CHAMBERS'S

SCIENCE MANUALS

SOUND

CHAMBERS'S
ELEMENTARY SCIENCE MANUALS.

SOUND

AND THE

PHYSICAL BASIS OF MUSIC

BY

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GENERAL PLAN OF THE SERIES.

THE subjects of these Manuals are for the most part, though not exclusively, the same as those of the Syllabus of the Science and Art Department, South Kensington, and the treatment will be found to meet the requirements for the Examinations held by that Department.

In their wider scope the Manuals are intended to serve two somewhat different purposes :

1. They are designed, in the first place, for SELF-INSTRUCTION, and will present, in a form suitable for private study, the main subjects entering into an enlightened education ; so that young persons in earnest about self-culture may be able to master them for themselves.

2. The other purpose of the Manuals is to serve as TEXT-BOOKS IN SCHOOLS. The mode of treatment naturally adopted in what is to be studied without a teacher, so far from being a drawback in a school-manual, will, it is believed, be a positive advantage. The subject is made, as far as possible, to unfold itself gradually, as if the pupil were discovering the principles himself, the chief function of the book being, to bring the materials before him, and to guide him by the shortest road to the discovery. This is now acknowledged to be the only profitable method of acquiring knowledge, whether as regards self-instruction or learning at school.

PREFACE.

FIFTY years ago Acoustics, or the Science of Sound, was generally treated as a mere section of Pneumatics; but the subject has been so widely extended by modern research, that it now ranks—co-ordinate with Heat, Light, and Electricity—as one of the principal branches of Physics. It has not, indeed, been one of the most popular branches until recently, that the profound researches of Helmholtz and the brilliant expositions of Professor Tyndall have brought it into prominence. No doubt it has been kept in the shade by the series of splendid discoveries which, since the beginning of this century, have advertised the other physical subjects. A knowledge of Acoustics is, however, deserving of much more extended diffusion than it has yet attained. Apart from the interesting nature of the study itself, the subject is very important by reason of the light which it throws on the theory of music, giving simple objective explanations of much that would otherwise seem purely subjective. In few, if any, of the multitude of school manuals on the theory of music are these explanations furnished with sufficient scientific accuracy for the purposes of the student or the practical teacher.

The present manual is an untechnical sketch of the main principles of the subject, adapted primarily for use in schools, where, if possible, experimental illustrations should be given as an accompaniment: these may mostly be provided at small cost and trouble by any teacher with a little mechanical ingenuity. For the sake of the general reader and the musician, the musical bearings of the subject have been introduced as far as space would allow; and these have been explained in the simplest language. We have added a sketch of Musical Instruments, for fuller information as to which the reader is referred to Engel; and in this connection an account has been given of the organs of speech and hearing, which are both in a sense musical instruments.

The manual contains all that is needful to pass the elementary and advanced stages of the South Kensington science examinations; and specimen answers to some of the papers set by the Department have been appended. These, it is hoped, may be found useful as a guide to the student.

Of course the present sketch is merely to be looked on as an introduction or stepping-stone to more exhaustive works on the science, such as those of Airy, Tyndall, Herschel, Helmholtz, Sedley Taylor, &c., to acquaintance with which it is to be hoped the reader will aspire.

EDINBURGH, *October* 1877.

CONTENTS.

PART III.

DIFFERENT MODES OF EVOKING MUSICAL SOUNDS.

SOUND.

1. **THE ART OF MUSIC**, although, perhaps, the most ancient and most widely appreciated of the arts, has been one of the latest to have its principles embodied in scientific form. Thousands of years ago the Egyptian tuned his flute, the Hebrew strung his sacred psalter, and the Greek his favourite lyre, with no accurate knowledge of the laws and relations of musical tones, but guided solely by the autocratic instinct of the ear ; and, though the art has been carried to a considerable degree of perfection by many ancient and modern nations totally ignorant of the laws of acoustics, there can be no better proof of the value of the science for the furtherance of the art, than the perfection to which musical instruments have attained since the rapid advance of acoustical science within the last century.

Five hundred years before the Christian era, the Grecian sage Pythagoras is said to have invented the monochord, an instrument to be described in a future page, and by its means to have lighted on a few of the now well-known laws of acoustics ; but it is probable that he found in them rather illustrations of the beauties of number, than revelations of the wonders of a musical sound. At all events Euclid, who followed the method of Pythagoras two centuries afterwards, is said to have written two treatises on the *Division of the Scale*, and *Introduction to Harmony;* and whatever was known of acoustics seems then to have been accounted a branch of geometry. It has been reserved for comparatively recent times to analyse the first cause of a musical sound, to picture it in its invisible passage from the sounding body through the conveying medium, and to reveal the wondrous mechanism of the human ear, the means of so much utility and of so much enjoyment.

In the present work we shall describe (1) the leading phenomena of sounds in general; (2) the physical facts underlying the laws of musical sounds; (3) the principal contrivances employed for the production of musical sounds, including the vocal apparatus; and (4) the human ear, that delicate organism adapted for the appreciation of sonorous effects.

PART I.

THE PHENOMENA OF SOUNDS GENERALLY.

2. **SOUND, THE RESULT OF VIBRATION.**—A sound may be defined as the sensation of a rapid quiver of the drum or tympanum of the ear, caused by the motions or vibrations of some elastic body conveyed, through the air usually, to the ear.

If we touch any sounding body with the finger, such as a bell, a tuning-fork, a wire, a drum, &c., we may easily *feel* it to be in a state of rapid quiver or vibration; and we instantly damp the motion and with that the sound. What reveals itself to one sense as sound, thus reveals itself to another as motion. The same fact may be simply proved by laying the fingers across the throat while we speak or sing; with a loud vocal effort, the tremulous motion of the larynx is very apparent indeed. In this way different sounds may be *felt*, and distinguished by deaf persons; and it has even been found possible to teach the deaf and dumb this tactile method of translating speech.

What is thus felt as motion may be also made *visible* to the eye as motion. In some cases, as of a sounding string or wire, or a large bell or drum, the motion may be directly visible; in other cases, it may be exhibited by the aid of some simple contrivance. Thus, if a small drum be placed upright and struck, and a few peas or bits of paper, or pith-balls, be then placed on the upper end, these will be projected to a considerable height by the vibrating membrane; and the dancing motion will be visible as long as the sound continues. Other experiments illustrative of the fact that sound is the result of a vibratory motion are represented in

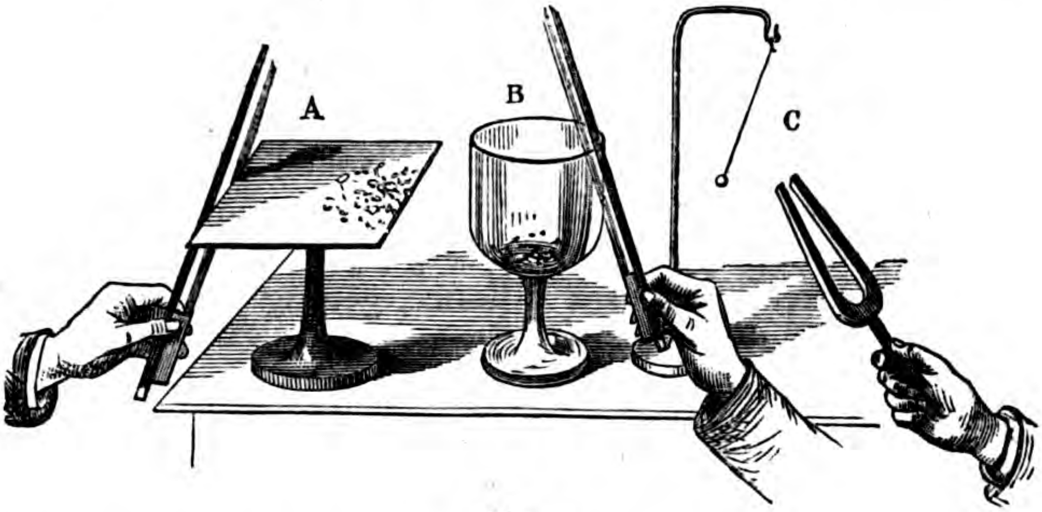


Fig. 1.

fig. 1. If, as in A, a violin-bow be drawn down the side of a square or circular brass plate fixed at its centre to a stand, it gives forth a note or sound, and small pieces of paper laid on the opposite side of the plate will be instantly tossed off. If, as in B, some wafers or piths be placed inside a common bell-shaped tumbler, and a sound elicited by the violin bow, or by passing a wetted finger round the edge, the vibration of the bell-glass will throw the piths or wafers into a violent commotion. If, again, as in C, a small bead or a pith-ball be hung up by a thread, and any sounding body such as a tuning-fork be brought to touch the bead or pith, the latter is instantly repelled as if kicked away; and if the bead should be brought between the prongs of the fork, it rattles to and fro between the prongs with very great rapidity.

PROPAGATION OF SOUND.

3. **The Air the usual vehicle of Sound: No Air—no Sound.** The vibrations of sounding bodies are transmitted to the drum of the ear, not directly, but through the air usually as a medium or vehicle.

If life could exist on our globe without an atmosphere, it would be a vitality passed in all the silence of death; no audible language, no music, or sound of any sort would alleviate the tedium of such an existence. This is demonstrated by enclosing a music-box capable of playing for a considerable time under a glass-receiver from which, by means of an air-pump, the air can be exhausted. After the vacuum is made nearly perfect, no sound will be heard, though we press our ear close to the glass: the moment we re-admit the air, however, the music begins to grow audible, as if approaching from a distance, getting louder as the density of the air increases.

If we admit some other gas, such as hydrogen or carbonic acid, instead of common air, it transmits the sound, but with a difference of intensity. Hydrogen transmits the sound more quickly, but more feebly, because a lighter and more active vehicle; carbonic acid gas transmits it more slowly but more loudly, because a heavier, duller vehicle. This dulling effect of carbonic acid may be readily illustrated by striking a glass tumbler in which some effervescing substance, such as citrate of magnesia or soda-water, is generating this gas: so long as the effervescence lasts, the sound is dull and heavy, almost as if the vessel were cracked; but the 'ring' gets gradually clearer as the carbonic acid is replaced by common air. The lessened density of the air on the top of a high mountain has a similar weakening effect on the strength of sound. It has been observed that a rifle fired on the top of Mont Blanc has a sound like the report of a toy-pistol.

4. **Air-pulses of Condensation and Rarefaction.**—The vibrations of a sounding body communicated to the air assume in it the form of alternately condensed and rarefied layers.

