient contrivance. The orifice which conducts from the bellows in this case opens into a small wind-chamber separate for each pipe. This, which is termed the foot of the pipe, is filled at its enlarged upper extremity by a wooden or metal block, to which the speaking apparatus is attached. This is not dissimilar from the oaten straw reed named above. A semi-cylindrical brass tube, closed at the lower end and open along one side, is fixed firmly into the larger of two orifices in the block, the vibrating plate being wedged against its open side. This latter is burnished so as to present a slightly convex figure to the tube, and thus to leave a slight fissure between the two at the free end. From the upper surface of the block the hole containing the reed spreads out into a long conical or trumpet-shaped bell. The smaller hole in the block contains a bent wire, the lower end of which presses against the foot of the vibrator, for purposes of tuning. The effect of compressed air passing into the foot is to flatten the curved vibrator against the flat orifice of the tube (here by a singular change of names termed the reed). The elastic



ORGAN REED.

resilience of the metal then comes into play, and a vibrating column of air is sent into the bell. It is obvious that if the amplitude of the vibrations becomes excessive, the point of the brass or steel vibrator may actually "beat" or whip against the "reed," whence the name given to this form is clearly derived.

27. Among instruments blown by the breath, that which most resembles the organ reed is the mouthpiece of the clarinet. The vibrator here is *single*, but, instead of being curved, it is flat, whereas the necessary curvature is formed in the wood of the instrument itself. The tuning-wire is replaced by the graduated pressure of the lower lip, and by this means also the single reed is enabled to vary its length sufficiently to produce a compass of over three octaves.

In the oboe and bassoon two vibrators, opposed laterally to one another, are employed, whence they are termed *double* reeds.

28. MEMBRANOUS REEDS are divided by Helmholtz into two classes: (1) those in which the aperture is closed by the air (*einschlagend*), namely such as *beat*; and (2) those which are opened (*aufschlagend*), or *free* reeds. The beating reeds, in this and the other cases, give a lower tone than if vibrating freely, the free reeds a higher tone. The human lips, in playing instruments with cupped mouthpieces, and the human larynx in singing, belong to the class of free reeds. The mode of action in both cases is somewhat complicated, and will be considered in a subsequent chapter.

29. VIBRATIONS OF FLAMES have long been known as a physical fact, and, although even now hardly incorporated into music, cannot be entirely passed over. In 1777 Dr. Higgins heard them with burning hydrogen, and they were investigated about twenty years later by Chladni, who showed that the tones were those of the open tube surrounding the flame. Their rationale has, however, been explained, and many new facts added to their observation by Schaffgotsch and Tyndall.*

The former observer noticed "that when an ordinary gas-flame was surmounted by a short tube a strong falsetto voice, pitched to the note of the tube, or to its higher octave, caused the flame to quiver. In some cases, when the note of the tube was high, the flame could even be extinguished by the voice." If the flame be of the proper height in the tube, and of sufficient strength, instead of going out it begins to sing its proper note directly this is sounded, even from a considerable distance. One singing flame can thus be made to communicate its note to another. Even naked flames can be made sensitive to musical sounds, a phenomenon first accidentally noticed by Professor Leconte in the United States. The action depends on their being near the

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* Tyndall "On Sound," p. 224 *et seq.*

point of *flaring*. They do not in this case utter an individual note, but jump upwards and alter entirely in form. They afford an extremely delicate test of vibration, especially of its more rapid and high-pitched varieties, such as the tinkling of small bells, the jingle of silver coin, or the rattling of a bunch of keys. The different characters of the various vowels referred to in chapter iii. par. 71 can thus be discriminated. Even fine jets of smoke, or of water issuing from small orifices, can in a similar way be rendered sensitive.

Several attempts have been made to utilise this property of flames in the construction of purely musical instruments. Professor Wheatstone constructed an apparatus of this nature, which is now preserved in the Museum of King's College. The jets were therein lifted by means of a small keyboard to the proper height in the tube, usually at one-third from the lower opening.

Monsieur F. Kastner endeavoured to bring the action under control in a different manner. He employs two flames in each tube, which can be united or separated by finger keys. The tone is said to be good, but the pitch uncertain, owing to varying pressure of gas. The PYROPHONE, as it was termed, although promised at the Paris Opera, was not actually employed.

30. VIBRATION IN COLUMNS OF AIR has been purposely left to the last on account of its special importance. It was experimentally as well as mathematically investigated by Daniel Bernouilli. The column of air is inclosed in a pipe, and set in motion by various contrivances. The chief distinction is between open and stopped pipes. The former, as the name implies, are open at the end most remote from the embouchure or lip; the latter have that extremity closed.

A simple experiment may be made to show the method of excitement, and the distinction between the two varieties. If a glass tube, of an inch or more in diameter and about eighteen inches long, be held in one hand, and the palm of the other brought against its smooth extremity with some force, a wave of compression is sent through it which causes a distinct though only temporary note. If the hand be left against the end the note remains unaltered until extinction; but if it be rapidly lifted off the sound immediately jumps up an octave, and can be heard distinct from that first elicited.

The first law of Bernouilli is thus shown, without encumbering mechanism, that (1) the note of an open pipe is an octave higher than that of a stopped pipe of the same length.

An almost equally simple illustration of the vibrations in open pipes occurs in the *Nay*, or Egyptian flute,* an instrument which has been found in the tombs, and is still played by the fellahs on

* See Novello's Music Primer, "The Organ," fig. iii. p. 9.

the banks of the Nile. One of these, founded on a tetrachord, is to be seen in the British Museum; another, only differing from its predecessor in possessing a scale of seven notes, was brought from Egypt by Mr. F. Girdlestone, of the Charterhouse, and has been kindly lent to the writer. The mode of playing will be seen from the accompanying woodcut. Instead of the lateral orifice peculiar to the modern flute, the upper edge of the tube itself is thinned down, so as to present a sharp circular obstacle to the impinging stream of air. The exhaustive action thus originated, acting on the elastic contents of the tube itself, originates sufficient vibration to produce a loud, though rather loose and windy note. It may be looked on as intermediate between the pandean-pipe, which is a stopped tube excited in the same way, and the ordinary

EGYPTIAN FLUTE.

diapason pipe of the organ, which adds specific mechanism of "foot," "lips," and "languid" to insure the same result. It is somewhat remarkable that the specimen in the British Museum was suspected of being a forgery owing to the absence of the lateral embouchure, until its more modern kinsman made its appearance.

If a mouthpiece be added so as to produce a continuous tone, the second law of Bernouilli can be demonstrated, namely that, (2) if the pipe be open at the opposite end, by increasing gradually the force of the air current we can make it yield successively the primary note and its harmonics, the vibrations being in the proportion of the natural numbers as follows :—

C_1	C_2	G_2	C_3	E_3	G_3	&c.
1	2	3	4	5	6	

(3) If the organ-pipe be closed at the end opposite to the mouthpiece, by a similar process, it yields notes whose vibrations are proportional to the series of natural odd numbers, as follows (X denoting a sound not in the natural scale):—

C_1	G_2	E_3	X	D_4
1	3	5	7	9

The reason for these facts is that air vibrating in an open pipe divides itself into two halves, with a node in the middle, somewhat similar to that in a string speaking its first harmonic, though the motion in the tube is horizontal and that in a string mainly vertical.

The open extremity of a pipe always corresponds to a loop, the air remaining there always at the density of the atmosphere, whereas at the node it is alternately more and less dense than this. In a closed tube the closed end must correspond to a node, and the open end to a loop, so that the entire tube must consist of a whole number of nodal intervals *and a half interval in excess*, which excludes harmonic notes corresponding to even numbers.

The open pipe gives a note corresponding to a wave double, the closed pipe to four times, its own length, as will be more fully detailed in speaking of wave-lengths.

31. The above laws are correct for cylindrical or prismoidal pipes. Conical pipes were shown by Sir Charles Wheatstone to possess the same succession of harmonics as the former, but as the apex of the cone is approached the nodal line moves further upwards towards it, until actual coincidence is established. The greater, moreover, the difference between the diameters of the two ends of conical tubes, the greater the difference between the notes produced; the note of the highest pitch will be produced when the open end is the larger of the two. If the open end is four times the diameter of the smaller, the note produced is an octave below the cylindrical closed pipe; so that from the same tube it is possible to produce two octaves.*

32. The mouthpiece named in par. 30 is the same in principle for all flue-pipes (see Novello's Music Primer, "The Organ," par. 32). A linear slit projects compressed air against the sharpened lower edge of the tube itself. The breaking of the stream of air against the sharp lip has been accepted by Helmholtz and other physicists as sufficient explanation of what occurs. It would seem, however, that the action is in reality more complicated. Schneebeli† drove air rendered opaque by smoke through

* "On the Musical Inventions of the late Sir Charles Wheatstone, F.R.S.," *Proceedings of the Musical Association*, 1876, by Professor W. G. Adams, F.R.S.

† M. Poggendorf's *Annalen*, 1874; quoted in Ellis's translation of Helmholtz's "Sensations of Tone," Appendix XIX.

a movable slit. When it passed entirely outside the pipe no sound was produced, but appeared when the issuing sheet was gently blown on at right angles, continuing when once started until a counter-current was produced by blowing down the upper orifice of the pipe. Little or no smoke penetrated into the pipe. If the sheet of air passed into the pipe entirely there was also no sound, but on blowing into the upper end sound was produced. He concludes that the *Lüft-Lamelle*, or aerial lamina, acts a part analogous to that of the reed in reed-pipes. Hermann Smith has come by independent observations to a similar conclusion, terming the sheet of air an "aeroplastic reed." Schneebeli considers its effect to be condensatory; Hermann Smith, with far greater probability, holds it to be exhaustive, and similar to the common spray-producing apparatus. The tones of the air reed and pipe he believes to be distinct, that of the former being far more acute than the latter, and sometimes capable of coercing it. There can be no doubt that this condition of things exists in the case of the reed fitted with a consonant pipe, for the lower notes of such an instrument as the clarinet reach low into the four-foot octave, whereas the tube itself is hardly two feet long, and without a reed would be entirely unable to produce them.

CHAPTER II.

VELOCITY—REFLECTION—REFRACTION—INTERFERENCE—TONOMETRY.

33. In speaking of wave-motion (par. 2, 3, 4), the question of Velocity was intentionally postponed. It was shown that when any disturbance is produced in an elastic body, whether gaseous, liquid, or solid, it extends in spherical waves. It has been proved by mathematics that the velocity of such a movement is always equal to that which a falling body would acquire in falling through half the height of the modulus of elasticity, which in the case of air would be half the height of the atmosphere if homogeneous, or everywhere of the same density. This velocity can be shown to be the same as that of a long superficial wave.

34. The height of the hypothetical homogeneous atmosphere is 28,000 feet, and a body in falling through half this height would acquire a velocity of 946 feet per second, whereas the actual velocity of sound is 1,090 feet per second at freezing point, and 1,130 feet at the ordinary temperature and pressure. Laplace was the first who suggested that this discrepancy between calculation and observation was due to change of temperature accompanying condensation and rarefaction, although the question had been previously mooted by Newton. From these causes the effective elasticity of the air corresponds to a height of homogeneous atmosphere equal to 40,000 feet.

35. The actual velocity has usually been determined by comparing the inappreciable interval required for the propagation of light with that of a coincident sound. Determinations were made by the French Academy in 1738, by Arago in 1822, and in Holland in the same year. Cannon were fired alternately at two stations several miles apart, and the interval between the flash and the report was noted. The results agreed closely in giving 332 metres, or 1,090 feet. The temperature increase is proportional to the square root of the absolute temperature, or about a foot per second for each degree Fahrenheit. Aqueous vapour, being lighter than air, somewhat increases this velocity. The height of the barometer does not affect it. In gases generally, at the same pressure, the velocities will be inversely as the square roots of their absolute densities.

36. In water, the velocity was measured by Colladon at Geneva in 1826. Two boats were moored in the lake at 13,500 metres apart, one carrying a bell below the surface, the hammer of which was moved by a lever which ignited gunpowder at the moment of striking the bell. In the other boat was an immersed ear-trumpet covered with membrane, by listening through which the conveyed vibration could be compared with the visual appreciation of the flash. The velocity was 1,435 metres per second, at a temperature of 8°·1 centigrade, or 47° Fahrenheit. In solids the velocity has been measured both directly and by indirect methods. Biot examined it in iron water-pipes 951 metres long. The blow of a hammer could be heard at the distant end both through the metal and through the contained air, the former preceding the latter by 2·5 seconds. The time of air-transmission being 2·8 seconds, that of the metal was 0·3, or about nine times as fast. In steel it is still more rapid, having from fourteen to more than fifteen times the speed in air, and in pine or firwood it increases to over seventeen times that velocity.

37. The length of the sound-waves thus propagated has been shown to depend on the rapidity with which the vibrations follow each other (par. 4), and their *frequency* is the number in a second, the increase of which determines elevation of pitch. PERIOD is the reciprocal of frequency, and an absolute measure of pitch. From these data, and the observed rapidity of transmission, the wave-length of any note can easily be determined. In a given medium the wave-length is thus also a measure of pitch, provided the temperature be constant. For in all vibratory movements

$$\lambda = V \times T$$

or the wave-length λ equals the velocity V into the period T Thus for bass C of 32 vibrations, the wave-length

$$\lambda = 1{,}130 \times \tfrac{1}{32} = 35{\cdot}31 \text{ feet.}$$

38. Sound is REFLECTED and REFRACTED according to the same laws as light. To reflection are due the manifold phenomena of echos. A spherical balloon of thin membrane, filled with a heavy gas, such as carbonic anhydride, acts as a condensing lens, and has a definite focus. Echos require a certain distance to separate the returning impression from the original source of sound. Neither of these physical facts has much bearing on the musical aspect of the subject, though Tyndall's curious experiments as to the acoustical opacity of the air, and the consequent transmission of fog-signals at sea, offer good illustrations of both processes. The INTERFERENCE of sonorous undulations furnishes the important department of beats and dissonances, which will be independently treated in the following paragraph.

39. INTERFERENCE of sound-waves occurs when two systems are transmitted through the same matter. If they be similar, and in the same direction, the result is their sum ; if opposite, their difference. If they be equal and opposite the result is zero, or *silence*. Thus, if of two equal sound-waves, one be half a wave-length before the other, their respective motions will neutralise one another, and the individual particles, doubly acted on, will remain at rest. The simplest experimental illustration of this essential fact is given by the tuning-fork, the prongs of which move in opposite directions. If a tuning-fork be struck and rotated on its axis near the ear, four positions will be found in which its note is clearly heard, and four, between these, in which it is inaudible. The four first occur when either of the prongs or either of the flat sides of the fork are towards the ear. The four others are almost at an angle of 45° to these. Here the lines of motion are exactly opposite and of equal strength. If, however, a tube be slipped over one prong without touching it, the sound returns, from the withdrawal of the influence of the antagonising prong. In the case of a tuning-fork the silence caused by interference is permanent. If, however, two sound-waves slightly differing in length be propagated through the same medium simultaneously, the longer wave will have a tendency to gain steadily on the shorter, and periods will occur at which the two mutually reinforce one another, causing an increased amplitude of the oscillation, and consequent increase in the loudness of the sound. These reinforcements are intersected by points at which they interfere with each other, and cause diminution in the amplitude, evidenced by a lessening of the loudness, amounting even to extinction. The rising and falling inflections thus originated are termed BEATS. It will easily be seen that a beat, that is a moment of comparative silence, must occur at each difference of a whole undulation. Each beat is in consequence exactly coincident with the difference of one vibration between the sounding bodies. For instance, if one of two tuning-forks vibrate 256 times in a second, and the other 257, there will be a single beat in each second. The same would occur if the second fork had 255 vibrations. Beats therefore do not at once show which is the sharper and which the flatter of the two sonorous bodies. But, notwithstanding this, they furnish the most accurate and satisfactory mode of determining small differences of pitch, and are so utilised in the process of tuning. *The number of beats in a given time is equal to the difference in the numbers of vibrations executed by the two tones in the same time.* It is usual to count the points of maximum intensity, rather than the intervals of silence, and hence these are commonly designated by the name, although the beat really consists of the pair of phenomena together. The influence of beats in determining the nature

of concord and discord has been materially extended by the researches of Helmholtz, who has shown that they may occur not only between fundamental tones, but also between the harmonics or upper partial tones which almost invariably accompany them: intervals in which they are few or weak being termed concordant; those in which they are many and strong, discordant.

40. Interferences may also occur between waves moving in opposite directions, as, for instance, between a direct and a reflected system. Hence arise what are termed Nodes and Antinodes. The nodes, which have been partially explained previously, are points of the greatest change of density and the least change of place, whereas the antinodes exhibit the least change of density and the greatest of place.

41. Methods of Counting vibrations are clearly essential to the accurate determination and measurement of sound. It has been shown above (par. 5) how intermittent noise in regular period gradually merges into musical tone. Upon this principle the first researches were made. These were followed by optical methods of observation; the latter again by electrical. A computative process was suggested by Scheibler in 1834.

The various methods of Tonometry, as this branch of acoustics has been termed, may be given, in tabular form, as follows:—

I. Mechanical methods	1. Savart's toothed wheel. 2. Cagniard de la Tour's siren. 3. Duhamel's vibroscope. 4. Leon Scott's phonautograph. 5. Perronet Thompson's weighted monochord.
II. Optical methods	1. Lissajous' method. 2. Helmholtz's vibration microscope. 3. Koenig's manometric flames. 4. McLeod and Clarke's cycloscope.
III. Electrical methods	1. Meyer's electrical tonometer. 2. Lord Rayleigh's pendulum experiment.
IV. Computative methods	1. Scheibler's *Tonmesser* with tuning-forks. 2. Appunn's tonometer with free reeds.

The first vague attempt at tonometry originated with Galileo, who noticed that a musical sound could be produced by passing a knife over the serrated edge of a piastre. In 1681 "Mr. Hooke showed an experiment of making musical and other sounds by the help of teeth of brass wheels, which were made of equal bigness for musical sounds but of unequal for vocal sounds."*

42. I. Savart first reduced the system to accuracy. In a solid frame, a wheel, with a given number of teeth in its circumference,

* Birch's "History of the Royal Society," published in 1757; quoted in Tyndall "On Sound," p. 50.

was made to rotate rapidly; a counting apparatus being attached, with the view of recording the rotations in a given time. A piece of card, or a metallic plate, was applied to the passing teeth, which of course received in a second as many blows as the product of the teeth into the rotations. The blows, from being successive, gradually became continuous to the ear, and a low musical note was produced, which rose in pitch with increased rapidity of rotation. The pitch could at any time be compared with a standard, and the revolutions counted by means of a chronometer. A rough estimate could thus be obtained, though the difficulty of insuring perfect equality of rotation precluded anything like accurate determinations.

43. (2) The SIREN, in spite of the quaint inaccuracy of its name,* was a considerable advance upon Savart's wheel. The teeth of the latter are here replaced by coincident openings in two similar circular plates, the one fixed, the other rotating above it, with but slight friction, upon an axis. In the act of rotation similar superposed rings of holes alternately open and close a passage for the wind, issuing in a steady stream through the lower fixed plate. The isolated "puffs" soon unite into a continuous note; rising, as before, with increased rapidity of rotation. At the upper end of the axis is placed a counting apparatus, which can be thrown in and out of gear at will, and the rotations in a given time are noted by a chronometer. It was an apparent afterthought to place the rings of holes diagonally in opposite directions to one another. The plan supplies indeed a motive force, but causes a constant and ill-controlled acceleration. The Double Siren used by Helmholtz is driven by a small electro-motor. It has been materially modified and improved by that physicist, and seems to have done good service in his hands. It is, however, like Savart's wheel, far too inaccurate for the minute determinations now required.

44. (3, 4) The VIBROSCOPE and PHONAUTOGRAPH both aim at a graphical representation of vibration on smoked paper. This is carried round in a spiral direction in front of a tuning-fork, one prong of which is furnished with a light style, which scratches off the black incrustation, in the form of a wavy line, each wave corresponding to a double oscillation. In the phonautograph a membrane, like that of a drum-head, connected with a collecting cavity, replaces the tuning-fork.

45. (5) The best of the early attempts at tonometry was undoubtedly that of Perronet Thompson by means of which his enharmonic organ was tuned. He employed a monochord, the steel string of which, four feet in length, was stretched by a

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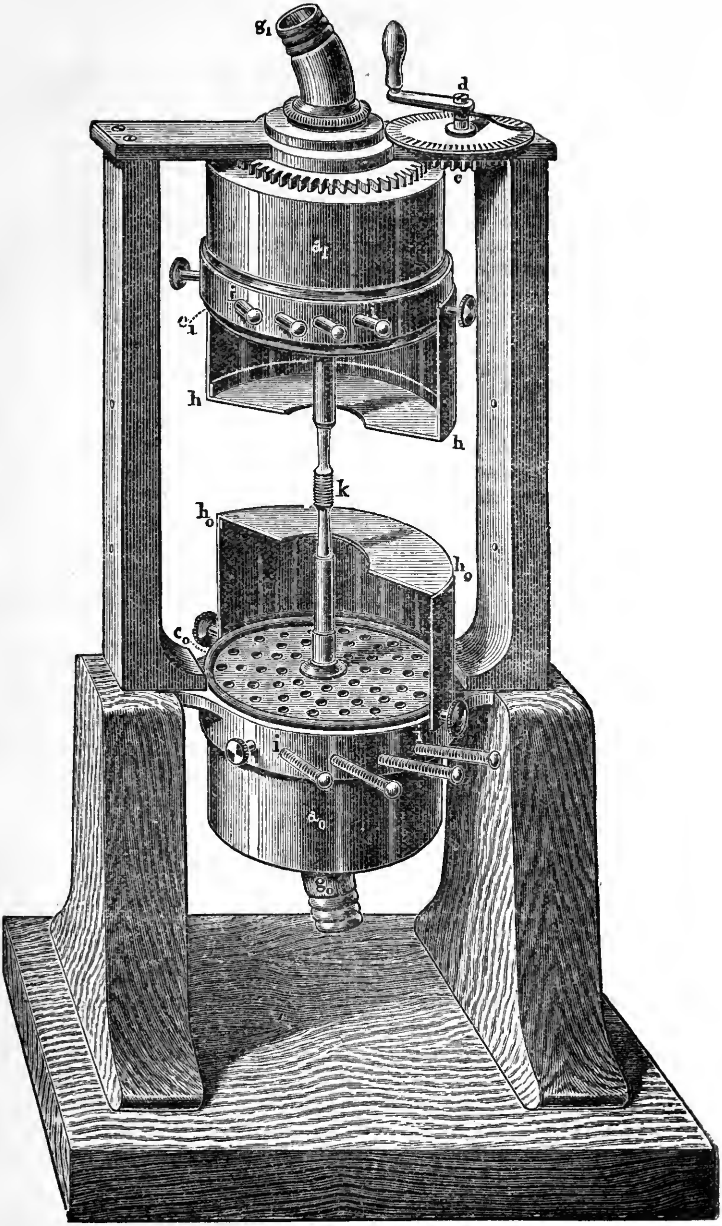
* It is said to have derived its name from its power of singing under water, a gift with which Homer's Σειρῆνες were not endowed.



HELMHOLTZ'S DOUBLE SIREN.

very heavy weight, amounting to 240 or 250 pounds for tenor C, and excited by a resined bow. It was more intended for obtaining the natural division of the scale than for determinations of absolute pitch. But as the frequency of vibration varies as the square root of the stretching weight (par. 11, 12), small errors in the latter produced a much diminished inaccuracy in the former.

46. II. Optical Methods of tonometry appear to be due to Monsieur Lissajous. He attached a mirror to the vibrating end of a vertical tuning-fork, and threw a ray of light reflected from it on to a screen in a darkened room. When the fork vibrates the image moves rapidly up and down, producing a vertical line of light, owing to the persistence of impressions on the eye. If a second fork, with attached mirror, placed horizontally, be made to receive the image from the first, and the ray, after double reflection, be projected on a screen, by the composition of the two harmonic motions very beautiful and symmetrical figures are produced. If the forks be in unison, or bear some simple ratio of vibration to one another, the curve first formed remains unchanged in shape, but gradually decreases in size by the lessening of vibration amplitude; but with the slightest aberration from accuracy, such as almost always occurs in practice, the eye detects progressive changes in the figure, due to differences of pitch far too minute to be perceived by the ear.

47. By a modification of this method, very similar to the vibration microscope of Helmholtz, tuning-forks or other vibrating bodies can be compared with the greatest precision. (2) The object glass of the microscope is affixed to the prong of one fork, and is made to give a real image of a bright point or scratch upon the other; the two forks are placed with their planes of vibration at right angles to one another, as in Lissajous' experiments or in those (3) of Koenig with manometric flames.

48. By far the best form of the optical apparatus is (4) that proposed by Messrs. McLeod and Clarke under the name of the cycloscope. It is impossible within the limits of the present primer to give details of this beautiful instrument, originally intended to determine the speed of machinery,* but the results obtained by it will be adverted to presently.

49. III. The same remark applies to the electrical tonometer of Professor Alfred Meyer, of Stevens's Institute of Technology at Hoboken, in New Jersey, U.S. An induction coil, connected with a seconds pendulum, makes regular perforations in a sheet of smoked paper rotating on a metal cylinder, against which a light style attached to a vibrating tuning-fork is tracing sinuous curves. The number of sinuosities between two such sparks gives the vibration number with considerable accuracy.

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* For the original description see *Proceedings of the Royal Society*, April 1877.

50. Another, and probably even more accurate, method of obtaining absolute pitch has recently been communicated to *Nature* (November 1, 1877), by Lord Rayleigh, who employs a seconds pendulum, an electrical interruptor, and a tuning-fork of 128 complete vibrations in a second.

51. IV. Of Absolute Computative Tonometers, the oldest and best is that of Scheibler, an account of which is given in a work published at Essen in 1834. In the form usually made it consists of sixty-five tuning-forks, beginning at 256 vibrations and rising to 512. Each intermediate fork beats with its neighbours four times in a second. This series has two functions. In the first place it affords an easy and accurate means of ascertaining the pitch of any given note within this octave, which can never be as much as four vibrations away from one of the forks without coming into unison with another. In the second place it can be applied to determine absolute pitch, a determination "which does not require precision of tuning, all that is necessary being to count with sufficient accuracy the number of beats per second between each pair of consecutive forks. The sum of all these numbers gives the difference of frequency between the first fork and its octave, which is thus of course the same as the frequency of the first fork itself."*

52. (2) A more recent instrument of the same kind has been introduced by Appunn of Hanau, preserving the same number of intervals but substituting harmonium reeds for Scheibler's tuning-forks. There can be no doubt that for musical purposes a reed is far superior to a fork. It has a much stronger tone, gives far louder beats, and is permanent in its oscillation instead of rapidly fading away. Unfortunately it is open to errors from which the fork seems free. These have been admirably demonstrated by Lord Rayleigh in the paper just quoted. "It would appear," he says, "that when reed 63 sounds the pitch of reed 64 is raised, the amount of the disturbance being much in excess of what would be expected from the performance of the instrument when tested in other ways." It is much to be regretted that this instrumental error should vitiate the results of Mr. Alexander Ellis's laborious researches "On the Measurement and Settlement of Musical Pitch" recently brought before the Society of Arts.† He stated therein that the French normal diapason A gave 439 instead of 435 vibrations per second, a statement which has been warmly controverted by M. Rudolph Koenig, and which, from the careful observations of Messrs. McLeod and Clarke, followed by those of Lord Rayleigh, appears to be entirely erroneous. The various copies of the French normal pitch are

* Lord Rayleigh in *Nature*, November 1, 1877.
† *Journal of the Society of Arts*, May 25, 1877.

allowed, even by Mr. Ellis, to agree very well with one another, and may be therefore accepted as hardly, if at all, at variance with their inscribed vibration number.