A single shock or impulse, such as a blow, a clap, or a shot, transmits a motion in all directions through the surrounding air, which announces itself to the ear as a more or less violent knock against the membrane called the drum of the ear. The nature of this transmitted motion is, however, peculiar, and requires some consideration. It is not an onward movement or flow of the air-particles bodily, but is merely an impulse-transmission, which may be illustrated in the following way. Suppose we take half a dozen or more similar bagatelle ivory balls, and lay them along the edge of the board so as to be exactly in one line. If we then roll one ball so as to strike the end of the row, there will be no apparent motion of the middle balls, but the ball at the other end will move away in virtue of the transmitted shock. If two balls be similarly rolled together against the end of the row, then two will move away at the other end, and so on. Thus, without any visible motion of the intermediate balls, and through any number of such, there will be an exact reproduction, at the far end of the row, of the impulses at the other end.

We live in an aërial ocean composed of countless millions of tiny balls, infinitely more elastic than ivory, which in this way transmit to us with unerring truth, and from very great

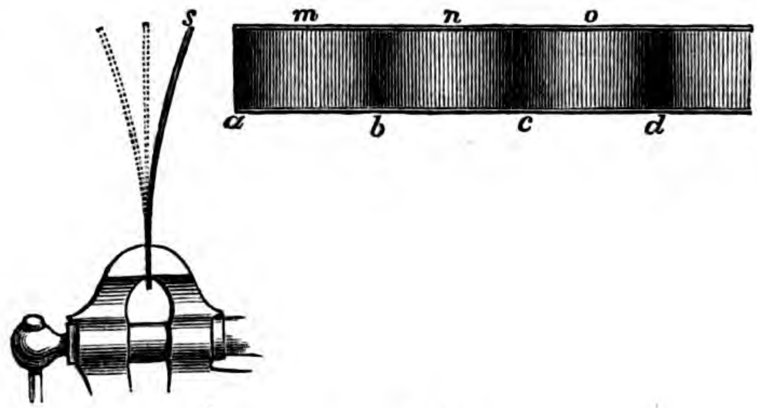


Fig. 2.

distances, the shocks or impulses of any vibrating body. When these shocks or impulses are repeated with sufficient energy and rapidity, they affect the ear as the sensation of *continuous sound.* Now, since this shock does not pass through the air instantly, but, as will be more fully discussed afterwards, at the rate of about 384 yards a second, and since a vibrating body such as a steel spring or a tuning-fork may vibrate many hundreds of times in a second, it follows that in a length of air, such as *a b c d*, fig. 2, there will be several impulses progressing simultaneously. The effect of a forward impulse of the spring *s* is to condense or crowd the air-particles together, while the effect of a backward motion of the spring is to rarefy the air : a succession of impulses will consequently set up a succession of condensations of the air as at *a*, *b*, &c., separated by a succession of rarefactions at *m*, *n*, *o*, &c.

The vibrating spring is thus said to throw the air into **sonorous waves or pulses**, the section between two successive condensations constituting **a wave-length.** Each air-particle oscillates back and fore in the direction in which the sound advances; it copies in fact the motion of the vibrating spring, being in turn in the centre of condensation and of rarefaction. Now, as a sonorous wave is evidently the length of air disturbed during one vibration,* or backward-and-forward movement of the steel spring, it is merely another way of stating the same fact to say that the sound advances through one wave-length in the time of one vibration of the sounding body or of an air-particle; but of course each air-particle does not oscillate to and fro through the extent of an air-wave. This will be more clearly understood if we compare the oscillation of liquids, from which by analogy the term wave has been borrowed.

5. **Liquid Waves.**—On watching closely the motion of a boat or ship simply floating on the surface of the sea, it will be seen that the ship merely rises and falls with the waves, and that the onward movement of the latter is apparent and not real. Each water-particle oscillates up and down through the vertical distance between the crest and hollow of a wave, and the whole extent of water dis-

* It is to be noted that the French call one backward *or* one forward motion of an oscillating body a vibration; while the English and German physicists reckon a vibration as one backward *and* one forward movement.

turbed during one such oscillation constitutes a wave. Waves may be long or short, lofty or shallow, tiny rapid ripples, or slow and like rolling mountains. The figure

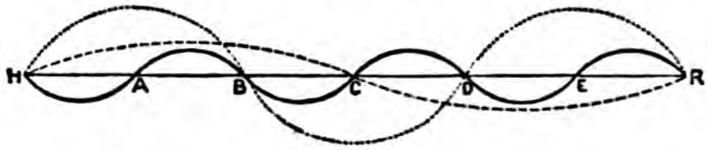


Fig. 3.

represents three different sizes of waves into which the horizontal liquid surface HR may be heaved.

Liquid waves are due to *transverse* oscillations of the water-particles, and are consequently different in their nature from sonorous air-waves, where the particles vibrate *longitudinally*, or in the line of their advance. We may illustrate the same sort of transmission of a wavy form by means of a long chain or rope, or elastic cord, or spiral of brass wire. In fig. 4, we represent the different links of

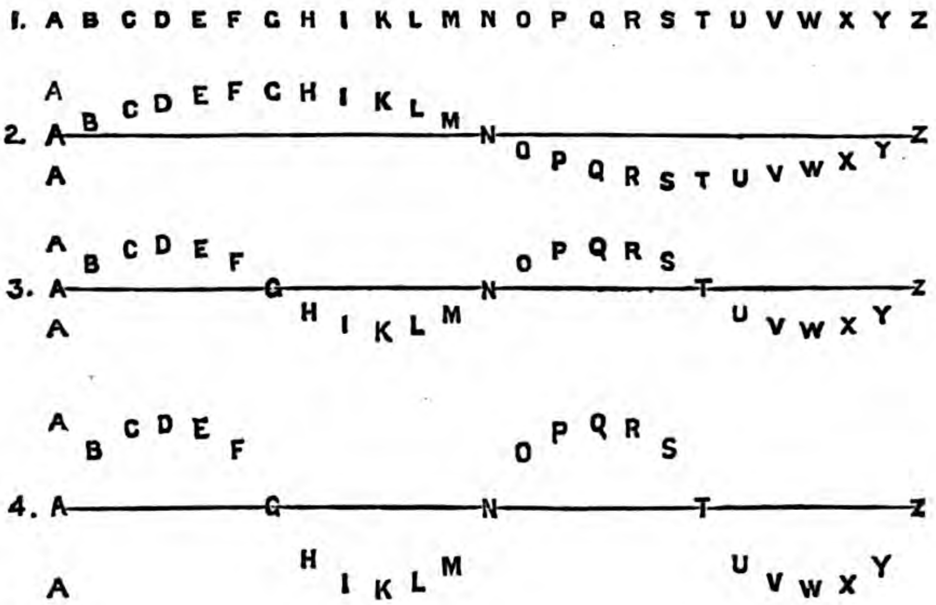


Fig. 4.

a chain by a series of different letters : (1) represents the chain at rest or in its natural position ; (2) shews the whole thrown into one complete wave by the up-and-down motion of the first link A between the dotted positions marked, which motion of A is repeated by each of the other links in turn; (3) shews the chain thrown into two undulations, A having just oscillated twice between the extreme positions marked by the dotted letter; while (4) shews the same chain thrown into two undulations of double the **amplitude** of the former, A having moved twice through twice the space in the former instance.

Chain-waves, as we may call these, are graphically used to represent air-waves, and they aid very materially the study of the latter. The amount of deviation of the curved line above or below the horizontal corresponds to the degree of condensation or rarefaction of the air; so that a sounding column of air, such as is shewn in fig. 2, thrown into three pulses, may be represented by the triplicate curved line in fig. 3. In this way we are enabled to study the effect of a *compound undulation*, for an aërial as well as a liquid mass may be acted upon by several different undulations simultaneously, and it is sometimes an important but intricate problem to determine the conjoint or resultant effect of the whole.

6. **Conversion of Longitudinal into Transverse Vibration.**—This translation, as it were, of the back-and-fore pulses of sound-waves into up-and-down waves is not a mere theoretical operation, but is based on a natural transformation which may readily be effected experimentally, as fig. 5 will serve to shew. If an elastic cord, such as a thread

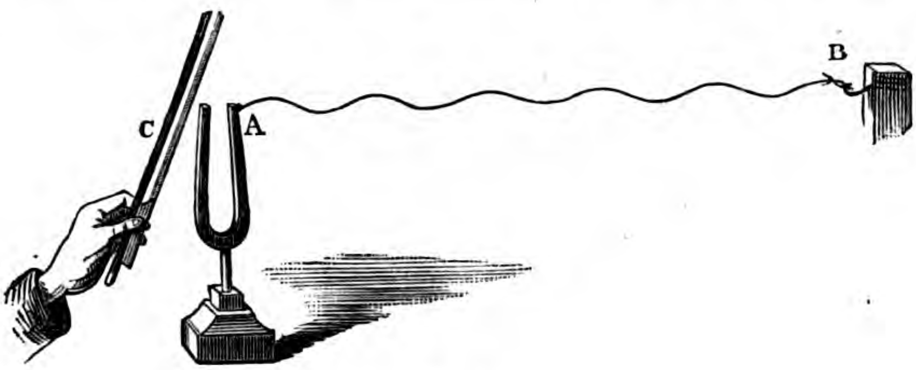


Fig. 5.

of thick white sewing-silk, be attached to the end of a steel spring or a tuning-fork A, firmly fixed in a wooden block; and if it be stretched horizontally and tied to a peg at the other end, B, then, on causing the steel spring to vibrate, or the tuning-fork to sound, with a fiddle-bow well resined, C, we throw the cord into a series of undulations whose number depends on the rate of vibration of the steel or fork. When performed with care this experiment is an exceedingly pretty, no less than instructive one.

By other means, mechanical and optical, these back-and-fore motions of a vibrating fork may be translated into up-and-down waves, and the rate of vibration of the fork accurately estimated. These, however, will be described subsequently.

7. **Sound-concussions.**—Many instances might be given corroborative of the statement that the passage of sound through the air is a case of the transmission of mechanical concussions. The effects of loud sounds are sometimes remarkable. A strong peal of thunder will shake the doors and windows of a house, or glasses standing on the table, or sometimes even the whole house. It is well known that the noise of the firing of heavy cannon in the neighbourhood of houses will shatter the glass in the windows. During the recent trials at Shoeburyness of the monster eighty-one-ton gun, several of the soldiers' dwellings were completely wrecked by the mere concussion of the air; walls being driven bodily out of their place, and windows smashed to the extent of several hundred pounds' worth. When the barge laden with gunpowder accidentally exploded on the Regent's Canal in 1874, the effects of the concussion were destructive of property within a radius of a mile, and were violently felt within a radius of two or three miles.