53. STANDARDS OF PITCH will thus be seen to be far more difficult to set up than might have been supposed. When, as in the above case, such a one has been authentically obtained, it is still more difficult to keep it. The first error arises from variations of temperature. Even tuning-forks vary appreciably from this cause. Perronet Thompson showed that a fork, giving middle or treble C at freezing point, flattened by a third of a comma when dipped in boiling water. Professor Meyer found that a fork of 512 vibrations lost 0·7 of a vibration in rising from 60° to 90° Fahrenheit. Professor McLeod made the loss nearly double this amount. These discrepancies are doubtless due to different qualities of steel. All other producers of sound vary infinitely more, with the exception of the harmonium reed, which, though its actual variation with temperature is greater than that of the tuning-fork, has the compensatory advantages named above.

54. Strings are eminently affected by temperature when made of metal, and when made of catgut by moisture also. A steel wire through which a heating current of electricity passes can be made to sink an octave or more in pitch, as was shown by the writer before the Musical Association.*

55. In wind instruments the problem is much more complicated, because in them there is a compensatory action going on. The material of the instrument, especially if it be made of metal, expands with heat, and thus becomes flatter. This occurs when instruments tuned to correct pitch are taken out to hot climates. In colder regions the air passing through them, being the human breath, becomes rarefied by increase of temperature, and the latter action predominates over the corresponding enlargement of the metal.

56. Organ-pipes do not indeed vary so much as orchestral instruments, being played with wind at ordinary temperatures; but in our climate the difference often ranges from below 32° to above 80° Fahrenheit; the variation is therefore very considerable. This was noticed by Perronet Thompson, who introduced a temperature regulator into his enharmonic organ, which acted on the principle of shading the mouths of the speaking pipes more or less. The smaller pipes are most affected, and become sharper than those below them.

57. Reeds follow a somewhat different course, because the vibrator, of which the dominance is great, expands in one direc-

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* *Vide* paper "On Standards of Musical Pitch," *Proceedings of the Musical Association*, 1875-76.

tion, causing flattening, while the expansion of the air acts in the opposite sense, causing sharpening. Much of the blame thrown on the reeds in an organ is due to the alteration of the flue-pipes. But the influence of moisture, or watery vapour, is singularly large on reed pipes. Free reeds, like those of the harmonium, vary according to the material—brass, steel, or German silver—of which they are made, but, with the exception of tuning-forks, less than any other sound-producers; they are therefore the most practical standards of pitch for general musical, as distinguished from scientific, purposes.

CHAPTER III.

MUSICAL TONE—HARMONICS—CONSONANCE—QUALITY.

58. THE COMPOUND NATURE OF MUSICAL TONE, as influencing the character or quality of sound, had long been known, and indeed followed of necessity from the fact that QUALITY or timbre could not depend on frequency of vibration, which only influences pitch, nor on amplitude, which only affects loudness. It was first clearly shown by Helmholtz that "on exactly and carefully examining the effects produced on the ear by different forms of vibration, we meet with a strange and unexpected phenomenon, long known indeed to individual musicians and physicists, but commonly regarded as a mere curiosity, its generality and great significance for all matters relating to musical tones not having been recognised." The discovery thus made, or at least brought into due prominence, was the law of HARMONIC UPPER PARTIAL TONES. This fundamental principle of music may be accurately stated as follows :—

When any note is sounded on a musical instrument, in addition to the primary tone, there are produced a number of other tones in a progressive series, each note of the series being of less intensity than the preceding. If m *denote the number of vibrations of the primary tone in a given time, the vibration numbers of the whole series will be in the order* m, 2m, 3m, 4m, 5m, 6m, 7m, &c.

Thus, if the primary note be C, the whole series will be, for the first three octaves,—

Ratio	*m*	*2m*	*3m*	*4m*	*5m*	*6m*	*7m*
Note	C_1	C_2	G_2	C_3	E_3	G_3	X
Vibration number	64	128	192	256	320	384	448

We have here three C's, two G's, one E, and a note marked X lying between A_3 and B_3. If the octave above C be sounded with it, the harmonic series produced by C_2 will be, in the first three octaves,—

Ratio	*2m*	*4m*	*6m*	*8m*	*10m*	*12m*	*14m*
Note	C_2	C_3	G_3	C_4	E_4	G_4	X_2
Vibration number	128	256	384	512	640	768	896

again giving three C's, two G's, one E, and one X an octave above the former.

If then the two notes C_1 and C_2 be sounded together, the first three octave harmonics of C_1 will be compounded with the first two octaves of C_2, as follows :—

C_1 1st intensity.
$C_2 + C_2$ 1st and 2nd intensity.
G_2 3rd intensity.
C_3 2nd and 4th intensity.
$G_3 + G_3$ 3rd and 6th intensity.
E_3 5th intensity.
X_1 7th intensity.

59. It is therefore evident that when two notes C_1 and C_2 are sounded together, they produce *Overtones*, *Upper Partial Tones*, or *Harmonics*, in which, besides C's, the note G (the fifth) with its octaves, and the note E (the third) with its octaves, are more nearly related to C than any other notes are.*

Herein lies the physical explanation of par. 64 in Novello's Music Primer, "The Rudiments of Music," which states that "any sound and its octave bear the same name, in accordance with nature, since the two sounds so accord or tune together that they seem to be almost like one sound."

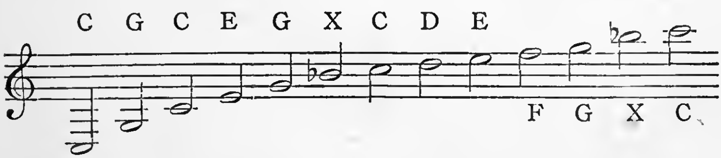
It may be remarked that the effect of the combination of notes differing by an octave is to throw the notes X further back, making them less audible, and bringing out more clearly the relationship of C, E, and G. Now this group of notes—which are actually sounded whenever C, either alone or with any of its octaves is played—forms the MAJOR TRIAD, the first, third, and fifth of the natural scale; their vibration numbers being in the simple ratio of the natural numbers 4, 5, 6.

60. The harmonic series has another most important bearing on music, which has already been adverted to by anticipation (par. 13), but which now may receive its full elucidation.

(1) In the regular division of the sounding string,
(2) By increasing the blast of wind in an organ-pipe,
(3) Or by alteration of the embouchure in brass instruments,

the same order and sequence of sounds is obtained successively as has been here shown to co-exist simultaneously.

(1) The production of harmonics in stringed instruments has been already noticed. (2) In organ-pipes the use of harmonic stops, the consonant tubes of which are made twice their proper length, perforated with a small hole in the middle, and with this a high pressure of wind (see Novello's Music Primer, "The Organ," par. 21), illustrate the same principle. (3) In the French horn and similar instruments nearly the whole harmonic series is utilised in the scale of what are termed "open notes," as follows:—



* For further details see Haughton's "Natural Philosophy," p. 170 *et seq.*, where this subject is treated with great lucidity.

The real foundation note is of course an octave lower than the lowest here given; it is all but impossible to produce with the usual mouthpiece, but can easily be obtained by affixing to the tube some other source of sound, such as a clarinet reed.

61. If the harmonic series be extended to the full range of over five octaves, the seven sounds of the musical scale can be developed out of it in regular succession from the gradual approximation of the constituent ratios. This has been well demonstrated by Mr. Colin Brown, Euing Lecturer on Music at the Andersonian University, Glasgow, as shown on the page opposite, on the note F, where the twenty-fourth, twenty-seventh, thirtieth, thirty-second, thirty-sixth, fortieth, forty-fifth, and forty-eighth harmonics produce a correct enharmonic scale of eight consecutive notes. The harmonics which do not belong to the scale are marked with a cross on the approximate line of the staff to which they belong.

62. It has been shown that C, whenever sounded, introduces E and G. In similar fashion it is possible, without using other notes than these and their octaves or natural representatives, to establish two other major triads, in this manner.

C : E : G	:: 4 : 5 : 6	... Tonic triad.
G : B : D_2	:: 4 : 5 : 6	... Dominant triad.
F : A : C_2	:: 4 : 5 : 6	... Subdominant triad.

B and D_2 standing as third and fifth to G; A and C_2 as third and fifth to F. For if G or F were sounded alone, or with octaves, they would respectively introduce B—D_2 and A—C_2.

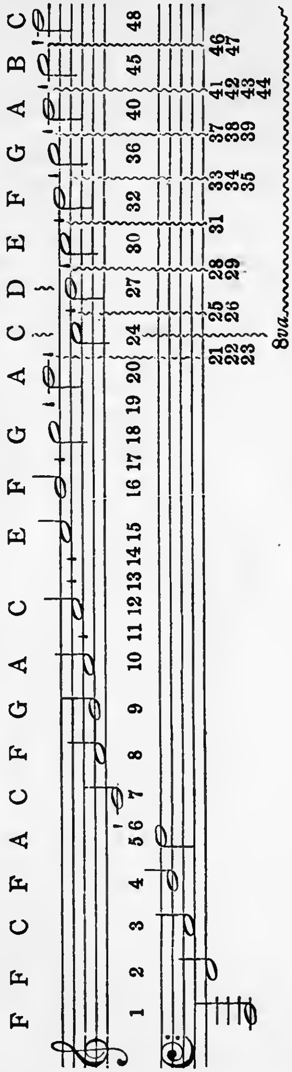
63. The sensation of pleasure felt on sounding certain notes together depends therefore on the agreement of the harmonic sounds necessarily accompanying them, and on the simplicity of the succession of impulses produced on the ear by both primary and secondary tones. There is only one form of vibration which gives rise to no harmonic upper partial tones. This is peculiar to pendulums and tuning-forks, and may thence be called simple pendular vibration.

"A compound," says Helmholtz, "has, properly speaking, no single pitch, as it is made out of various partials having each its own pitch. By the pitch of a compound tone we mean the pitch of its lowest or prime tone. Every musical tone in which harmonic upper partial tones can be distinguished may be considered in itself as a chord or combination of various simple tones."*

64. Sympathetic Resonance affords the method by which the laws just named, forming the foundation of musical theory, can be tested experimentally. It is a well-known fact that any oscillatory or undulatory motion can be reinforced by a number of small consecutive impulses which coincide in time with the original undulation. The simplest instance is that of the child's

* *Vide* Ellis's translation, p. 35.

swing, where the swinger voluntarily employs muscular force to counteract the effect of friction and to prevent the diminution



Development of Scale from Harmonic Series.

of the movement. It is also recognised that the measured tread of a regiment on march crossing a suspension bridge is competent to impress on the latter such vibration as may endanger its safety, unless the individual soldiers composing it be allowed to fall out, and to walk each at his own independent pace. Large church bells may be set in motion by periodical application of a force hardly competent to move them when singly applied. Even the massive tower in which bells are hung may be made sensibly to oscillate by the periodic action of a well-ordered peal. In the latter case it is obviously the multiplication of small efforts derived from the ringers, transmitted to the bells, and from them to the masonry itself, which produces such large results from forces originally small. The essential magnifying power is periodicity. What is true of slow mechanical vibrations holds perfectly for the more rapid oscillations of sound. Any elastic body which is so fixed as to be able to continue in vibration for a definite time when once started can also be made to vibrate sympathetically by agitations of small amount having a periodic time corresponding to its own. Thus every sonorous body is also able to produce CONSONANCE.

65. The simplest mode of demonstrating this fact is to lift off the dampers of a pianoforte by means of the pedal, and to sing some note into its cavity. The note will be heard to echo back from the instrument. Any other instrument besides the voice can be used as a means of exciting the sympathetic vibrations; and other vibrators may thus be excited, but with a slowness proportional to their mass. Membranes are especially sensitive to this method of excitement, and so are columns of air contained within partially closed cavities. The latter possess proper notes of their own, to which, and to which alone, they consonate. If the two be combined, as by stretching an elastic membrane over the larger orifice of a receiver, a very delicate test is obtained, the prime tone of the membrane, slightly altered by that of the sympathetically vibrating mass of air in the receiver, alone being audible. Of this character were the RESONATORS first employed by Helmholtz in his experiments. He afterwards found that greater sensitiveness was secured by omitting the membrane and employing only a globular or cylindrical receiver with a larger opening communicating with the external air, and a smaller, drawn out to a conical point, so as to be inserted into the ear passage. The tympanic membrane, or drum of the ear, itself served instead of an artificial membrane. If such a resonator, tuned to a particular note, be held to the ear, "any one, even if he has no ear for music, or is quite unpractised in detecting musical sounds, is put in a condition to pick the required simple tone, even if comparatively faint, from out of a great number of others." *

66. With a properly tuned series of such resonators extensive observations were made, which have resulted in the great advance of knowledge which has been detailed above. "Hence," says

* Helmholtz, *op. cit.* p. 69.

this distinguished observer, "each single simple tone can be separated from the composite mass of tones by mechanical means, namely by bodies which vibrate sympathetically with it. Hence every individual partial tone exists in the compound musical tone produced by a single instrument just as truly and in the same sense as the different colours of the rainbow exist in the white light proceeding from the sun or any other luminiferous body. . . . We must not therefore hold it to be an illusion of the ear, or mere imagination, when in the musical tone of a single note we distinguish many partial tones; as I have found musicians inclined to think, even when they have heard those partial tones quite distinctly with their own ears. If we admitted this, we should have also to look upon the colours of the spectrum, which are separated from white light, as a mere illusion of the eye." *The real outward existence of partial tones in nature can be established at any moment by a membrane which throws up sand by sympathetic vibration.*

67. Success in the observation of upper partial tones depends rather on a power of mental abstraction than on musical training. The uneven partial tones, such as fifths, thirds, and sevenths, are easier to hear than the even, the twelfth above the prime being the easiest. It is advisable to sound the note you wish to distinguish gently, just before producing the musical tone you wish to analyse.