By special contrivances similar mechanical effects may be exhibited in the case of ordinary sounds. Thus, if we make a tube some three feet in length by rolling brown paper round a cylinder, and fix a funnel-shaped mouth at the one end, and a pointed or conical piece at the other end, and support this as in fig. 6, so that the pointed end shall be near a candle flame, C; then by clapping the hands, H, or two books at the open end, we may extinguish the candle flame. Professor Tyndall performs this experiment through a tube some fifteen feet long: by filling the tube with the smoke of brown paper he shews that it is a pulse and not a puff of air that produces this effect; for there is none of the

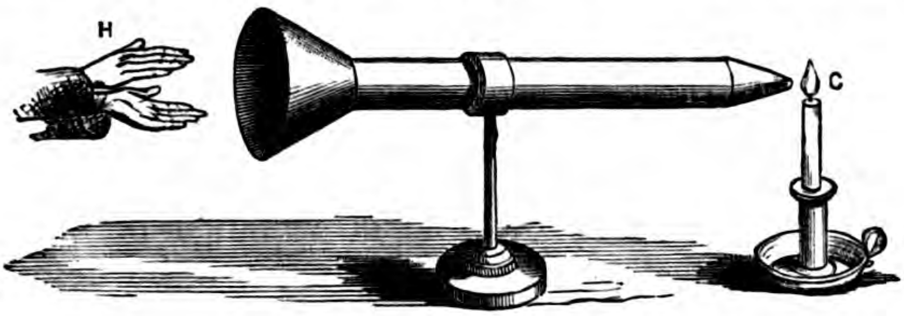


Fig. 6.

smoke ejected at the other end. A pistol-shot fired *across* the mouth of the tube will extinguish the candle flame at once.

8. **SENSITIVE FLAMES.**—By the arrangement shewn in fig. 7, a yet more sensitive detector of aërial concussions has been devised. Instead of the common metal gas burner, we fix with sealing-wax one made of a small piece of glass tube heated and drawn out to a fine point, B, and over this, at a distance of one or two inches, depending on the pressure of the gas, we support a square of fine wire-gauze, G. If then we light the gas *above* the gauze, we know that it will continue to burn without catching fire underneath. After some little adjustment of the distance of the gauze from the burner and of the gas pressure, we obtain a flame, F, so sensitive to aërial shocks or sounds that a whisper, a scratch, or a rustle will make it start like a sensitive creature; and a laugh or any sharp noise will nearly extinguish it. If all the gasaliers in a room were provided with burners of this description, the lights would be most impatient of any noise on the part of an assembled company; and a tune played on an organ or harmonium would keep all the lights in a fitful fever. The

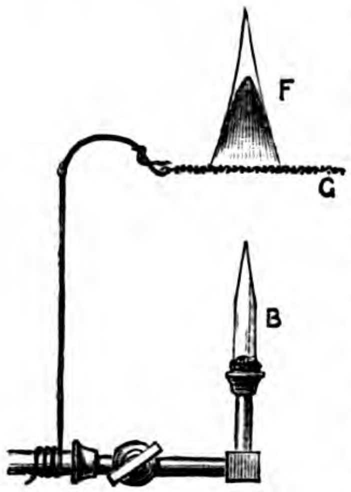


Fig. 7.

falling of a pin, the scratching of a pencil, the turning of the leaves of a book, will suffice to affect such a flame; while it will do obeisance to a person speaking for every syllable he utters. The real seat of sensitiveness is below the gauze, and not in the flame, as will be better understood after we have discussed the laws of musical sounds.

A gas jet issuing under strong pressure from a round or V-shaped opening, so as to give a flame 12 to 24 inches long, is also exceedingly sensitive; to some sounds it is completely indifferent, while a single tap of a hammer on an anvil, or a note sounded on a whistle, will cause it instantly to cower, or to spread out and split up into two or more tongues. The probable explanation we shall give in connection with the more general phenomenon of sympathetic vibrations.

VELOCITY OF SOUND IN AIR.

9. The passage of sound through the air is not instantaneous, but at the rate of from 1090 to 1120 feet per second, according to the temperature of the atmosphere.

It is matter of common observation that the flash of a cannon or the fall of a hammer at some distance is seen a few seconds before the sound is heard; and that the lightning precedes the thunder by a length of time which depends on the distance of the thunder-cloud.

Many experiments have been made with a view to ascertain the exact rate at which sounds pass through the air. Among the most celebrated were those made in 1738 by the members of the French Academy of Sciences. They chose for stations the observatory on Montmartre, and the heights of Fontenay-aux-Roses and Montlhéry, near Paris. The observations were made at night, commencing after a given signal, the firing of a rocket from the observatory. Thereafter a cannon was fired at one of the stations, at intervals of from six to ten minutes, while at each of the other stations they measured the interval which elapsed between the flash of the gun and the arrival of the sound. The distance of the stations having been accurately surveyed, the velocity was calculated by dividing the distance by the time. These observations were continued during several days under very different atmospheric conditions ; and it was established

(1) That the velocity of sound is independent of the pressure and hygrometric condition of the air.
(2) That it is always the same for the same distance, or that it is uniformly transmitted.
(3) That it increases with the temperature.
(4) That it is increased or diminished by the coincidence or opposition of the wind.
(5) That it is equal to 333 metres (or 1090 feet) per second at the temperature of freezing water.*

In 1822, a fresh measurement of the velocity of sound was made under the superintendence of Arago by the French *Bureau des Longitudes*; the time taken by sound to pass between the heights of Villejuif and Montlhéry, near Paris, being ascertained on much the same principle as in the former experiments. It was found that the sound took 54½ seconds to traverse an interval of 20,355 yards ; which gives a velocity of 1120 feet a second.

An interesting experiment was subsequently made by Biot. He found that a familiar air played at the far end of the Arceuil aqueduct was heard without any alteration of the measure at the other end ; and from this he concluded that different sounds are propagated at the same rate.

To get rid of the error arising from the influence of the wind, experiments were made by the Dutch philosophers Moll and Vanbeek in 1822, when cannon were fired *simultaneously* at two stations nine miles apart, the intervals between seeing the flash and hearing the report being noted at each. All these different observations agree very closely in ascribing to sound a velocity of about 1110 feet or 370 yards per second, at an atmospheric temperature of 50°. There are other indirect methods of estimating the velocity of sound in the air, which will be explained later on.

10. **Theoretical Calculation of the Velocity of Sound.**— It is worthy of remark that, by dynamical principles, the

* Jamin, *Cours de Physique.*

velocity of sound in air may be calculated *theoretically* from the known elastic force of the air and the known density; account being taken of the fact that the sonorous condensations are in themselves a source of increased *temperature*, and therefore of increased elasticity in the medium, and consequently of increased velocity in the passage of sound. The first theoretical estimate of sound-velocity was made by Sir Isaac Newton, but it fell considerably short of that determined by experiment, on account of his having failed to apprehend this increase of aërial elasticity. As a general rule, it is found, both theoretically and experimentally, that the velocities in different gases are inversely proportional to the square roots of the densities of the two gases. Thus, while the velocity in air is 1092 feet per second at the zero of temperature, that in oxygen is 1040 feet; in hydrogen, 4164 feet; and in carbonic acid gas, 858 feet. In hydrogen, therefore, with one-sixteenth of the density of oxygen, the velocity is almost exactly quadrupled.

TRANSMISSION OF SOUND BY LIQUIDS AND SOLIDS.

11. **Liquids and Solids, as well as Gases, serve to transmit Sonorous Pulsations.**—The transmission of sound, like the transmission of a mechanical shock through a row of ivory balls, is at once the result of, and a proof of, **elasticity** in the transmitting particles. Now, though the elastic play of the particles in liquids and solids is very much more limited than in gases, still their return to their original situation is all the more prompt and perfect. Hence liquids and solids transmit sounds even more readily than air and gases do.

The high conducting power of liquids for sound was proved conclusively by experiments conducted by MM. Colladon and Sturm at the Lake of Geneva in 1827. A bell rung under the water was heard distinctly at the other side of the lake, a distance of nine miles; and by the following arrangement, the time which the sound took to travel through this distance was also ascertained. Two boats were moored on the lake, and from the one was suspended, so as to be immersed in the water, a bell, which could be struck by a hammer. The hammer was fixed at one end of a bent lever, at the other end of which was a lighted match, which inflamed some gunpowder at the same instant as the hammer struck the bell. At the second boat was immersed a hearing-trumpet, or acoustic horn (see sect. 15), whose wide end was plunged below the water, while the other was placed in the ear of the observer. In this way the interval elapsing between the luminous signal and the arrival of the sound could be accurately measured. These experimenters found that the sound travelled 4708 feet, or nearly five-sixths of a mile, in one second ; a rate fourfold as great as in air.

By an indirect method Wertheim determined the velocity of sound in a variety of liquids ; he found that a solution of any salt in water invariably improves its conductibility, calcic chloride increasing it as much as fifty per cent.

12. **Illustrations of the high conducting power of Solids for Sounds.**—The schoolboy descries the approaching train, while yet miles away, by applying his ear to the line. The child is astonished when he puts his ear to a poker or to a stick resting on the lid of a kettle on the fire, to hear the boiling of the water increased to a loud rumbling noise. Skaters on the ice can be heard most distinctly by laying one's ear on the ice, at a much greater distance than through the air. If we support a common poker by a string tied round its head and held by our teeth, while we strike the lower end of it, the sound is painfully strong, being conducted to the sentient ear, not through the air as usual, but through the bony structure of the skull. Similarly, if we strike a common tuning-fork and hold it against the teeth, the sound is much stronger than if simply held in the hand ; the sound of a music-box playing while it rests on the top of the head may be even painfully intensified.

In the case of solids it is seldom that continuous lengths of sufficient extent can be obtained for the direct method of measurement, such as that described for air and water, and recourse is therefore had to indirect modes of calculating their sound conductivity, such as will be explained at a later part of the manual. M. Biot, however, determined directly the time taken by the sound of a hammer to traverse a continuous conduit of about 1000 yards of iron water-pipes, in the city of Paris : he found that while the sound took $2\frac{4}{5}$ seconds to travel along by the air inside the pipes, it took only $\frac{3}{10}$ths of a second to traverse the metal pipes themselves ; or that the velocity in the latter was more than nine times that in air.

The transmission of musical notes through miles of wire by the TELEPHONE is not really a case of sound transmission at all, but an electrical contrivance, and will be explained after we have discussed musical sounds.