68. It being thus demonstrated that the character of musical tones is due to their composite nature, an easy explanation of the different QUALITY possessed by various instruments is open to us. This is the chief æsthetical result of Helmholtz's great discovery. He showed that, whereas a few sources of sound may be considered simple—such, for instance, as a tuning-fork attached to a resonance box, a large stopped diapason pipe blown very gently, and the ordinary flute—others differ greatly in the number, variety, and intensity of their upper partials. He not only proved this by an analytical process, with the assistance of resonators, as above described; but he was able to proceed to the converse demonstration, and to build up a characteristic compound tone from its individual components. He used for this purpose a complicated instrument formed of many tuning-forks kept in vibration by means of electricity. Each fork was furnished with a resonance tube, the orifice of which could be opened or closed at will, thus increasing or diminishing the force of any particular component. He showed that the oboe and bassoon have proper tones, the same as those of open tubes of the same length, and corresponding to open organ-pipes. They give, by an increase in the force of the wind, the octave, twelfth, and second octave in succession.

69. The clarinet, with a cylindrical tube, has proper tones corresponding to the third, fifth, seventh, &c. partial tones of

the fundamental note. In this respect it resembles a closed organ-pipe. By forcing the wind it rises to the twelfth at once, and then to the major third above the next octave.

70. In the free reed of the harmonium there can be heard, even with unassisted ears, a long series of strong partial tones up to the sixteenth or twentieth; and even above these there are many higher, which it is impossible to distinguish from their lying so close to one another. To this cause is due the harsh and unmusical character of free reed instruments.

71. By far the most important result, however, of Professor Helmholtz's researches in this direction was the theory of Vowel Sounds in the human voice. It is well known that on the same musical note a number of characteristic modifications can be superinduced which, even in ordinary conversation, are competent to distinguish individuals from one another, to discriminate different nationalities, to give an indication of the place of birth, and generally to alter the same fundamental tone into an infinite number of easily perceived varieties. The chief and most essential of these are the various vowel sounds. Upon them Willis made valuable observations, which were followed out by Wheatstone. It may be easily shown that the foundation tone is given by the larynx. This is found to consist of a very long series of partials belonging to a compound musical tone. With resonators, and a powerful bass voice, they can be recognised up to the sixteenth. Each partial would probably decrease in force with rise in pitch, but for the resonance of the cavity of the mouth. If, however, this cavity be altered by the lips and tongue, some partials should be reinforced, and others damped. From observations with resonators such appears to be the fact. "The first six or eight partial tones are clearly perceptible, but with very different degrees of force according to the different forms of the cavity of the mouth, sometimes screaming loudly into the ear, at others scarcely audible."*

72. The importance of investigating the resonance of the mouth being thus established, it was examined by means of tuning-forks of different pitches held before it. The cavity, being under the influence of the will, can be made to coincide with any fork, and thus to discover what shape it must assume for a determinate pitch. The result was found to be that "the pitch of strongest resonance of the oral cavity depends solely on the vowel for producing which the mouth has been arranged, and alters considerably for even slight alterations in the vowel quality, such, for instance, as occur in different dialects of the same language. On the other hand, the proper tones of the cavity of the mouth are nearly independent of age and sex, the resonance being generally the same in men, women, and children. The want of space in

* Ellis's translation of Helmholtz's "Sensations of Tone," p. 156.

the oral cavity of women and children can be easily replaced by a greater closure of its opening, which will make the resonance as deep as in the larger oral cavities of men."

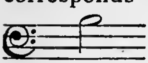
73. The vowels were divided by Du Bois Reymond into three classes; the first of which is represented by the broad A as in *father*, running on into O in *more*, and OO as in *poor*. The second comprises A, E, and I, which have each a higher and a lower resonance tone, the deeper proper tones sinking and the higher ones rising as we pass from the first to the last of these. The third series from A, through the modified German Ö, or the EU of the French language, passes on to Ü, corresponding nearly to the French *u* as in the word *pu*.

The tuning of the mouth to different pitches for the different vowels was first discovered by Donders, and incompletely by older observers. For fuller details Helmholtz's work must be referred to, but a general expression for the *German vowel sounds* in musical notation is given in that work as follows:—

According to the experiments of Willis, very short cylindrical tubes attached to reeds gave I; then, increasing the length of the tubes, E, A, and O were successively produced, up to U, the tube for which exceeded a quarter of a wave in length.

Speaking generally, the deepest pitch is that belonging to the vowel sound expressed in English by *oo* as in *moon*, and the highest to *ee* as in *screech*.

According to Koenig* the notes of strongest resonance for the vowels *u*, *o*, *a*, *e*, *i*, as pronounced in North Germany, are the five successive octaves of B flat, beginning with that which corresponds to the space above the top line of the bass clef



Willis, Helmholtz, and Koenig all agree as regards the note of the vowel *o*, which is very nearly that of a common A tuning-fork. They are also agreed as to the note of *a* as in *father*, which is an octave higher.

* *Comptes Rendus*, 1870; quoted in Deschanel's "Natural Philosophy," p. 858.

CHAPTER IV.

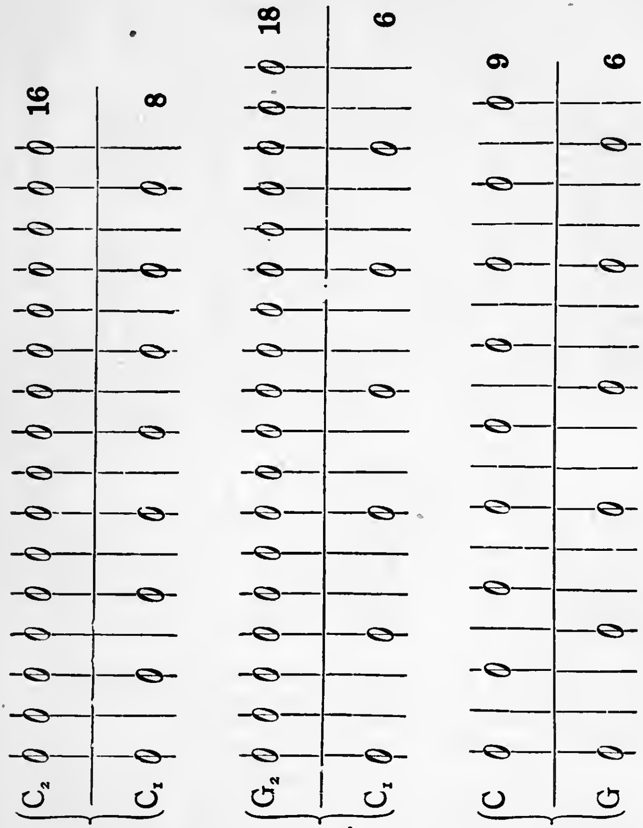
CONCORD AND DISCORD—RESULTANT TONES.

74. It has been already shown that the reproduction of a given sound in the octave above or below amounts to a more or less complete repetition of the same compound series of tones as is elicited when similar notes are struck. The two are "almost like one sound" ("Rudiments of Music," par. 64), and hence the combination is closely allied to unison, the ratio between the two vibrations being the simplest possible after that of identity, namely 1 : 2. But, besides this primary relation, there are several others, which, when produced together, leave a pleasing and satisfied impression upon the cultivated ear. They have therefore been termed Concords. These are the combined octave and fifth, or twelfth, = 1 : 3; the fifth, = 2 : 3; the fourth, = 3 : 4. Somewhat below these in smoothness of effect, but still pleasant, are the major third, = 4 : 5; the minor third, = 5 : 6; the major sixth, = 3 : 5; and the minor sixth, = 5 : 8. All other intervals, with the exception of the harmonic seventh, which is not used in music, are considered discordant.

75. The chief cause of pleasure in consonant intervals depends doubtless on the coincidence of harmonics, as has been already shown; but the important element of simplicity in succession of impulses produced on the ear is not to be neglected. The diagrams on the opposite page, modified from those constructed by Dr. Haughton, well illustrate the fact.

76. As on the one hand coincidence of impulse produces consonance, so the production of beats is at the root of dissonance. These, by the observation of which accurate tuning can alone be accomplished, increase in unpleasant effect up to about 33 in a second, after which the harshness diminishes by their merging into a continuous note. It is not, however, impossible for notes at a distance apart to produce beats. Such phenomena accompany octaves, fifths, and other intervals when slightly false. They also increase in rapidity with augmented error in the interval. It is obvious that they must be due to some harmonic or upper partial common to the two beating notes. For instance, referring to Diagram III., where the fifth is graphically represented, the third impulse of the note C should correspond with

the fourth of G if the interval be accurate; but, if it be not, such a beat would necessarily be the result. Beats therefore are always due to imperfect unison, whether of fundamentals or of upper partials. If a fifth be falsified so as to give the ratio 200 : 301



Diag. I. Octave. II. Twelfth. III. Fifth.

there will be two beats to every 200 vibrations of the lower note. The upper partial tones which beat together are therefore 600 and 602. Intervals such as the unison, octave, twelfth, fifth, and indeed that from any note to one of its natural harmonics, can be tuned so as to be perfectly free from beating. The third, fourth, and sixth can, however, be only partially divested of the results of interference, and are therefore considered as imperfect concords. If C of 256 and E of 320 vibrations be sounded together, the interval being a major third, = 4 : 5, the first harmonics of 4 will be

4—8—12—16—20—24—28—32—36

those of 5

5—10—15—20—25—30—35—40—45

It will be easily seen that a difference of unity will exist between several. Omitting the two primes, these occur between 15 and 16, 24 and 25, and 35 and 36. As 256 is = 64 × 4 and 320 = 64 × 5, the number of beats per second will be 64, and the result to a limited extent discordant.*

77. COMBINATIONAL or RESULTANT TONES occur when two notes are sounded together under certain circumstances. They are of two kinds, termed respectively by Helmholtz *Difference Tones* and *Summation Tones*. The former has, as the name implies, a vibration frequency which is the difference, the latter one which is the sum, of the frequencies of their components. Resultant tones may arise from primary or upper partial tones alike. The first are known under the name of the Italian violinist Tartini, as "Terzi suoni" or as Tartini's tones. The summation tones were discovered by Helmholtz. The law that oscillatory motions of elastic bodies are the exact sum of the individual motions produced by each separate source only holds good where the vibrations are infinitely small; if, however, two simple tones sound loud enough to make the excursions of the particles of air bear a sensible ratio to the wave-length, a third tone is produced, having for its vibration number the *difference* of the vibration numbers of the generators.

78. When the generators are less than an octave apart, the difference tone is heard with the greatest ease, because it is deeper than either generator. The following are those which accompany the ordinary concordant intervals:—

Octave, Fifth, Fourth, Major third, Minor third, Major sixth, Minor sixth

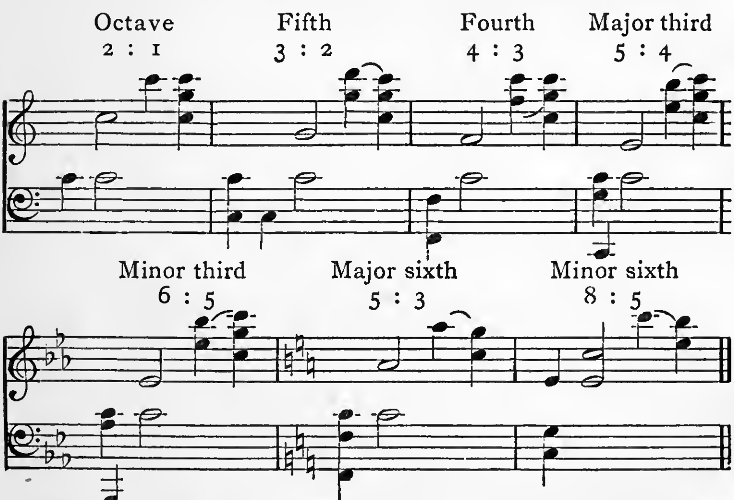
* Deschanel's "Natural Philosophy," p. 862.

79. The *summational* tones are weaker, and by their nature always higher than their generators. The following is the series for the simple interval:—

In the last two cases the summation note is intermediate between those given. Many of them are very inharmonic to their generators. Fortunately they are very weak, and only distinct on the siren.

80. Difference tones were formerly thought to be subjective, and produced in the ear itself, and were supposed to result from the coalescence of beats. This explanation, however, does not account for summation tones; and, moreover, the objective existence of such sounds may be proved by consonant membranes or resonators. In some cases beats and difference tones can both be heard simultaneously. Beats may occur between resultant tones.

Differentials and Upper Partials of Intervals.*



The notes of the interval are represented as minims, the differentials as crotchets; the second differentials to the left of the larger notes.

* From Curwen's "Musical Statics."

81. It is by beats and differentials that some consonant intervals are rendered far more precise and definite than others, and are therefore far more valuable for tuning purposes. Even in simple qualities of tone the octave will be seen by the figure to be defended by a differential which beats with the lower element. The fifth is only guarded by secondary differentials, and the fourth by the same. But when partials as well as differentials come into play the definiteness becomes much more marked.* The octave, besides the differential just named, is guarded by a second partial. The fifth has a second and third partial in unison, and two secondary differentials to protect it. These three, though quite competent to produce sensible roughness, even with slight flattening, are far less powerful than the defences of the octave. On the other hand the fifth has a partial dissonance of a third against a fourth partial, though they are at a remote distance, and contain a considerable interval between them. The fourth has a dissonance exactly where the fifth is strong in its partials. It is essential to the interval that the second and third partials should beat. The only defence which the fourth has is in one of its secondary differentials. The major third, minor sixth, minor third, and major sixth, like the fourth, are all only defended by a secondary differential. They all have partial dissonances, but only the sixths have beating partials of equal loudness with those of the fourth. The major third and its inversion have a closer and stronger dissonance than the minor third.

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* For fuller details and some excellent diagrams see "A Tract on Musical Statics," by John Curwen.

CHAPTER V.

THE SCALE AND TEMPERAMENT.

82. It has been shown that if any note which may be represented by C be played on a musical instrument it introduces, by the harmonic law, two other allied notes, E and G, the vibrations of which stand to those of the first in the simple ratio of 4 : 5 : 6, and form the harmonic triad. Similarly, if G, thus found, be taken as the basis of a triad, it will be followed by B, D_2, bearing the same relation. We should then have the following scale :—

	C		D		E		G		B		C_2
	1		$\frac{9}{8}$		$\frac{5}{4}$		$\frac{3}{2}$		$\frac{15}{8}$		2
	First		Second		Third		Fifth		Seventh		Eighth
Intervals		$\frac{9}{8}$		$\frac{10}{9}$		$\frac{6}{5}$		$\frac{5}{4}$		$\frac{16}{15}$	

the fractions representing the ratios of the vibrations of each note to that next below it.

But it is obvious that the spaces between E and G, as well as the space between G and B, require filling up. D has been suggested as the basis of a new triad, but this note gives very complex results. If, however, C_2 be taken as the upper element of a third triad, the two lower members of which would be F and A, we get an $A = \frac{5}{3}$ and an $F = \frac{4}{3}$, with which we can complete the scale of eight notes with the following intervals and vibration numbers, *m* representing that of the foundation note :—

	m		$\frac{9}{8}m$		$\frac{5}{4}m$		$\frac{4}{3}m$		$\frac{3}{2}m$		$\frac{5}{3}m$		$\frac{15}{8}m$		$2m$
	C		D		E		F		G		A		B		C
Intervals		$\frac{9}{8}$		$\frac{10}{9}$		$\frac{16}{15}$		$\frac{9}{8}$		$\frac{10}{9}$		$\frac{9}{8}$		$\frac{16}{15}$	

83. Here we have three unequal intervals only employed, which are termed respectively,—

Major tone	$\frac{9}{8}$
Minor tone	$\frac{10}{9}$
Major semitone	$\frac{16}{15}$

This forms a sufficient and satisfactory scale for a single key. But as it is possible to take any other note besides C as the foundation of a scale, terming it the key-note, it becomes necessary to interpolate intermediate sounds between those thus found, so as to preserve the same rotation of intervals. These are five in number, situated between the larger intervals, or whole tones. They are not given new names, but termed the Flats or Sharps of the sounds between which they lie.

It may here be noticed that the difference between the major and minor tones is not without importance. This difference may be obtained by inverting one fraction and multiplying it into the other :—

$$\frac{9}{8} \times \frac{9}{10} = \frac{81}{80} = \text{Comma},$$

as this computational interval is termed (see par. 86). Another fractional difference may also be adverted to in this place. The major third from C to E is given above as $= \frac{5}{4}$ and the fifth as $\frac{3}{2}$. If these be divided into one another the difference $= \frac{6}{5}$, which is termed a minor third. Now $\frac{5}{4}$ exceeds $\frac{6}{5}$ by $\frac{25}{24}$, as above.

$$\frac{5}{4} \times \frac{5}{6} = \frac{25}{24} = \text{Minor Semitone}.$$

84. We thus obtain two semitones of different size, corresponding to the two tones just named. The interpolated flats and sharps may be conveniently tuned to this second interval by altering the vibration number in the given proportion. We have thus the usual twelve notes of the scale termed chromatic, constructed on the simple plan that a note is sharpened by increasing its vibrations in the proportion 25 : 24, or flattened by diminishing them in the ratio 24 : 25. If all the notes of the simple scale be thus treated we obtain twenty-one to the octave which are of sufficient importance to deserve tabulation.

TABLE OF TWENTY-ONE NOTES TO THE OCTAVE.*

	Interval	No. of Vibrations	Ratios
C ...	First ...	1·0000	1
C♯ ...	... ...	1·0417	$\frac{25}{24}$
D♭ ...	... ...	1·0800	$\frac{27}{25}$
D ...	Second	1·1250	$\frac{9}{8}$
D♯ ...	... ...	1·1719	$\frac{75}{64}$
E♭ ...	... ...	1·2000	$\frac{6}{5}$
E ...	Third ...	1·2500	$\frac{5}{4}$
E♯ ...	... ...	1·3022	$\frac{125}{96}$
F♭ ...	... ...	1·2800	$\frac{32}{25}$
F ...	Fourth...	1·3333	$\frac{4}{3}$
F♯ ...	... ...	1·3888	$\frac{25}{18}$
G♭ ...	... ...	1·4400	$\frac{36}{25}$
G ...	Fifth ...	1·5000	$\frac{3}{2}$
G♯ ...	... ...	1·5625	$\frac{25}{16}$
A♭ ...	... ...	1·6000	$\frac{8}{5}$
A ...	Sixth ...	1·6666	$\frac{5}{3}$
A♯ ...	... ...	1·7361	$\frac{125}{72}$
B♭ ...	... ...	1·8000	$\frac{9}{5}$
B ...	Seventh	1·8750	$\frac{15}{8}$
B♯ ...	... ...	1·9531	$\frac{125}{64}$
C♭ ...	... ...	1·9200	$\frac{48}{25}$
C ...	Eighth...	2·0000	2

* Professor Haughton's "Natural Philosophy," p. 181.

It will be observed that E sharp is higher than F flat, and B sharp than C flat, but the notes are all really distinguishable.

Taking in succession all the other naturals as key-notes, we could construct on each a similar scale of twenty-one, or 141 in all, of which many indeed would be identical, but of which about 100 would remain distinct. This number would therefore be needed if every possible key were to be exact.

The various methods of surmounting, or rather compromising, this difficulty are termed TEMPERAMENTS, and will be considered presently (par. 86).

85. MINOR SCALE.—It was shown in par. 83 that the harmonic triad, consisting of the ratio 4 : 5 : 6, may be broken up into two intervals, denoted respectively by the fractions $\frac{5}{4}$ and $\frac{6}{5}$, which are termed *major* and *minor* thirds. These unequally divide the containing fifth, the ratio of which is the product of these fractions, or $\frac{3}{2}$. In the major scale given above the major third precedes, and is followed by the minor. But if they be transposed, and the minor third taken first, we entirely alter the musical character of the scale, and produce an essentially different sensorial or emotional effect: whereas the major scale has a cheerful and exciting tendency, the minor, to most if not to all hearers, is melancholy and pathetic. The altered position of the component notes, moreover, still further complicates the constituent ratios, and renders the question of temperament even more arduous. The scale thus formed has the ratios as follows:—

C	D	E♭	F	G	A♭	B♭	C
1	$\frac{9}{8}$	$\frac{6}{5}$	$\frac{4}{3}$	$\frac{3}{2}$	$\frac{8}{5}$	$\frac{9}{5}$	2

in which the alteration of the three notes E, A, and B has been denoted by affixing to them the sign of flattening. Or, without altering the pitch of individual notes, a key-note may be assumed a minor third below that of the corresponding major scale; A, for instance, instead of C, and so on (see "Rudiments of Music," par. 170-74).

86. TEMPERAMENT.—It will already have become apparent to the reader that there is an obvious lack of arithmetical agreement between the various intervals as represented fractionally. The cause of this lies deep in the nature of numbers, and is well expressed by Mr. Ellis. "It is impossible," he says, in an appendix to his translation of Helmholtz's work, "to form Octaves by just Fifths or just Thirds, or both combined, or to form just Thirds by just Fifths, because it is impossible by multiplying any one of the numbers $\frac{3}{2}$ or $\frac{5}{4}$ or 2, each by itself, or one by the other, any number of times, to produce the same result as by multiplying any other one of these numbers by itself any number of times." The physical fact may be otherwise stated by saying that the octave

and the fifth are incommensurable just as are the diameter and circumference of the circle.

The simplest way of representing this incommensurability is to take a case. If the octave be divided into twelve equal semitones, the fifth ought to be seven of these; but it was found out very early in the history of music that a fifth is a little more than seven. It is about 7·01955. Consequently, taking twelve of these fifths, they give rather more than seven octaves. They do not return to the corresponding octave of the starting note. The difference or departure is the above figure multiplied by 12, or 0·23460 of a semitone. This old discovery is generally attributed to Pythagoras, and the figure 0·23460 is termed the "Comma" of Pythagoras. Whether Pythagoras deserves the credit of the discovery, or whether he imported it from Egypt, is matter of doubt; but, at any rate, the Greeks knew of the monochord, of the ratios to be derived from it, and of the divisions of the scale. Euclid wrote a work called the "Sectio Canonis," or the Division of the String, which enters into full details. The third of the Greek scale was made by four fifths taken upwards, and is still called a Pythagorean third. In the same way six major tones exceed an octave by the Pythagorean comma.

It should be distinctly noted that this discrepancy is a law of nature, not inherent in any particular system or method, and entirely beyond man's control.

87. Temperament may be defined as *the division of the octave into a number of intervals such that the notes which separate them may be suitable in number and arrangement for the purposes of practical harmony*. The possibility of any other division than that recognised in the ordinary piano and harmonium will be new to many readers; for the usual form of keyed instrument is so engraven on our minds that most persons are unaware that any other arrangement exists. The common instrument has of course its own system of temperament, one that, though not the oldest, is certainly the simplest, and which is usually termed equal.

88. *Equal Temperament* aims at dividing the octave into twelve equal parts or semitones. If it so happened that the octave could be divided thus, and the other intervals, such as the fifth and third, retained in tune, it would be a great boon. Unfortunately nature has not so ordained it.

89. The attempts to remedy this inherent incommensurability of the musical scale have been numerous and varied, some dating back to ancient times, others of very modern construction. Their varieties may be given best in a tabular form. They have chiefly been applied to keyed instruments such as the organ, piano, and harmonium, where their necessity is most felt.

1. Systems retaining the ordinary keyboard.
   a Unequal or mean-tone temperament.
   b Equal temperament.
2. The ordinary keyboard with additional keys.
   a Handel's Foundling organ.
   b The old Temple organ.
   c The digitals of the concertina.
3. Additional keyboards.
   Helmholtz's harmonium with Gueroult's modifications.
4. Additional keys and keyboard.
   Perronet Thompson's enharmonic organ.
5. The ordinary keyboard with combination stops.
   Mr. Alexander Ellis's harmonium.
6. Entirely new arrangement of keyboard.
   a Poole's system.
   b Bosanquet's generalised keyboard.
   c Colin Brown's voice harmonium.

90. (1, *a*) The old unequal or MEAN-TONE SYSTEM was an attempt to get the more common scales fairly accurate, leaving those less needed out of account, the most faulty being termed "wolves." There was a consequent condition in dealing with this tuning that the player should limit himself to a prescribed circle, and should never modulate into forbidden keys. The temperament had many merits, and some organists even now prefer it to the equitonic system. Its principle is as follows.* If we take four exact fifths upwards they lead to a third a comma sharper than the perfect third. If then we make each of the four fifths one-fourth of a comma flat, the resulting third is depressed a whole comma, and coincides with the perfect third. This is the rule of the mean-tone system. It is so called because its tone is the arithmetic mean between the major and minor tones of the diatonic scale. It can be traced back to two Italian authors of the sixteenth century, Zarlino and Salinas, from which time it spread slowly, and about 1700 was in universal use. It was employed by Handel and his contemporaries, and kept its ground in this country until within the last few years. Many organs were till lately tuned on this plan, and some, such as that in St. George's Chapel, Windsor, still remain. The change from this to the equal temperament is generally supposed to be due to the influence of Bach, though Mr. Bosanquet, in the work above quoted, adduces some strong evidence to the contrary. The differences of the old and equal systems, and their respective departures from just intonation, may be seen in a compact form from an abbreviation of Ellis's table as follows :—

* "An Elementary Treatise on Musical Intervals and Temperament," by R. H. M. Bosanquet.