13. **Relative Conductivity of Solids.**—Of solids the best conductors are glass, fir, and steel ; wires of the latter forming the best conductors known. The following table is based on Wertheim's calculations for the velocity of sound in some solids, that in air being taken as unit :

Lead	about 4	Brass	$10\frac{1}{3}$
Gold	$5\frac{1}{2}$ to $6\frac{1}{2}$	Copper	11
Tin	about $7\frac{1}{3}$	Oak	10 to 12
Silver	8	Fir	$12\frac{1}{2}$ to 17
Platinum	$8\frac{1}{3}$	Glass	15 to $16\frac{1}{2}$
Zinc	10 to 11	Steel	15 to 17

Much, however, depends on the **molecular structure** of the solid. Thus wood transmits sound more than three times as readily along the fibres as across them ; just as it transmits heat and other molecular affections better in the one direction than in the other.

In liquids and solids, as in gases, the velocity of sound may be calculated *theoretically* from a knowledge of the density and of the degree of compressibility of the material ; the results so obtained have been found to agree wonderfully with those obtained by actual experiment. Conversely, from a knowledge of the density of any material, and of the velocity of sound through it, we may calculate the degree of its compressibility—a proof of the fact that those parts of physics or natural philosophy which appear at first sight most widely separated may turn out to be closely connected.

REFLECTION OF SOUND.

14. **Sound reflected like Light.**—When a sonorous pulse or sound-wave meets any obstacle, it is reflected or rebounds from it very much as an elastic ball rebounds from a hard surface, or like the reflection of light from a polished surface. Thus a person A, as in fig. 8, shouting in the neighbourhood

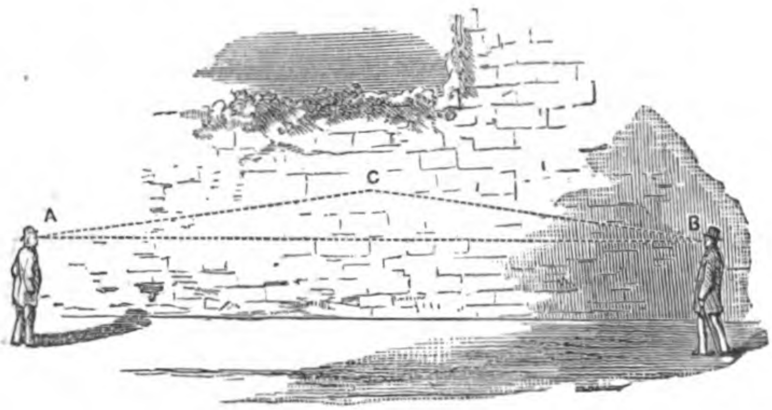


Fig. 8.

of a gable of a house, or of a high wall, or of a perpendicular rock, will be heard by a party in the position B as giving double shouts, one sound having travelled directly along AB, the other having come to his ear after reflection at C. Also the law of the sound-reflection is precisely the same as that according to which a ball thrown by the party A in the line AC would have receded from the wall—namely, so that the directions of approach and recession make equal angles with a line perpendicular to the face of the wall at C. This is, moreover, the same as the law of light-reflection ; for if there were a mirror placed on the wall at C, the person B would then be just able to see the image of the person A.

This being so, it follows that all the phenomena of sound-reflection will be precisely analogous to those of the reflection of light; a fact which may be prettily illustrated in the following way (fig. 9). Two similar polished metal mirrors of a parabolic shape are placed facing each other as here represented, and at a distance of twenty feet or more. After some adjustment, it will be found that the light of a candle flame placed at A, the focus of the one mirror, will be reflected and gathered in an image at B, the focus of the other mirror. If we remove the candle and substitute a watch at A, it may be heard distinctly ticking by the ear placed at B, though quite inaudible anywhere else round B. The sound pulses are all gathered together or condensed at B exactly as the light and heat of the candle were.

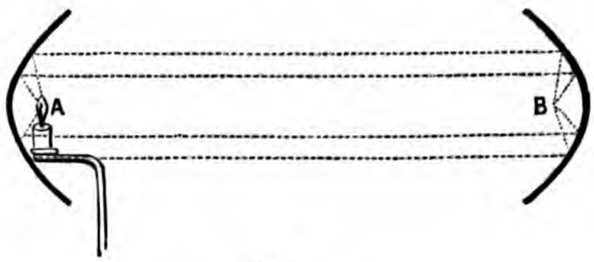


Fig. 9.

Many illustrations and applications of this concentration of sound by regular curved surfaces might be quoted. Two or three will suffice in this connection.

15. **The Ear-trumpet and the Speaking-trumpet.**—If we suppose one of the parabolic mirrors figured above to be prolonged at the back into a tubular shape, or to be pierced at the back and connected with a tube—which may be of metal, or glass, or india-rubber—we have the well-known **ear-trumpet**, used by persons hard of hearing. Its form is very various—sometimes simply conical, sometimes little more than a shell of metal worn attached to the ear or ears; but the principle is the same in all, and consists of a 'bell' or collecting mouth-piece, and a smooth tube for conveying the concentrated sound to the ear.

Again, by a slight modification of the ear-trumpet, adapting the tube to the larger opening of the mouth, we convert it into a **speaking-trumpet**, such as a ship-captain uses to convey his commands amid the noise of a stormy sea. It is often simplified into a wide-mouthed cone of metal. The speaking-trumpet acts the part of the reflector on the left, in fig. 9, and the hearing-trumpet that of the reflector on the right. The former preserves a body of sound, as it were, in the required direction, while the latter enlarges the natural collecting apparatus of the external ear.

The **Whispering Gallery** of St Paul's Cathedral, or any round room, acts as a condenser or reflector of sound to a focus; so that a person whispering at one side near the wall is heard distinctly by a person if exactly at the opposite side with his ear near the wall, but he is not heard by those at any other intermediate part. There is also a whispering gallery in Gloucester Cathedral, consisting of a passage leading from the one aisle to the other behind the east window of the choir. It is three feet wide, about seven feet high, and over seventy feet long; and two persons may converse in whispers, one placed at each end and near the wall; they hear as distinctly as if they were close together. Circular or dome-shaped vaults often exhibit this power of sonorous condensation in a remarkable degree.

The **Stethoscope** may be called a small wooden ear-trumpet by means of which the surgeon listens to the internal sounds of breathing in a patient, being trained to recognise by them the action of a healthy or a diseased state of the organs within (fig. 10).

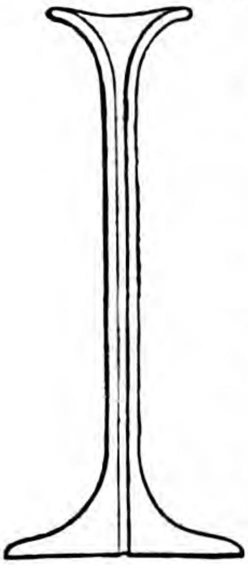


Fig. 10.

16. **Speaking-tubes** are simply cylindrical reflectors of sound, which prevent the dissipation of intensity that occurs in the open air, and which convey sounds almost unaltered to great distances. They are now in common use in offices, hotels, and other large buildings for conveying messages from one part to another; and they are sometimes used on board ship between the captain's cabin and the topmast. There must be a smooth interior, and no sudden bend, in the pipe, to allow the uninterrupted reflections. A deep well or a tall chimney-stalk acts also in the same way.

There can be no doubt that the magicians of olden times were acquainted with this means of transmitting sound, and made use of it for the practising of their deceptions. In the famous Egyptian labyrinth of Darius Hystaspes, there were twelve palaces and fifteen hundred underground vaults, where, if we may credit Pliny, the reverberations of a closing door produced a sound like peals of thunder;

and this artifice was employed to impose on the awe of the people and impress the divinity of the king.

The 'speaking heads' of Greece were in all likelihood but the mouth-pieces of priestly impostors, whose 'oracular' responses were conveyed by pipes from some neighbouring apartment ; and similar deceptions have been palmed off as speaking-machines even in modern times.

17. **ECHOES.**—The familiar *echo*, which is to the youthful mind such a source of wonder and delight, is caused by the reflection of sound from a large even surface at some distance, such as a wall, or rock, or hill, or cloud ; and just as a ball thrown right against a hard surface rebounds along the line of its approach, so a person shouting in front of a lofty wall or perpendicular rock, hears his words thrown back in his face as by some unseen tantaliser.

The distance of an echoing surface may be readily ascertained by noting the time which it takes to return or echo a single shout. Since, as we have seen (sect. 9), sound travels at the rate of about eleven hundred feet per second, it is clear that a sound will take one second to reach and return from a reflecting surface at half that distance, or 550 feet. Hence if, for every second elapsing between a shout and the return of its echo, we allow a distance of 550 feet, or 183 yards, we can ascertain at once the approximate distance of any inaccessible object, such as a mountain or rock, across a ravine or a river.

Further, on the distance of the echoing surface depends the number of syllables which will be heard when a person stops speaking. If the surface be a very good reflector, and at the distance of 550 feet from the speaker, as many syllables will be heard as have been pronounced during the last second—three or four on an average : and at a greater or less distance, a number of syllables proportionally greater or less than this will be audible.

18. **Multiple Echoes.**—If there are several reflecting surfaces, as in an amphitheatre of precipitous mountains, nothing can be grander or more sublime than the primary and secondary echoes produced by the discharge of a piece of ordnance : the reflected sounds blend together in terrific

confusion, like the reverberations of a thunder-clap between masses of cloud. Several examples of artificial and natural multiple echoes are given in Sir D. Brewster's *Natural Magic*, and in Sir J. Herschel's *Treatise on Sound*, to which reference must be made for full particulars on this part of acoustics. We shall extract only one of these examples: At the Marquis of Simonetta's villa, near Milan, there are two parallel walls, extending from the main body of the villa, and with surfaces unbroken by doors or windows. It is stated that a word sharply spoken between these walls is repeated some forty times; while a pistol-shot is echoed about sixty times. In ordinary rooms, as those of a dwelling-house, the reflected sounds are heard so nearly at the same instant with the original that they cannot be distinguished, and no confusion ensues: but in larger rooms, especially if empty of people and unfurnished, the mixing up of the reflected with the original sounds is very apparent; and though the presence of an audience, of furniture, &c. in a lecture-room serves considerably to destroy these troublesome reflections of sound, by destroying the uniformity of surface requisite to an echo, still instances of ill-planned churches, theatres, and halls are frequently to be met with, where a speaker's words are followed by this disagreeable commentary.

PROFESSOR TYNDALL'S EXPERIMENTS.