Note	Old	Just	Equal
C	30,103	30,103	30,103
B	27,165	27,300	27,594
A	22,320	22,185	22,577
G	17,474	17,609	17,560
F	12,629	12,494	12,545
E	9,691	9,691	10,034
D	4,846	5,115	5,017
C	0	0	0

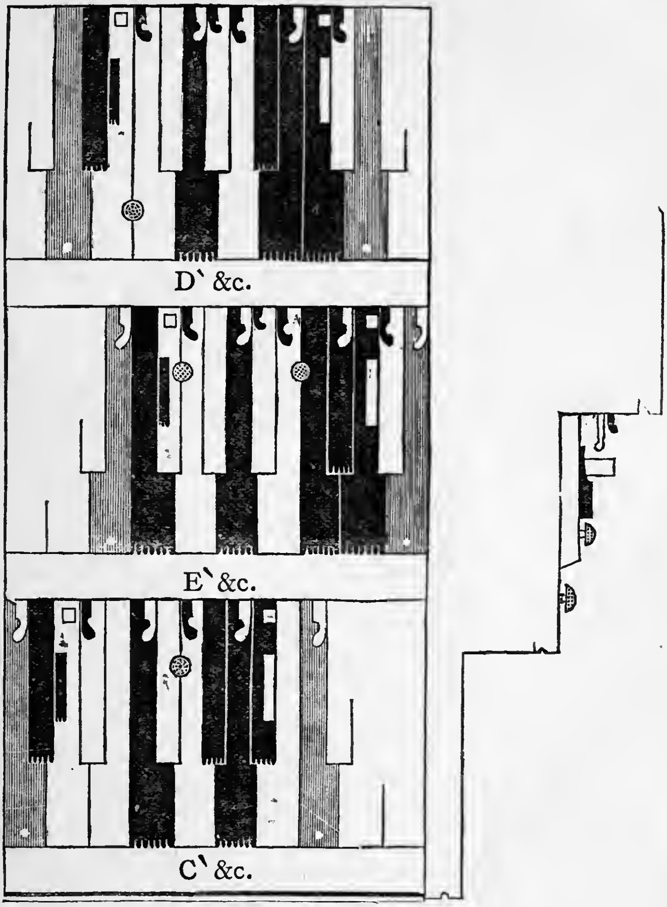
91. (*b*) According to the EQUAL TEMPERAMENT the octave is divided into twelve perfectly similar intervals, seven of which are taken for the fifth, although its real measure is $7\frac{1}{51}$ of these. It is thus somewhat flattened, from 17,609 to 17,560, or the interval termed a *Schisma* = 49, though less so than in the older system, which lowers it to 17,474, as will be seen from the table. On the other hand the third is far too sharp, 10,034, or nearly two-thirds of a comma, instead of 9,691 as it stands correctly in both the other columns. The sixth, moreover, is rendered extremely sharp in equal temperament, namely 22,577, *or eight schismas*, as against the true 22,185. The seventh is flattened in the old *more than two schismas*, and considerably sharpened in the equal method, by exactly six schismas. The fourth of the scale is less altered in proportion to its sensitiveness, being raised rather more than two schismas in the old, and only one in the equal system. The second of the scale stands in a peculiar position, being a double note. The old temperament places it about half-way between its grave and acute forms, whereas the equal method removes it nine schismas above the grave form, thus constituting the largest departure from accuracy to be met with.*

92. (2, *a*) Even as early as the time of Handel the advantage to be derived from additional keys was obviously appreciated, for it is known that he presented to the Foundling Chapel an organ thus furnished. (*b*) The original organ in the Temple Church, built by Father Smith in 1688, possessed fourteen sounds to the octave instead of twelve, the A♭ and G♯ as well as the E♭ and D♯ being distinct and divided.† The keys themselves were split across in the middle, the back halves rising above the front portions, so that the finger could be placed on either at the player's discretion. The range of good keys on the unequal system was thus materi-

* See Curwen's "Tract on Musical Statics," pp. 11, 103.

† (*c*) The same contrivance has been applied to the just English concertina, which is tuned to the mean-tone temperament, with duplicate studs for D♯—E♭ and G♯—A♭.

ally extended. (4) The device of additional keys was, however, carried to its fullest development by Colonel Perronet Thompson in his enharmonic organ, which may still be seen at the South Kensington Museum. He used the large number of seventy-two



PERRONET THOMPSON'S KEYBOARD.

to the octave, which were further distributed on three different key-boards, but which also differed among themselves in colour, shape, appearance, and in name. Besides the ordinary digitals there were others termed *Flutals*, *Quarrills*, and *Buttons*. By this means, though still retaining the ordinary arrangement of the keyboard, he was enabled to produce accurately twenty-one scales with a minor to each of them. He employs the cycle of fifty-three sounds, of which he uses about forty, the full cycle being discontinued at a certain point.

(3) The difficulty of adding new sounds without undue mechanical complication has been attacked in a different way by Helmholtz. The keyboards are in this case increased to two, so as to obtain twenty-four instead of twelve notes to the octave. They are of half the usual depth, placed one above the other, as in the organ. This has always seemed to the writer a practical and simple system. The instrument made for Helmholtz was so tuned that all the major chords from F♭ to F♯ could be played on it. On the lower manual were the scales from C♭ major to G, and on the upper those from E♭ major to B major. To modulate beyond B major on one side and C♭ major on the other it was necessary to make the enharmonic change between these two notes, which perceptibly alters the pitch by the interval of a comma, $\frac{81}{80}$. The minor modes on the lower manual were B or C♭ minor, on the upper D♯ or E♭ minor.

The same idea has been carried out with slight variation in an instrument shown at South Kensington, namely Gueroult's modification of Helmholtz's harmonium, of which the following is the maker's own description.

This instrument has a front and back keyboard, each divided into twelve semitones, like that of a piano, and each possessing five octaves. They are both tuned to true fifths, but the back keyboard is throughout a comma flatter than the front, which is on the normal diapason. The black keys on each keyboard therefore do duty for a flat and a sharp, but not in the same series. On the front keyboard, for instance, E♭ represents the D♯ of the back. Considered as flats, the black keys of the second keyboard represent sharps of a third board which would be tuned a comma lower than the second. By thus fusing the flat of one series with the sharp of the other, an error is committed equal to the interval $\frac{846}{845}$,* which is at the extreme limit of audible differences.

On the front keyboard, starting from A, the following notes are tuned to true fifths, so as to give no beat whatever: A, E; E, B; D, A; G, D; C, G; F, C; B♭, F; E♭, B♭. The perfect chords D, F♯, A; A, C♯, E; E, G♯, B are also made. The fifths D, A; A, E; E, B are those previously determined; the F♯, C♯, and G♯ are the thirds which give no beat in the perfect chords.

On the back keyboard B, E, A, D, G F, B♭ are in succession fixed by taking these notes as true thirds in the perfect chords G, B, D; C, E, G; F, A, C; B♭, D, F; E♭, G, B♭; D♭, F, A♭; G♭, B♭, D♭; of which the fifths C, G, F, &c. are taken on the front keyboard. The chords D, F♯, A; A, C♯, E; E, G♯, B, are formed

* In Helmholtz, $\frac{886}{885}$.

on the back keyboard, using for the fifths D, A, E, B sounds already found, and tuning the thirds without beats.

The B of the back keyboard forms a true fifth with the F♯ or G♭ of the front. The D♯ or E♭ of the back keyboard is got by taking it as the true third of the perfect chord B, D♯, F♯, the two first notes being taken on the back and the third on the front board. The G♯ or A♭ of the front board gives, with the E♭ of the same board, a fifth which is not quite true, being exactly equal to the tempered fifth. The C of the back board is determined by so taking it that the resultant tones of the two thirds about it should be free from beats. In the six major scales of C, F, B♭, E♭, A♭, D♭ the fingering is the same, the third, sixth, and seventh are on the back keyboard, all the others on the front. The keys of G, D, A are played with the sharpened notes on the front board. The key of G has thus only B and E on the back board, of D only B, and A has none. A can be played entirely on the back board also. The key-notes of all minor scales are on the back board. For the minor scales of A, D, G, C, F, and B♭ the third and sixth alone are on the front keyboard.

(5) A somewhat simpler method of working Helmholtz's system has been suggested by Mr. Alexander Ellis, and carried out by Mr. Saunders. The keyboard is single, but communicates with two rows of vibrators tuned according to the method given above, or in the following series:—

Back row	B♯	D♭	C♯♯	E♭	F♭	E♯	G♭	F♯♯	A♭	G♯♯	B♭	C♭
Front row	C	C♯	D	D♯	E	F	F♯	G	G♯	A	A♯	B

When no stops are drawn out, the arrangement is that of the front series, the white notes being naturals and the black sharps. On pulling out a stop, the vibrators of its name in the front series of the instrument are damped, and the corresponding vibrators of the back series come into action, until the notes speaking are those of the old-fashioned manual. Between these extremes any required combination of notes can be produced, from seven flats to seven sharps, according to the keys employed. This method, which entirely removes the difficulties of complex fingering, has the disadvantage of requiring a constant alteration of stops, which in transitory modulations is occasionally laborious.

93. (6) The last class of contrivance for producing true intonation does away with the ordinary form of keyboard altogether. It is impossible here to give full details of these instruments, which practically introduce a new principle into musical execution. Poole's, Bosanquet's, and Colin Brown's forms may be taken as typical representatives of many less perfect devices. In all, the series of tones are arranged diagonally one beyond another, so "that the form of a chord of given key relation is

the same in every key. But the notes are not all symmetrical, and the same chord may be struck in different forms according to the view which is taken of its key relationship."* They therefore possess the great advantage of similarity of manipulation, although this is quite different from that ordinarily taught. It would appear, however, that the new systems are far from difficult to learn by any person who has obtained some experience on the older form of instrument.

(*a*) The first attempt in this direction was made by H. W. Poole, of South Danvers, Massachusetts, U.S. The instrument does not appear to have been constructed, but it is described in *Silliman's Journal* for July 1867. His organ was intended to contain 100 pipes to the octave, and the scale to consist of just fifths and thirds in the major chords, and also the natural or harmonic sevenths. The arrangement of keys is best given by a diagram extracted from Mr. Bosanquet's work (see p. 59, facing).

According to Mr. Bosanquet's notation here used, notes are arranged in series in order of successive fifths. Each series contains twelve fifths from F♯ up to B. This series is *unmarked*. It contains the standard C. Each note of the next series of twelve fifths up is affected with the mark /, which is called a mark of elevation, and is drawn upwards in the direction of writing. The next series has the mark //, and so on. The series below the unmarked series is affected with the mark \, which is called a mark of depression, and is drawn downwards in the direction of writing; the succeeding series is marked \\, and so on. Where, as in Poole's keyboard, perfect thirds are tuned independently of the fifths, they are here represented by the note eight fifths distant in the series; this is a close approximation to the perfect third, according to a relation which has been called Helmholtz's Theorem. Thus C—\E means a perfect third; \E—\G♯ is also a perfect third (chord of dominant of \A minor). The places of harmonic sevenths are marked by circles (O).†

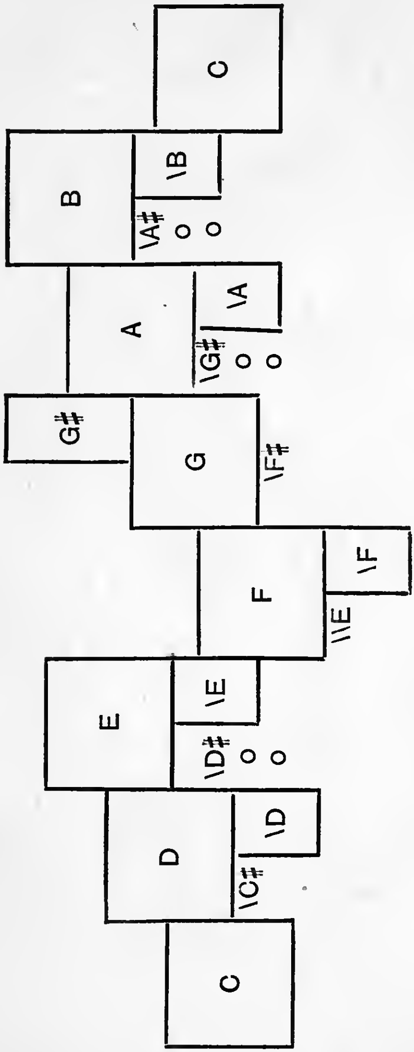
(*b*) Bosanquet's Generalised Keyboard.

In the enharmonic harmonium exhibited at the Loan Collection of Scientific Instruments, South Kensington, 1876, there was a keyboard which can be employed with all systems of tuning reducible to successions of uniform fifths; from this property it has been called the generalised keyboard. It will be convenient to consider it first with reference to perfect fifths. These are actually applied in the instrument in question to the division of the octave into fifty-three equal intervals, the fifths of which system differ

* Bosanquet, *op. cit.* p. 45.
† *Proceedings of the Musical Association*, 1874-75, p. 14.

from perfect fifths by less than the thousandth part of an equal temperament semitone.

It will be remembered that the equal temperament semitone is



POOLE'S KEYBOARD.

the twelfth part of an octave. The letters E. T. are used as an abbreviation for the words "equal temperament."

The arrangement of the keyboard is based upon E. T. positions taken from left to right, and deviations or departures from those positions taken up and down. Thus the notes nearly on any level are near in pitch to the notes of an E. T. series; notes higher up are higher in pitch; notes lower down lower in pitch.

The octave is divided from left to right into the twelve E. T. divisions, in the same way, and with the same colours, as if the broad fronts of the keys of an ordinary keyboard were removed, and the backs left.