19. **Aërial Reflection and Refraction of Sound.**—A special interest attaches to the subject of sound-reflection from the recent researches of Professor Tyndall on what he calls *Acoustic Transparency and Opacity of the Atmosphere.* Prior to the exhaustive experimental investigation of this distinguished physicist, the opinion was universally entertained that in damp days, especially if there be fog, or snow falling or fallen, sounds penetrate the atmosphere less readily than with an optically clear sky. By an extended series of observations made during 1873 and 1874, off the South Foreland, near Dover, Dr Tyndall proves the popular idea to have no foundation in fact. Experimenting

with air- and steam-whistles, with trumpets sounded by compressed air, and with guns, he obtained at first the most conflicting results: on some days the sounds could be heard only two or three miles from the shore; while on others they were audible at nine miles, or even more. On the 3d July 1873, with a calm clear atmosphere, and a smooth sea, the sound of the huge horn, eleven feet long, blown by compressed air, did not reach three miles out to sea; whereas two days previously, 1st July, in the midst of a dense haze which quite hid the Foreland, the sound of the horn was distinctly heard at ten miles out, and even at a distance of twelve and three-quarter miles in a direction oblique to that of the axis of the trumpet. These antagonistic results Professor Tyndall reconciles by ascribing the stoppage of sound on optically clear days to the presence of invisible **Acoustic Clouds**, or sections of air differently heated, and differently charged with moisture, which acoustically would produce the same effect as a mixture of spirits and water optically. They have nothing to do with ordinary visible fogs or haze; the intercepted sound is lost in repeated reflections between the strata of different density, as light is wasted by repeated reflections in an ordinary cloud.

He also found that **aërial echoes**, or reflections of sound, may occur with a perfectly clear atmosphere; for sounds were sometimes inaudible at a few miles in the direction in which they should have been strongest, while they were audible at a much greater distance in another and oblique direction; as if they had struck an invisible aërial wall.

Neither rain, nor hail, nor snow, nor fog has any sensible power to obstruct sound; on the contrary, fogs, being usually associated with a uniformly dense or homogeneous atmosphere, are rather favourable to the transmission of sound than otherwise. It seems probable also that the air exercises a **refractive** power on sounds; that is to say, that a diminished temperature and elasticity in the upper stratum of the atmosphere cause sound-waves to be lifted or bent upwards very much as light-waves are refracted or bent in traversing media of unequal density. Thus sounds may be inaudible at the level of the sea, but audible at a higher level on account of this refraction. It accords with this theory, that a lens-shaped bag of collodion filled with a gas denser than common air, carbonic acid gas, has been found to condense sound exactly as a glass lens condenses light. These remarkable results obtained by Professor Tyndall furnish a striking instance of the caution with which we should accept merely common observation as a foundation for physical arguments.*

PART II.

THE PHYSICAL BASIS OF MUSIC.

20. **Noise and Tone distinguished.**—All sounds may be classified into (1) *noises*—that is, sounds more or less harsh or disagreeable to the ear; and (2) *musical tones*, which are more or less pleasing. The physical fact underlying this distinction of sense is that noises are caused by *irregular* vibrations of the sounding body, while musical tones are due to *perfectly regular* vibration.

The tumult of an angry crowd, the raging of the wind and rain in a storm, the crash of falling timber, the rattle of a cab along the street, the rumbling of thunder, the dashing of the ocean waves among the rocks, have all an irregular element in them, which contrasts strongly with the soothing calmness of the sound heard when a key of a harmonium is held down, or a note sung by a female voice. In some cases indeed it is difficult to draw a sharp line and say whether a sound be musical or not; the truth being that every noise has in it musical elements, and may in reality be but an unpleasant combination of such—as for instance when several adjoining notes of a piano are struck together,

* See Tyndall, *On Sound*, 7th ed., pages 257—320, for full details of the experiments and observations in connection with this matter.

or when a person attempts to perform on the violin for the first time.

21. **Definition of a Musical Sound.**—Any regular sequence of aërial pulsations, in whatever way produced, will, if sufficiently rapid, constitute a musical tone.

If we draw an iron nail along the teeth of a file, or a walking-stick with sufficient rapidity along a railing, or the finger-nail along a piece of wire-gauze, we produce in a rough and ready way a musical note. The noise of a cab on the paved street has a slightly musical effect at a distance where the irregularities of the paving cannot be discerned; just as the thousand diverse sounds of London fuse into a massive bass hum to the listener on a quiet night in the outskirts of the metropolis. It is no matter how the aërial pulsations are set up: the puffs of a steam-engine, as Professor Tyndall remarks, following with sufficient rapidity would combine into a huge roar, which would render a whistle unnecessary to announce the approach of a train. So the flapping of a pigeon's wing, or the ticking of a clock, only requires to be accelerated to produce in the mind a musical tone.

These facts may be more philosophically and accurately studied by two methods which we shall indicate: the first, which may be called the **synthetical** method, builds up a musical note out of a rapid succession of regular pulsations of the air; the second, which may be called the **analytical** method, resolves a musical note into its component vibrations.

SYNTHESIS OF MUSICAL TONES.

22. Perhaps the simplest method of fusing vibrations into a tone, is to hold a piece of card against a toothed wheel which we can turn at any degree of speed we please. While we turn slowly, each separate tap is distinctly heard; but as we increase the speed, a low note begins to be heard, which gradually rises as the velocity is increased, until it may reach a shrill screech.

If our wheel had say sixty teeth, we should find that, if we turned the handle once a second, the resulting sound would be distinctly recognisable as a musical note ; as we turned more and more slowly, we should reach a limit beyond which we could not call the tappings a single tone. Different ears would assign a different limit ; but on the average it may be given at about twenty to thirty pulsations per second. This is called the **inferior musical limit.**

In like manner we should find that beyond the painful screeching sound there would come a rate of tapping which would fail to affect the ear at all ; this limit, which is still more vague, and more variously assigned, is called the **superior musical limit.***

It is illustrative of this subject to mention that the sound of a gnat is due to the flapping of the insect's tiny wings, and not to any mouth sound given forth ; to many people the sound is too acute to be audible, as is also the chirping of the cricket.

23. **THE SYREN.**—An equally simple and no less instructive method of building up a musical note out of individual pulsations is by what is called the *Syren.* In its simplest form as devised by Seebeck of Berlin, this is a disc of pasteboard, as in fig. 11, with several concentric circles of holes punched in it, and rotated by a set of multiplying wheels. If the disc be rapidly

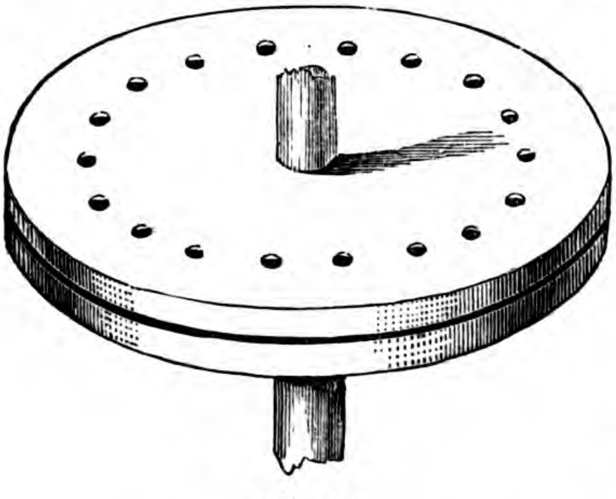


Fig. 11

whirled, while we blow through a tube against a circle of holes, we produce a note, more or less loud according to the velocity of rotation, by the succession of puffs which escape as each hole comes against the end of the tube. Having a mechanical counter to indicate the number of turns made per second, and having a fixed number of holes

* The employment of toothed wheels for the numerical estimate of musical sounds, is due to Savart, a famous French acoustician of the end of last century.

in each circle, this evidently serves the same purpose as the toothed wheels in giving us a numerical estimate of the rate of pulsation for the inferior and superior musical limits.

This simple contrivance developed in the hands of the French philosopher, Cagniard de la Tour, into a beautiful self-registering apparatus, rotated by the same blast which causes it to sound. Fig. 12 will give an idea of it. The air entering from a bellows by A, passes into the box B, which has a set of holes in its lid corresponding to a set in the movable disc, D, above it. The disc, D, fits so closely to the lid of B, that unless the holes are against each other, no air can escape from B. The holes are bored obliquely, so that after D is started, each little puff, as it escapes from B, will impinge on the side of the hole in the disc, and so cause the disc to whirl at almost any velocity we please. The axle of D registers the rotations of the disc by means of an endless screw and toothed wheels, C, C, which carry indicating hands. Knowing the number of holes in a circle of the disc, and the rate of rotation, we know of course the rate of aërial pulsation, and by this instrument we are enabled to study and demonstrate many of the physical laws of musical sounds. A modification of the syren, known as **Helmholtz's double syren**, which has proved of immense value in the hands of that renowned acoustician, will be explained under section 69.*

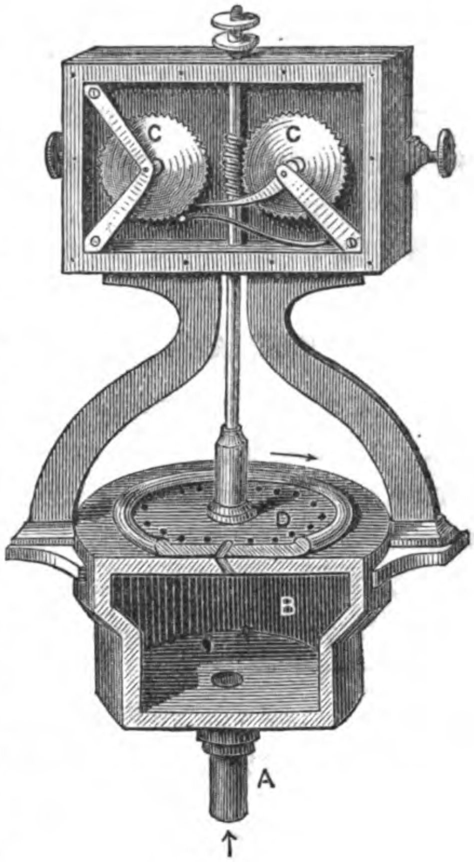


Fig. 12.

* The principle of the syren has recently found a remarkable practical application as a most powerful source of sound for fog-signalling. See Tyndall, *On Sound*, page 260.

24. **Isochronous Vibration of Elastic Bodies.**—The vibrations of an elastic body, such as a string, or spring, or membrane, are, like those of a pendulum of a given length, quite isochronous or regular; hence this property of elasticity furnishes the readiest means of obtaining a vibration sufficiently rapid and regular to give the sensation of sound; and the mass of our musical instruments, from the Jew's harp to the finest harmonium or piano, are dependent for their musical effects simply on the rapid isochronous vibration of elastic matter. The more particular consideration of their vibration will, however, come before us in an after part of the manual.

THE ANALYSIS OF MUSICAL VIBRATION.