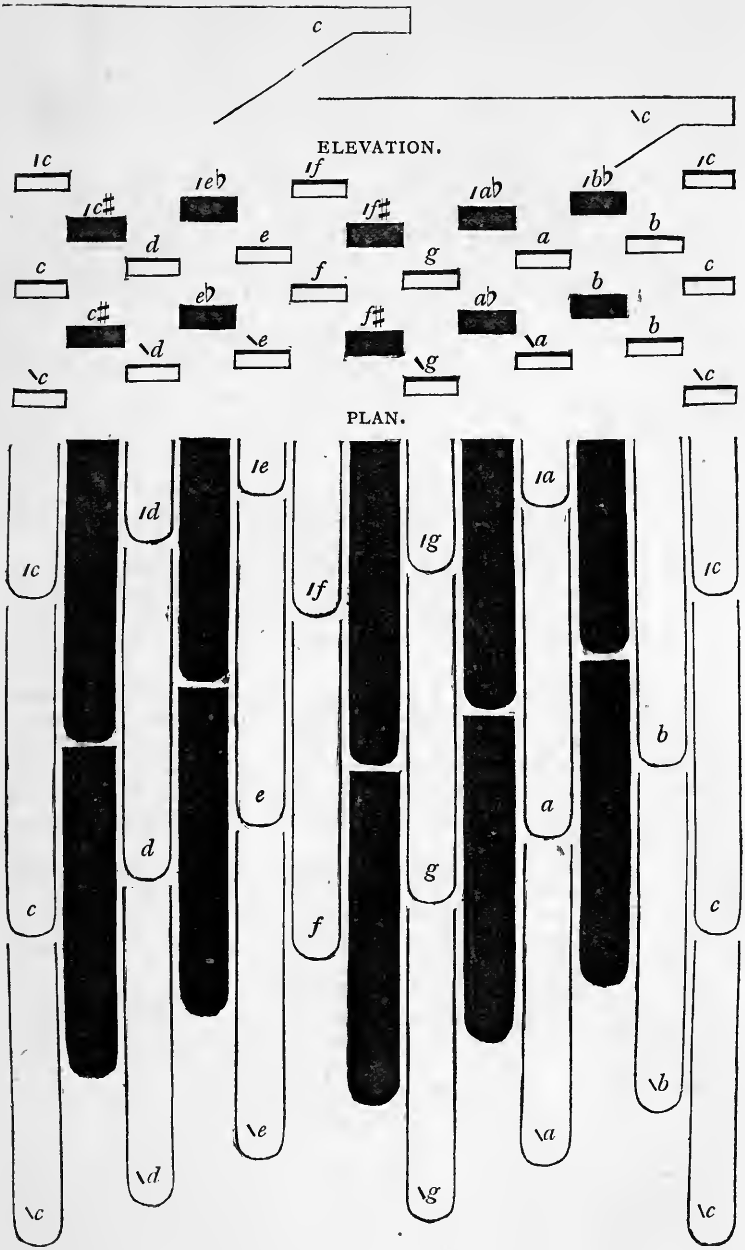
The deviations from the same level follow the series of fifths in their steps of increase. Thus G is placed one-fourth of an inch further back, and one-twelfth of an inch higher, than C; D twice as much, A three times, and so on, till we come to /C, the note to which we return after twelve fifths up; this note is placed three inches further back, and one inch higher, than the C from which we started.

With the system of perfect fifths the interval C—/C is a Pythagorean comma. With the same system, the third determined by two notes eight steps apart in the series of fifths (C—\E) is an approximately perfect third. With the system of fifty-three the state of things is very nearly the same as with the system of perfect fifths.

The principal practical simplification which exists in this keyboard arises from its arrangement being strictly according to intervals. From this it follows that the position relation of any two notes forming a given interval is always exactly the same; it does not matter what the key relationship is, or what the names of the notes are. Consequently a chord of given arrangement has always the same form under the finger; and, as particular cases, scale passages as well as chords have the same form to the hand in whatever key they are played, a simplification which gives the beginner one thing to learn, whereas there are twelve on the ordinary keyboard. (See diagram, facing.)

The keyboard has been explained above with reference to the system of perfect fifths and allied systems; but there is another class of systems to which it has special applicability, the mean-tone and its kindred systems. In these the third, made by tuning four fifths up, is perfect or approximately perfect. The mean-tone system is the old unequal temperament. The defects of that arrangement are got rid of by the new keyboard, and the fingering is remarkably easy. The unmarked naturals in the diagram present the scale of C when the mean-tone system is placed on the keys.*

* For further details on this important subject readers are referred to "An Elementary Treatise on Musical Intervals and Temperament, with an account of an Enharmonic Harmonium exhibited in the Loan Collection of Scientific Instruments, South Kensington, 1876; also of an Enharmonic Organ exhibited to the Musical Association of London, May 1875, by R. H. M Bosanquet, Fellow of St. John's College, Oxford." (London: Macmillan, 1876.)



OSANQUET'S GENERALISED KEYBOARD.

(c) Colin Brown's Natural Fingerboard with Perfect Intonation.

The digitals consist of three separate sets, of which those belonging to four related keys, representing the notes 2, 5, 1, 4, are white; those belonging to three related keys, and representing 7, 3, 6, are coloured; the small round digitals represent 7 *minor*, or the major seventh of the minor scale. These are the same in all keys.

This fingerboard can be made to consist of any number of keys. The scales run in the usual order in direct line horizontally from left to right *along* the fingerboard.

The keys are at right angles to the scales, and run vertically *across* the keyboard, from \C♭ in the front to /C♯ at the back, C being the central key.

The scale to be played is always found in direct line horizontally between the key-notes marked on the fingerboard, but the digitals may be touched at any point.

The order of succession is always the same, and consequently the progression of fingering the scale is identical in every key.

The first, second, fourth, and fifth tones of the scale are played by the white digitals, the third, sixth, and seventh by the coloured.

The sharpened sixth and seventh of the modern minor scale are played by the round digitals. The round digital, two removes to the left as in the key of B flat, is related to that in the key of C as 8 : 9, and supplies the sharpened sixth in the relative minor of C; so in all keys similarly related.

Playing the scale in each key the following relations appear (see diagram opposite):—

From white digital to white, say from the first to second and fourth to fifth of the scale, and from coloured to coloured, or from the sixth to the seventh of the scale, the relation is always 8 : 9.

From white to coloured, being from the second to the third, and from the fifth to the sixth of the scale, 9 : 10.

From coloured to white, being from the third to the fourth, and from the seventh to the eighth of the scale, 15 : 16.

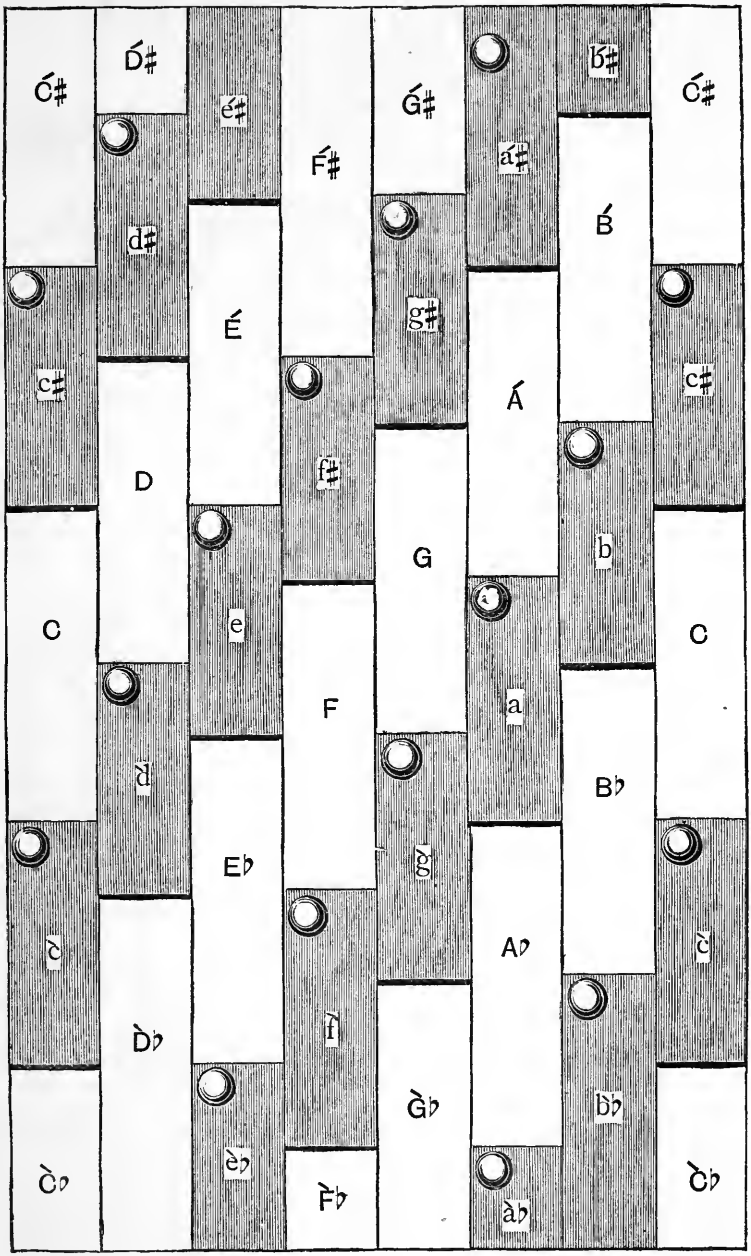
From *white* to *white*, or *coloured* to *coloured*, is always the *major tone*, 8 : 9.

From *white* to *coloured* is always the *minor tone*, 9 : 10.

From *coloured* to *white*, the diatonic semitone, 15 : 16.

The round digital is related to the coloured which succeeds it as 15 : 16, and to the white which precedes it as 25 : 24, being the imperfect chromatic semitone.

Looking *across* the fingerboard at the digitals *endwise*, from the end of each white digital to the end of each coloured im-



It will be observed that each line of digitals across the fingerboard bears one generic name, as C̀♭, c̀, C, c♯, Ć♯. So with every other line.

PLAN OF NATURAL FINGERBOARD.

mediately above it, in direct line, the relation is always 128 : 135, or the chromatic semitone; and from the end of each coloured digital to the white immediately above it, in direct line, the comma is found, 80 : 81.

Between all enharmonic changes, such as between A flat $404\frac{44}{81}$ to G sharp 405, the interval of the schisma always occurs, 32,768 : 32,805, the difference being 37.

These simple intervals and differences, 8 : 9, 9 : 10, 15 : 16, 24 : 25, 80 : 81, 128 : 135, and 32,768 : 32,805, comprise all the mathematical and musical relations of the scale. The larger intervals of the scale are composed of so many of 8 : 9, 9 : 10 and 15 : 16, added together. The "comma of Pythagoras," being a comma and schisma added together, is found between every enharmonic change of key, as from \C♭ to /B, or twelve removes of key.

The digitals rise to higher levels at each end, differing by chroma and comma, or comma and chroma, alternately. This causes separate levels on the fingerboard at each change of colour. Though these are not essential, they will be found very useful in manipulation, and serve readily to distinguish the different keys.

The two long digitals in each key are touched with great convenience by the thumb. The lower end of each coloured digital always represents the seventh in its own key, and the borrowed, or chromatic sharp tone, in every other; thus the seventh in the key of G is the sharpened fourth, or F sharp, in the key of C; and so in relation to every other chromatic sharp tone.

The white digital is to every coloured digital as its chromatic flat tone; thus the fourth in the key of F is B flat, or the flat seventh in the key of C; so in relation to every other chromatic flat tone. In this way all chromatic sharp and flat tones are perfectly and conveniently supplied without encumbering the fingerboard with any extra digitals, such as the black digitals on the ordinary keyboard, the scale in each key borrowing from those related to it every possible chromatic tone in its own place, in perfect intonation. The tuning is remarkably easy, and as simple as it is perfect.

While all the major keys upon the fingerboard, according to its range, have relative minors, the following, |\B♭, \F, \C, \G, \D, A, E, B, F♯, C♯, G♯, and D♯, can all be played both as major and as perfect tonic minors.

These secondary keys are more than appear at the first inspection of the fingerboard. A series of round digitals placed upon the white, and a comma higher, additional to those placed upon the coloured digitals, would supply the scale in every form the most exacting musician could desire, but it is a question if such extreme extensions are either necessary or in true key relationship, and whether simplicity in the fingerboard is not more to be desired than any multiplication of keys which involve complexity and confusion.*

Adaptation of True Intonation to the Orchestra.

94. There can be no doubt that the place in which the superiority of true over tempered intonation is most felt, and in which it could be most easily attained, is the orchestra. Unfortunately this is exactly where it has been most thoroughly neglected. To a certain degree it is instinctively and unconsciously produced; the stringed instruments having the power of modifying their notes accurately by ear according to the requirements of a particular chord or modulation. Even here, however, the result is marred by the erroneous practice of many violinists. But in the wind-instrument department this power is limited to the slide trombones, and the corresponding trumpet. It is much to be regretted that the natural and perfect quartett formed by the slide trumpet, alto, tenor, and G bass trombones should be so much disfigured at the present day, the alto being almost always replaced by a second tenor, the bass often omitted or transferred to the euphonium, and the inimitable trumpet spoiled by the cornet. But beyond these two types no endeavour whatever seems to have been made towards true intonation. Flutes, oboes, clarinets, and bassoons, as made and supplied to their respective players, are rarely in tune at all, even to themselves, and, at most, present a feeble approach to equal temperament. There is no insuperable obstacle in the way of their all being so manufactured and tuned as to give at least the principal enharmonic differences, by utilising duplicate fingerings for the same note, which already exist on all of them.