25. A sounding body, such as an elastic string, a tuning-fork, a musical pipe, or even the human voice, may, by various contrivances, either be made to exhibit its component vibrations momentarily to the eye, or permanently to record them on a suitable surface. The former is called the *optical* method of analysing musical sounds, the latter the *graphic* method.

I. Optical Methods of analysing Sound-motion.

26. The simplest mode of exhibiting the individual vibrations is one of the prettiest. We have only to fix a small piece of silvered glass bead on the end of one of the legs of a tuning-fork or of a steel spring, and after striking the fork or spring, move it quickly to and fro across the direction of vibration. The result of the two motions is to spread out the vibrations in a lovely luminous ripple; the size of the individual waves depending on the degree of vibration of the fork.

27. **Revolving Mirror-box.**—Instead of waving the fork to and fro, we may substitute another ingenious contrivance, represented in fig. 13; M is a box whose sides consist of four pieces of common looking-glass; the whole is suspended by three wires and a string, S, as here shewn, so that by twisting the string a rapid rotation can be given to

the mirrors. If now we strike a fork, F, provided with a small piece of reflecting bead, B, and hold it up in front of the whirling mirror-box, we shall see a lovely, luminous, wavy line reflected in the glass. We may in this way fix two or more forks underneath each other, and having sounded the whole, compare the rate of vibration by the comparative numbers of waves of the luminous lines. The whirling mirror-box may also be employed to shew the vibrations of an elastic string, by gluing a small piece of reflecting bead on the string.

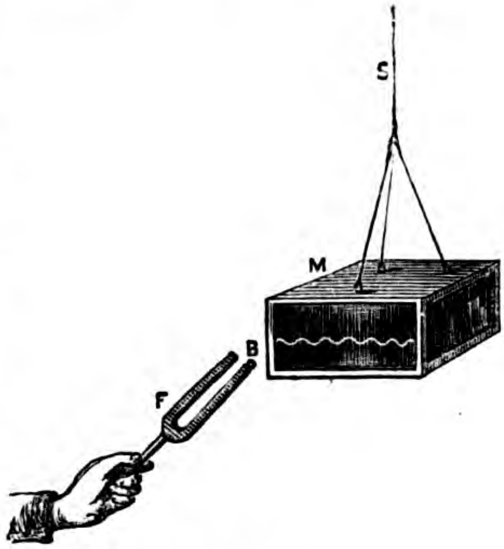


Fig. 13.

28. The **Flame-vibroscope**, as we may call it, is a simple contrivance employed along with a rotating mirror-box to render the vibrations of the human voice or of a sounding organ-pipe visible. This method is due to the distinguished acoustician, M. König of Paris, and is usually called the **Flame-manometer.** We have employed the following simple mode of constructing the apparatus. Two capsules, C, of

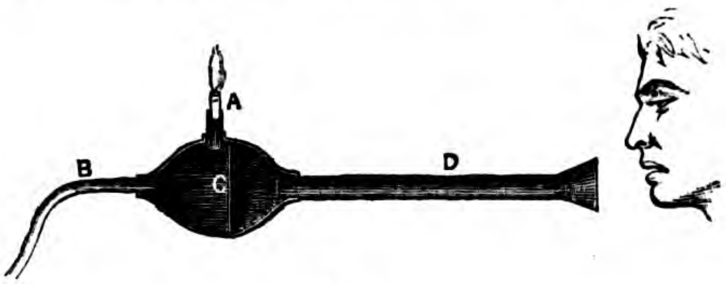


Fig. 14.

gutta-percha are moulded with the fingers by the aid of some hot water. Into the one we fix a small glass jet, A, and also a glass or lead tube, B; while into the other capsule we insert simply one tube or pipe, D. Over the first capsule we now fix, by heating slightly, a piece of common bladder or oiled silk, or even thin paper; we then heat the mouth of the other capsule gently and press the two together, so as to have, as in the figure, an air-tight separation of the two halves by an elastic diaphragm. On admitting some coal-gas by the tube B, and lighting at A, we get the vibroscopic flame. If we sing a note into the funnel of the pipe D, we cause the diaphragm to vibrate and the flame to 'bob' at the same rate. The bobbing of the flame can scarcely be detected by the eye alone; but if we look at the reflection of the flame in our revolving mirror-box, we see not a luminous band of flame, as we do when there is no sound, but a row of luminous tongues more or less crowded together according to the height of the note and the rate of rotation of the mirrors. This is one of the most striking experiments in acoustics, and we shall have occasion to refer more than once to this mode of examining sound-vibration. The appearance is most beautiful in a darkened room where there is no light but that of the small

Fig. 15.

vibroscope flame; the fiery tongues may then be seen to perfection by a large company at the same moment. It may, however, be employed for purposes of study in broad daylight.

29. **Lissajous' Experiments.**—Another method of studying the vibrations of sounding bodies, such as tuning-forks, is due to M. Lissajous. It is similar in principle to the first and simplest optical method mentioned by us; the only difference being in that the light from a silvered mirror attached to the fork is cast, not into the eye directly, but upon a screen. It will be readily understood. A large tuning-fork has a piece of mirror attached to one prong, with a counterpoise attached to the other. The light from a lamp is allowed to fall on the mirror so that when the fork is at rest a single bright spot will be reflected on the

screen. Thus, if we strike the tuning-fork and move it slightly with the hand, we cause the vibrations to write themselves on the screen in wavy lines of light. Instead of moving the tuning-fork, we may catch the reflected light on a second mirror and move it simply. In this way the white ceiling of a room forms a convenient ground on which to exhibit these lines.

M. Lissajous has employed, instead of this second mirror in the hand, a second mirror mounted on a tuning-fork like the first. Thus there may be depicted on a screen the optical resultant of the two simultaneous vibrations whose combined acoustical effect is revealed by the ear.

The results obtained from these experiments are exceedingly interesting, not only in their acoustical bearing, but as illustrative also of the mechanical resultant of simultaneous motions. Two tuning-forks are placed so as to have their mirrors perfectly parallel, the one capable of vibrating in a horizontal, the other in a vertical plane: the vibrations of the former tuning-fork stretch out the point of light in a horizontal line, and those of the latter in a vertical line; the superposition of the two images gives a curve which is quite determinate for the same two tuning-forks. For example, if the two tuning-forks are vibrating at the same rate (and their notes consequently in *unison*, as we shall afterwards explain), the resulting curve will be a *circle*. If one fork be vibrating twice as fast as the other (and the note of the one consequently the *octave* of that of the other), the luminous path is a *lemniscata*, or figure of eight. If the rates of vibration be as two to three, the curve is a double figure of eight. If again the rates of vibration be as three to four, the resulting curve is more complicated; and so on, *the more complicated the vibration-ratio is, the more complex is the resulting luminous scroll.*

If the rates of vibration be not exactly but only approximately as above, then we shall not obtain a steady luminous scroll, but a variable one passing through several phases, of which the above may be taken as the complete, central, or fully developed forms.

30. The **Vibration Microscope**, a modification of this method

of Lissajous, has been employed by Helmholtz to analyse the vibrations of a violin string. He fixes a grain of starch or some white substance on the string, and looks at it through a microscope whose object-glass is mounted on the prong of a tuning-fork, placed so that it vibrates across the string. The same optical composition of motions takes place as if a bright spot of the string reflected its light to a mirror mounted on the fork; but the device of Helmholtz is better adapted to individual examination of the motion than that of Lissajous.

31. A still simpler but very ingenious mode of studying these vibration-figures has been devised by M. Melde of Marburg. It consists of two pieces of similar spring soldered together by a square nut, so as to have their faces at right angles to each other, and therefore to be capable of vibrating only in rectangular planes. By fixing the lower spring in a vice, we may make the ratio of the length of the one to that of the other anything we please. A reflecting bead on the upper end serves to portray the resulting path of the end of the spring, which, by a suitable adjustment of lengths, will be any of the above figures.

32. **Blackburn's Pendulum.**—Lastly, for the more perfect comprehension and analysis of this composition of motions, a simple heavy ball or pendulum may be employed. If a heavy lead or brass ball, B (fig. 16) be hung, not by a single, but by a double string, attached to two separate points of support, A, D; then, by means of a stiffly sliding piece, C, we may make the ratio of CB to CE anything we choose. From the nature of the suspension, it is clear that the part CB can be made to vibrate in any direction we please, while the triangular portion ACD will vibrate only across the direction AD. Hence,

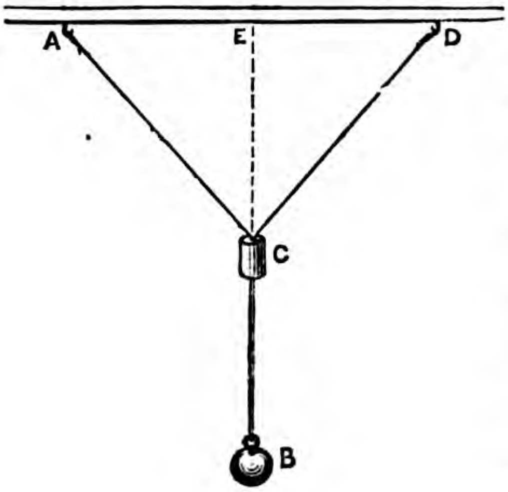


Fig. 16.

if we make CB oscillate along the direction AD, while ACD oscillates across it, we shall have a rectangular composition of vibrations sufficiently slow to be followed by the eye in its every phase. Thus we may compound cross vibrations of the ball B, and by attaching a needle or a camel's-hair pencil below, the resulting motion may be made to record itself permanently on sand, on smoked glass, or on paper. The subject is exceedingly interesting even from a purely mechanical point of view, and will amply repay fuller investigation than we can here afford to give it. From its immediate bearing on acoustics, many other mechanical contrivances have been devised to elucidate this composition of vibrations; among these we can simply name Sir Charles Wheatstone's apparatus, Mr Hubert Airy's apparatus, Mr Tisley's apparatus, and Mr Donkin's apparatus, descriptions of which will be found in the scientific magazines.

II. Graphic Methods of analysing Vibrations.

33. The automatic registration of motions is now employed in many departments of science. In the present instance it is valuable because the motions are too quick for direct perception; in other instances, it is because they are too slow or too complicated. Thus the motions of the earth during an earthquake, the rise and fall of the column of mercury in a barometer, the beating of the human heart, the motions of inspiration and expiration, the flappings of an insect's wings, may all be made to write their own story in a permanent form, which we can decipher at leisure, and which, when carefully examined, often reveals otherwise latent characteristics of the motion.