The writer has himself directed the construction of a clarinet and bassoon which, without any appreciable increase of mechanism, and without the slightest alteration of the system of fingering usually adopted, can be made to give nineteen notes to the octave, a number more than sufficient to provide for all the commatic differences involved. The clarinet, three forms of which are commonly used in the orchestra, lends itself particularly well to such an arrangement, from the fact that it is rarely if ever required to play in high flat or sharp keys. Those actually in use can therefore be tuned accurately, and a duplicate note provided in case of sudden and temporary modulations.

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* A full description of the voice harmonium may be found in the specification for patent. The principles upon which it is constructed and tuned will be found fully stated in "Music in Common Things," parts i. and ii., published by Messrs. William Collins, Sons, and Co., Glasgow, and Bridewell Place, New Bridge Street, London, and the Tonic Solfa Agency, 8, Warwick Lane, E.C.

It is, however, essential that the present music should be carefully gone over in score by a competent harmonist, and the modified notes marked into the band parts according to Mr. Bosanquet's, or any equally good notation, with a mark of elevation or depression, according to their specific key relationship. An orchestra in which perfect intonation were thus secured would instantly obtain what is very obvious in listening to keyboard instruments of correct scale, such as that of Mr. Colin Brown, namely, a largely increased volume of tone in proportion to the instrumental resources employed.

An excellent adaptation of the enharmonic principle to brass valved instruments has been devised by Mr. H. Bassett, F.C.S., in what he terms the COMMA and TELEOPHONIC trumpets. In all instruments furnished with the ordinary valves there are great faults in intonation. "It is not difficult," says Mr. Bassett, "to show, by calculation from the varying lengths of tube brought into action by the valves, that many of the intervals resulting from their combination are not in accordance with the just or tempered scales. The unfortunate practice of transposing parts written in widely different keys, so as to use only one or two crooks, greatly increases these errors, besides sacrificing the benefit of the natural intervals, and distinctive quality of tone of the different crooks."*

He first constructed a valve trumpet in which these faults of intonation should be avoided. In it the first and second valves remain as usual; that is to say they *lower* the pitch by the intervals of a major tone and a diatonic semitone respectively. The third valve *raises* the pitch of any note produced on the first valve by the interval of a comma, or, in other words, the first and third valves *together* lower the pitch a minor tone. This system of valves, which is also applicable to the French horn, enables the player to produce a practically perfect diatonic scale in the tonic, dominant, and subdominant keys, with the advantage of having only two valve slides to tune when changing the crook, the alteration theoretically required in the third or "comma valve" being so small as to be inappreciable.

In his second, which he terms the "teleophonic" instrument, he retains the original slide, thus keeping the power of adjusting each note to accurate intonation; but he adds a single valve tuned in unison with the open D, or harmonic ninth—in other words, lowering the pitch a minor tone. This valve is worked by the forefinger of the left hand, the instrument being held exactly in the usual manner. By the use of this single valve and the slide, separately or together, it is possible to produce a complete scale, major or minor, with a perfection of intonation limited

* *Proceedings of the Musical Association*, 1876-77, p. 140.

only by the skill of the player. The valve not only supplies those notes which are false or entirely wanting on the ordinary slide trumpet, including the low A flat and E flat on the higher crooks, but it greatly facilitates transposition and rapid passages.

In addition to devices for increasing the accuracy of the scale, it is highly important that errors due to variation of pitch from temperature should be more minutely studied in actual performance than has been hitherto done. The views of the writer cannot be stated more explicitly than by the reproduction of an article originally contributed to the *Concordia* journal.

On Tuning an Orchestra.

95. It is singular that this essential preliminary to correct orchestral playing should have hitherto attracted comparatively little notice, in our country at least. No doubt the first and almost instinctive act of every player on entering the concert-room is to try the pitch of his instrument by touching a few notes at random; with this, however, he too often rests satisfied, and the result is that the first bars of the performance disclose the incompleteness of the adjustment. Moreover, this important preparative is usually left to the last moment, when many players arrive at the same time, each of whom performs some familiar flourish *fortissimo*, and simultaneously with his neighbours. The delicacy of the ear is overwhelmed with discordant notes, no standard of pitch is referred to, the various instruments have not had time to attain the temperature of the room, and the noise itself tends to force them for the moment into an apparent agreement, which ceases directly they play independently of one another. The conductor, on arriving, takes it for granted that the band is in tune, and it is often only after a considerable interval that the united forces shake down into complete accuracy and its consequent sonorousness. Abroad a better custom prevails, there being a standard tuning-fork beside the conductor's desk, to which each player is expected to accommodate himself. One of Dr. von Bülow's many merits is attention to this detail, although his careful solicitude has been occasionally misrepresented and received with resentment. The chief boast of the Conservatoire band in Paris is the *premier coup d'archet*.

The matter is not quite so simple as it at first sight appears, and it deserves consideration under a threefold aspect—physiological, mechanical, and practical.

96. In a physiological point of view it is important to notice that there is considerable difference in even cultivated ears as to the appreciation of minute shades of pitch; some being much more sensitive than others; many possessing a personal peculiarity similar to what is termed "personal error" in astronomical

observation, by virtue of which they adopt slightly different estimates of concord or even of unison. In great observatories a figure is set against the name of each observer which is tolerably constant, and indicates that he will note the transit of a star over the wires of the telescope, or even the beat of a clock, by an appreciable interval before or after another of his colleagues. I have little doubt, from extended experiments, that there exists a similar phenomenon in the ear as in the eye. We have indeed a means of correcting it in the former case which we have not in the latter, namely by the beats or interferences; but what musicians, except pianoforte or organ tuners, ever employ these? Corresponding shades of sharpness and flatness elude even this test, and are often difficult to distinguish except by exaggeration. This tolerance of discord increases enormously when instruments of very different *timbre* or quality are compared. I was myself surprised at the amount of tolerance in making some observations, which I communicated to a musical periodical last year, respecting the so-called French pitch at the two opera-houses: the difference between the oboe and clarinet, for instance, which was marked when both were compared with a tuning-fork held to the ear, did not strike it painfully when unassisted by the unvarying standard.*

Slight dissonances are more audible at a distance than in their immediate neighbourhood. In this respect the plan adopted by organ-builders, of placing a listener in a remote part of the building to guide the tuner, might with advantage be imitated. Sharp notes, moreover, have a predominant power over the ear. If two notes be struck at nearly the same time, a player is almost certain to tune to the sharper of the two. No doubt this is one great cause of the constant tendency to sharpen which is the plague of our modern orchestras, and has necessitated the enforced adoption of a lower diapason.

97. In a mechanical light there is some difficulty in establishing an invariable standard of pitch. The oboe has the prescriptive right handed down from ancient times of tuning the band. This, no doubt, depends on the fact that in Handel's days it was almost the only wind instrument extensively used. But it is far from being the best for the purpose. Like all double-reed instruments, its pitch is susceptible of great variation, according to the state of the lip-muscles. It is not therefore uncommon to find a player give at the outset a tuning note much sharper than that he

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* A remarkable confirmation *e converso* of the statement here made is furnished me by Mr. Hipkins. He informs me that if two pianos of different quality be accurately tuned in unison by means of beats and placed side by side in a room, even the most practised musician, on trying them consecutively, will declare the softer-toned instrument to be the flatter of the two.

afterwards plays to. The clarinet is infinitely less easy to tune to various pitches on account of its single reed, and from the fact that a slight pulling in and out of the mouthpiece socket, which is the only method of tuning open to it, tells more upon the "throat notes" than on other parts of its scale, and thus makes it disagree with itself. On the other hand it rises with the warmth of the breath more than any instrument. In very cold weather I have found the difference in the B flat clarinet to amount to a whole semitone. Players seem hardly to appreciate the extent of this rise. To this fact also, no doubt, much of the tendency to sharpen orchestral pitch is due. The brass instruments and metal flutes rapidly cool again and sink to their original pitch; but the solid wood of the clarinet and wooden flute retains heat, and may continue to sharpen for a whole evening. If the pitch is to be taken from any orchestral instrument, I think the one chosen ought to be the clarinet, on the ground of its inability to alter; but it should be well warmed first and closely watched afterwards to counteract the tendency to sharpen. Players often show great unwillingness to tune down their clarinets, apparently not knowing that warmth mainly affects the upper parts of the bore, and that a slight lengthening of a warm instrument improves its accuracy. It is in pianoforte concertos that this defect of the wood-wind, and particularly of the clarinets, is most noticeable; principally on account of the rise of the wind, but also a little from the sinking of the metal strings of the piano by dilatation with heat. On this fall in pitch of stretched metal strings under heat, or the passage of an electric current, I have commented elsewhere (*Transactions of the Physical Society*, 1874).

98. The organ is not devoid of the same source of error. A diapason pipe fed with cold and hot air varies very considerably, even to the extent of a quarter tone. Few organ-builders, with the notable exceptions of Mr. Willis and Mr. Lewis, pay sufficient attention to this fact. The large, flat, and unwieldy organ at Exeter Hall, for instance, is fed by wind from the cold stone corridors and staircases below it, which communicate almost directly with the outer air. Consequently, at the beginning of a performance, when the air of the room itself is well heated and dried by the abundant gas in the roof, the organ is very flat, as it is drawing a denser supply from below and outside, whose undulations are calculably different from those in the rarefied medium in which the clarinets, contra-fagotti, and others are breathing and expiring. If all external apertures at the back were shut, and the bellows made to draw their wind from the hot dry air near the ceiling by means of a large air trunk or wind sail, the organ would rise in pitch and would cypher much less than it now does in damp weather. Besides this, the very defective ventilation of the room would be improved.

99. The best standard of pitch, however, is in my opinion a free reed. This, though producing a poor musical note, is very little affected by changes of temperature, especially if made of a metal like German silver, which is well known from electrical experiments to alter its molecular condition very slightly for a given increment of heat. The thinness of the tone and the facility with which "beats" are produced, though æsthetical defects, are in the case before us converted into advantages. All instruments should tune to open notes, whether strings or wind; and the standard of pitch should possess not only the A, usually employed, but several others; notably the D in the bass. This latter I consider on the whole a better note to tune to than A; certainly it is so for the bass instruments. If the perfect fifth of D, A be sounded together, even the fiddles will hardly be able to tune sharp, owing to the marked dissonance which accompanies any augmentation of that interval. The D is, moreover, the middle string of the double-basses, as used in our English orchestras; and, this being fixed, a fourth on either side is more easily found than if two such intervals are built up from the lowest and least brilliant string.

In all orchestral tuning the double-basses require an attention which they have not yet received. They appear to have an immunity from rule or censure. This is due, in part, to the fact that long and special training of the ear is required to enable it to realise small differences in very grave notes. I have never yet known a case where the double-basses were called to account for their pitch; and yet, as a rule, they tune sharp. The most ludicrous case of this kind occurred in the late futile attempt to introduce French pitch at the operas. I am not aware that any change was made in the double-basses, although an expensive and very bad set of wind instruments was procured from abroad. The basses simply slackened their ordinary thin strings, instead of putting on a full set of stouter strings in proportion to the diminished rate of vibration. Of course the bow transmitted an instinctive sense of lessened tension, very unpleasant to practised players, and in a few minutes they were up to their discarded pitch; the treble instruments, attacked as being flat, were obliged to meet the difficulty by having *as many as four successive* slices hacked off their new outfit. In less than a month I found the pitch as high as it had formerly been. Two other instruments are commonly responsible for sharpness of the bass, namely the G bass trombone and the drums; the former is usually in the hands of a military player, accustomed to the foolishly sharp pitch to which our Guards band have risen, but the latter is the more serious cause of discord. According to the arrangement of modern English orchestras, in most of which four-string double-basses and other instruments, such as the contrafagotto, of sixteen-foot tone, are ignored, the kettledrum stands alone in possessing two, or at most three, notes of this octave. When these are correct the effect is very fine; but many of our English copper-made drums are so deep in the kettle, and so large in the head, that the note they give is very complex, more resembling a gong or a bell than an orchestral instrument; and as the drummer has to change their pitch frequently, by means of a clumsy mechanism of key and screws, during performance, it requires great tact and experience to keep them even moderately near the proper note. The tendency to tune a shade sharp is more marked with drums than even with double-basses, and they are still more commonly overlooked at the outset. Where great changes of key occur, the kettledrummer should always be provided with a third, and sometimes even with a fourth, drum. An octave of sixteen-foot reeds, in the form of a simple harmonium, placed within his reach, for comparison, would often prevent a mysterious but very painful wolfing, which we have all at times noticed, but which, like inaccurate tuning of the double-basses, is very difficult to localise by the unassisted ear.

100. One other point requires notice, that on the occurrence of sudden enharmonic changes from flat to sharp keys the necessary difference of pitch is often only gradually and imperfectly arrived at. It principally occurs in the change from flats to sharps, at which time the wind instruments should as a rule flatten somewhat; in the opposite change from sharps to flats the natural tendency to rise is sufficient. The strings have, of course, the matter in their own power, except as regards open notes.

A great deal might be accomplished by very simple means if conductors would consider it their duty to run through the principal instruments one by one against a trustworthy standard, but that not, if possible, a tuning-fork. The note of even the best tuning-fork is so feeble and evanescent that it is not fitted for the noise and bustle of the concert-room, and, moreover, it is greatly under the influence of temperature. A free reed would be far better. The comparison of pitch should not be limited to a few treble instruments, but should begin with drums and double-basses, and so proceed upwards. The process, lastly, should not be carried on by compelling all to tune up to the sharpest, but by bringing the sharper instruments slightly down to a medium pitch; this would obviate the constant need for cutting instruments to pieces which is now felt, and prevent the steady tendency to sharpen, which is ruining our voices, and rendering much classical music impossible to all but singers of rare and exceptional organisation.

APPENDIX.

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