To record the vibrations of a tuning-fork, we attach to one of the prongs, with a little wax, a common pin or a small pointer of steel spring; we next smoke a slip of glass or of card-board, and having struck the fork, and held it so that its pointer just grazes the smoked surface, we draw the latter smartly along. The result is a wavy line, which shews the actual number of vibrations made by the fork while we drew along the surface. Of course a much more exact method is required in practice for actual calculation of the number of vibrations made by a fork per second. To do this, we employ a cylinder of brass covered with a sheet of smoked paper for our recording surface, which we can turn at a uniform rate by a handle or by clock-work; and we have our tuning-fork fixed in a suitable position, using a well-resined fiddle-bow for sounding the fork.

34. **THE PHONAUTOGRAPH** is an apparatus by means of which any sound whatever, whether of the voice in speaking or singing, or of a musical instrument, or of thunder, may be made to picture itself on a sheet of smoked paper. The instrument, as constructed by the famous acoustician of Paris, M. König, consists of a large conical or funnel-shaped body, made of sheet-zinc, open at the wide end, and provided with a ring of metal at the other end, over which a second ring fits, so as to keep tightly stretched an exceedingly delicate membrane. About the centre of this membrane is fixed, with a little wax, a single hog's bristle, tipped with a feather tuft, to serve as a style. This style just grazes the recording cylinder, which is covered with a sheet of smoked paper. Any sound or mixture of sounds of fair intensity entering the mouth of the instrument is condensed, as by a large ear-trumpet, on the membrane, setting it in vibration. The tremblings of the style carve themselves on the smoked surface, as it is turned by the hand; and the result is a wavy line, more or less composite, according to the character of the sound. The figures obtained in this way are sometimes very curious and instructive.

35. **Sound-Photographs.**—One of the most recent achievements in this branch of science is that detailed by Dr Stein in *Poggendorff's Annalen*, for Nov. 9, 1876, where he describes his method of actually *photographing* the vibrations of sounding bodies, such as a tuning-fork or vibrating string. A tuning-fork is fixed horizontally, and having a hole in one of its prongs, through which a beam of light passes, so as to fall on the sensitised plate of a camera. The vibrations would simply photograph a vertical line on an ordinary camera plate;

but by introducing an arrangement, such as a spring, whereby the plate can be rapidly moved in a horizontal direction, the result is that a sinuous line of light acts on the plate. This method is one of considerable promise. The very *rate* of vibration of the tuning-fork is said to be indicated by the brightness of the image; for it is faintest where the motion of the fork was fastest, and brightest where it was slowest. Dr Stein finds it possible to photograph all ordinary musical tones, and even those which transcend the limit of hearing; thus shewing that the chemical sensitiveness of the plate is more acute than the auditory sensitiveness of the brain.

THE THREE ELEMENTS OF TONE:

INTENSITY, PITCH, TIMBRE.

36. Musical sounds have three distinct elements, corresponding to the three elements of vibratory movements, which we have seen to be the fundamental characteristic of such sounds. These are: (1) *loudness or intensity* of the sound corresponding to the *extent* of the vibration; (2) *height* or *pitch* of the sound corresponding to the *rate* of the vibration; and (3) *character*, *colour*, or *timbre* of the sound, which distinguishes the same note as produced by different instruments, such as the violin, the flute, the human voice, &c., and which corresponds to the *nature* of the vibration.

37. **Intensity.**—Musical sounds, otherwise the same, may differ in mere loudness, as when the same tuning-fork is struck sharply and then lightly. There is the same number of vibrations per second if we reckon them by any of the methods described above; only, in the former case, they sway to and fro through a greater extent than in the latter, and consequently they set up more vigorous air-pulsations and more violent tappings on the drum of the ear. Sometimes indeed we may have a body vibrating with all the rapidity and regularity needed for a musical sound; yet the vibrations may be inaudible for mere lack of energy. Unless a sufficient volume of air be set in pulsation by its connection with a large elastic surface, the vibrations of

an elastic string or of a tuning-fork are very faint. This can be shewn by stretching an iron or brass wire tightly between two pegs in the stone walls of a school-room: on plucking or 'bowing' the wire, no sound will be heard; but if one of the ends of the wire be connected with the black-board, it takes up the vibration, and the sound then becomes audible to all in the room. It is well known that a tuning-fork, simply held in the hand when struck, gives little or no sound; but if it be placed on the lid of a box, or on a table, or on a pane of glass, its note sounds forth full and strong; and if placed against the teeth, painfully so.

38. **Importance of the Sounding-board of a Musical Instrument.**—For a like reason, the sound of a music-box may be poor if held in the hand, but very rich if laid on a table. Thus the musical quality of a violin, of a pianoforte, of a harp, or of any stringed instrument, depends not on the strings, but on the elastic material of the frame or sounding-board which publishes their vibrations. The value of an old Cremona lies in the elimination by time of those resinous particles of the wooden body which in the green state fetter the vibration.

An experiment illustrative of this same fact, as well as of the remarkable sound-conductivity of wood, used to be performed at the London Polytechnic. In a room below the lecture-theatre, where the audience was assembled, there was placed a piano, and resting on the sounding-board of the piano was a rod which, passing through the floor, ended in a broad elastic board in the upper room. Tunes played by a performer in the lower room were given forth in perfection by the board in the midst of the audience above, whose imagination might easily ascribe them to spiritual agency, were the simple scientific explanation withheld.

This experiment of Wheatstone's may be imitated in miniature by inclosing a music-box within cases of thick felt or sheets of cotton-wool, with a rod passing through these layers, and resting on the wooden box. So long as the simple rod connects the box with the external air, no sound is heard; but if a thin disc of wood or card-board be fixed to its outer end, the music instantly becomes audible.

39. **Pitch of Tones: Musical Relations of Pitch: The Sonometer.**—The second quality of musical sounds is *pitch* or *height*, by which they are distinguished into high and low, treble and bass, and the delicate appreciation of which constitutes a *musical ear*. We know that the number of vibrations made by a sounding body in a given time can be measured, and we have now to inquire the relation that exists between the rate of vibration and the height of a note as perceived by the ear. In order the better to apprehend these relations, we shall describe here an apparatus by which they are experimentally proved, as this tends to give a more concrete form to the bare numerical ratios. This instrument is called the **Sonometer**, and is represented in fig. 17, as usually constructed. In a more primitive shape, no doubt, it was

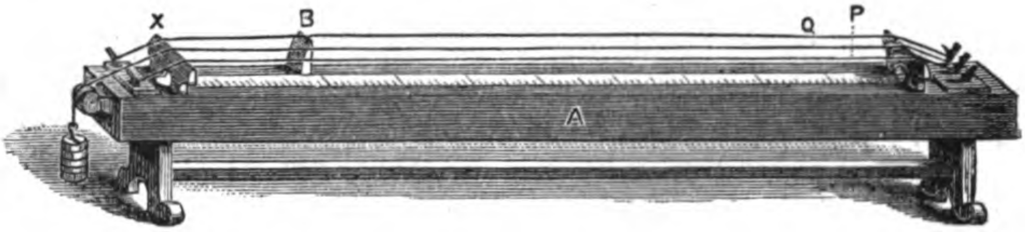


Fig. 17.

employed more than two thousand years ago by the Grecian philosopher, Pythagoras, to prove some of those very relations we are now to enumerate.

It is composed of a hollow wooden case, A, over which the sounding-strings of brass or steel wire or catgut are stretched, and which is meant to act as a resonator of the sound. A scale of reference (usually one metre long, and divided into one hundred equal parts) is marked underneath. There are generally three strings,* the two outside ones being similar, and the middle one of a different thickness or material. The two outer ones are tightened by means of screw-pins, as in a common violin; while the middle one is stretched by weights suspended from the end of the string, and is used for determining the relation

* The original instrument as used by the Greek teachers had but one string; hence the name *monochord*, which is still employed sometimes.

between the degree of tension and the note. We shall not further refer to the middle string at present, as we shall require only the outer two to illustrate our explanations. The strings may be sounded either by plucking with the fingers, by striking with a small hammer, or by an ordinary fiddle-bow. We must premise also that it is found, both from theory and by experiment, that the rate of vibration of a string is inversely proportional to its length, so that for half, third, or fourth the length, the vibration is increased two, three, or four times accordingly, the tension remaining unaltered.

Understanding this, we adjust the tension of the two strings till, when sounded, the ear detects no difference in the tone, and if sounded together their two tones fuse into one with the most perfect concord, or *unison*, as it is expressed. Both strings are vibrating at exactly the same rate; and if we were to sound a note on a tuning-fork, or a bell, or a plate, or an organ pipe, so as to be in unison with this note again, we should find, by the methods detailed above, that the rate of vibration is exactly the same in each case; so that, whatever the note may be, it has a perfectly fixed and invariable **Vibration-number** which may be used to define or designate the note.

40. **Key-tone—Consonance, Dissonance.**—Keeping the length and tension of one of these wires unaltered, we possess in it *a reference note* or *key-tone* with which we may compare the tones obtained by placing a sliding bridge under the second wire at different points. We find that if we sound different lengths of the string along with this fundamental tone, the impressions on the ear are sometimes agreeable, sometimes very harsh or discordant. When the effects of two tones agree, there is said to be *consonance;* when they disagree, *dissonance.* There are many shades or degrees of consonance, as well as of dissonance; which the ear has the faculty of discriminating, of comparing, and of classifying. Some agreements are more perfect and more pleasing than others; some disagreements are more harsh and harrowing than others. The science of music fixes and names those sounds, which, being more or

less concordant, are to be admitted within the pale of musical art; while it brands those which are to be banished from the society of the others. The test of musical fellowship among sounds is instinctive, and based, as we shall see, on the physiological structure of the ear; which, until recently, it was generally supposed to be both unnecessary and impossible to analyse. Trained musical ears were like a sort of vast masonic brotherhood, which by an instantaneous gripe could recognise those who should be admitted within the circle of their sympathy; but to seek to analyse or reveal the real basis of this sympathy was supposed to endanger the charm of the whole. Now, however, acoustics steps in, and by its anatomy of music unfolds to the intellect a gorgeous reign of law which confirms just those rules of fellowship which the musical ear had already recognised. That the man without any 'ear' at all may now *see* a beauty in the laws of melody and harmony, should only intensify the charm to those fortunate enough to enjoy it also from the emotional side.

41. **The Physical Relation of Concordant Tones.**—We shall now explain the results of the experiments made on this subject. Suppose we take any two musical tones which form a perfect and easily recognised concord, as, for example, C and E, a note and its *third*, or *doh* and *me*, as named by some musicians: in the first place, the ear tells us that the same character of concord may exist between two notes of any pitch, either high or low; and that it is consequently independent of the *absolute* number of vibrations made. Secondly, we find that if we place the movable bridge, B, of our sonometer under the second string Q, at the distance of one-fifth of the whole length of the string from one end, then the notes sounded by the string P and the shortened one will be in this relation of a *note* and its *third*; and this is independent of the actual *tension* of the strings to begin with, and therefore of the actual number of vibrations, but is dependent simply on the *relative lengths* of the two strings. From this we conclude that two strings (or for that matter two sounding bodies of any kind) vibrating at rates in the ratio of four to five, will sound a note and its

third. Conversely the ear is always satisfied with the musical effect if the rates of vibration are as five to four.

By an extended series of similar experiments with the sonometer, the following general acoustical law is arrived at:

Every musical accord between two notes is defined and can be expressed by the arithmetical vibration-ratio of two whole numbers.

It remains to examine the values of this ratio corresponding to the different concords of tones, which by experience we have come to recognise as being the most agreeable to the ear. For this purpose let us select the simple musical intervals known as the most concordant; namely, the *octave*, the *fifth*, the *fourth*, and the *major* and *minor third.*

If, keeping the strings P and Q as originally tuned to vibrate in unison or at the same rate, we move the bridge under Q so as to divide it equally, we find, on sounding half of the string Q along with P, that we have the musical relation of a note and its octave—a relation which the ear declares to be the closest possible next to absolute coincidence or unison. If we move the bridge so as to be $\frac{1}{3}$ of the length of the string from the end X, we find, on sounding P and the part of Q equal to $\frac{2}{3}$ of it, that we have the musical relation of a note and its fifth; and the agreement of a note with its fifth the ear pronounces next in order of closeness to the former. If we move the bridge so as to leave only $\frac{1}{4}$ of the string between it and X, we get a note and its *fourth;* if so as to leave just $\frac{1}{5}$, we get a note and its *major third;* if to leave $\frac{1}{6}$, we get a note and its *minor third.*

Generalising these results, we obtain another acoustical law, namely: *If we sound together two notes whose vibration-ratio is expressed by two terms of the series of natural numbers* 1, 2, 3, 4, 5, 6, *&c., we shall have a musical concord more or less perfect or pleasing according to the simplicity of the numerical ratio, and more or less displeasing as the ratio is more or less complex.* The whole series of such notes is known in music as **harmonic notes**; and we shall see at a subsequent stage that they give rise to more serious complications than might at first be imagined.

NUMERICAL RELATIONS OF THE MUSICAL TONES OF THE SCALE.

42. **The Musical Scale** is the naturally selected group of tones possessing these concordant relations. Like the numerical scale, to which it has a close relation, the gamut or musical scale is limited; for, as the whole range of numbers is obtained by repetitions of the decimal scale, with increased absolute but the same relative values, so the whole range of musical tones is obtained by repetitions of notes having higher or lower *absolute* rates of vibration or pitch, but having the same *relative* rates as those in the scale. The common scale is composed of seven notes, or steps, which are named by the seven letters, C, D, E, F, G, A, B, or by the seven monosyllables, *Doh*, *Ray*, *Me*, *Fah*, *Soh*, *Lah*, *Te*; subsequent notes being merely repetitions of these on a different level, and denoted by the same symbols, with the addition of figures to shew their relative positions, as C^1, D^1, E^1, F^1, G^1, A^1, B^1, C^2, D^2, E^2, &c.; C_1, C_2, C_3, &c. The following are the names of the notes, with their vibration-ratios relative to the first or fundamental note:

C	D	E	F	G	A	B	C^1
Doh	Ray	Me	Fah	Soh	Lah	Te	Doh^1
1	$\frac{9}{8}$	$\frac{5}{4}$	$\frac{4}{3}$	$\frac{3}{2}$	$\frac{5}{3}$	$\frac{15}{8}$	$\frac{2}{1}$
1st	2d	3d	4th	5th	6th	7th	8th

It is to be noted that the names of the successive notes, second, third, fourth, &c., here given in the fourth line, are merely *ordinal*, and have nothing to do with the fractional ratios in the third line.

Fig. 18 shews the divisions of a string or wire of the sonometer, corresponding to the successive notes of the major scale. Since the lengths of a string are inversely proportional to the rates of vibration, the ratios of the lengths are obtained by *inverting* those of the vibrations given above: hence they are 1, $\frac{8}{9}$, $\frac{4}{5}$, $\frac{3}{4}$, $\frac{2}{3}$, $\frac{3}{5}$, $\frac{8}{15}$, $\frac{1}{2}$. A convenient length to take such a string would be three feet or 36 inches; each inch corresponding to 5 of the scale in fig. 18; hence with a three-foot string we should obtain the major scale by sounding in succession (1st) 36, (2d) 32, (3d) $28\frac{4}{5}$, (4th) 27, (5th) 24, (6th) $21\frac{3}{5}$, (7th) $19\frac{1}{5}$, and (8th) 18 inches. If for the third ratio $\frac{5}{4}$ we substitute $\frac{6}{5}$, and sound a length

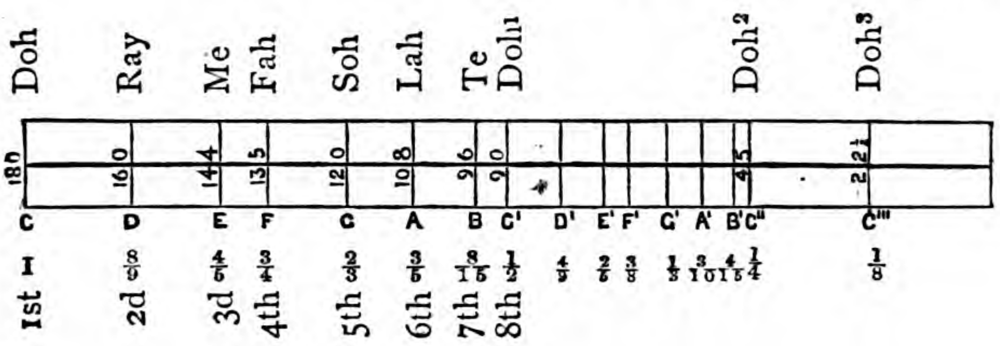


Fig. 18.

of 30 inches of the string, we get a tone which blends pleasingly with the fundamental tone of the whole string, and which is known as the *minor third;* and if for the sixth ratio $\frac{5}{3}$ we substitute $\frac{8}{5}$, or sound $22\frac{1}{2}$ inches of our string, we get a consonant tone with the fundamental, which is called the *minor sixth.* These two intervals of the minor third and minor sixth, substituted for the common or major third and sixth given above, constitute what is called a *minor scale.* Be the explanation of it what may, these intervals of $\frac{6}{5}$ and $\frac{8}{5}$ have a distinctly sad or plaintive effect, compared with a bolder or more joyous effect of the major intervals $\frac{5}{4}$ and $\frac{5}{3}$.

43. **Musical Intervals.**—The interval between one tone and another is estimated not by *subtracting* their fundamental ratios, as we might imagine at first, but by *dividing* them. Thus $\frac{5}{4}$ and $\frac{3}{2}$ are the intervals of a third and a fifth from the same fundamental tone, and the interval between these is $\frac{6}{5}$; or a perfect fifth bears to a major third the relation of a minor third to the fundamental tone. From this it will be easily understood how the calculations are made for the following table, which gives all the musical intervals between any two notes of the scale.

Seconds.	Thirds.	Fourths.
$\frac{Ray}{Doh}=\frac{9}{8}$	$\frac{Me}{Doh}=\frac{5}{4}$	$\frac{Fah}{Doh}=\frac{4}{3}$
$\frac{Me}{Ray}=\frac{10}{9}=\frac{9}{8}\cdot\frac{80}{81}$	$\frac{Fah}{Ray}=\frac{6}{5}\cdot\frac{80}{81}=\frac{5}{4}\cdot\frac{80}{81}\cdot\frac{24}{25}$	$\frac{Soh}{Ray}=\frac{4}{3}$
$\frac{Fah}{Me}=\frac{16}{15}=\frac{9}{8}\cdot\frac{80}{81}\cdot\frac{24}{25}$	$\frac{Soh}{Me}=\frac{6}{5}=\frac{5}{4}\cdot\frac{24}{25}$	$\frac{Lah}{Me}=\frac{4}{3}$
$\frac{Soh}{Fah}=\frac{9}{8}$	$\frac{Lah}{Fah}=\frac{5}{4}$	$\frac{Te}{Fah}=\frac{4}{3}\cdot\frac{25}{24}\cdot\frac{81}{80}$
$\frac{Lah}{Soh}=\frac{10}{9}=\frac{9}{8}\cdot\frac{80}{81}$	$\frac{Te}{Soh}=\frac{5}{4}$	$\frac{Doh^1}{Soh}=\frac{4}{3}$
$\frac{Te}{Lah}=\frac{9}{8}$	$\frac{Doh^1}{Lah}=\frac{6}{5}=\frac{5}{4}\cdot\frac{24}{25}$	$\frac{Ray^1}{Lah}=\frac{4}{3}\cdot\frac{81}{80}$
$\frac{Doh^1}{Te}=\frac{16}{15}=\frac{9}{8}\cdot\frac{80}{81}\cdot\frac{24}{25}$	$\frac{Ray^1}{Te}=\frac{6}{5}=\frac{5}{4}\cdot\frac{24}{25}$	$\frac{Me^1}{Te}=\frac{4}{3}$

Fifths.	Sixths.	Sevenths.
$\frac{Soh}{Doh}=\frac{3}{2}$	$\frac{Lah}{Doh}=\frac{5}{3}$	$\frac{Te}{Doh}=\frac{15}{8}$
$\frac{Lah}{Ray}=\frac{3}{2}\cdot\frac{80}{81}$	$\frac{Te}{Ray}=\frac{5}{3}$	$\frac{Doh^1}{Ray}=\frac{9}{5}\cdot\frac{80}{81}=\frac{15}{8}\cdot\frac{80}{81}\cdot\frac{24}{25}$
$\frac{Te}{Me}=\frac{3}{2}$	$\frac{Doh^1}{Me}=\frac{8}{5}=\frac{5}{3}\cdot\frac{24}{25}$	$\frac{Ray^1}{Me}=\frac{9}{5}=\frac{15}{8}\cdot\frac{24}{25}$
$\frac{Doh^1}{Fah}=\frac{3}{2}$	$\frac{Ray^1}{Fah}=\frac{5}{3}$	$\frac{Me^1}{Fah}=\frac{15}{8}$
$\frac{Ray^1}{Soh}=\frac{3}{2}$	$\frac{Me^1}{Soh}=\frac{5}{3}$	$\frac{Fah^1}{Soh}=\frac{9}{5}\cdot\frac{80}{81}=\frac{15}{8}\cdot\frac{80}{81}\cdot\frac{24}{25}$
$\frac{Me^1}{Lah}=\frac{3}{2}$	$\frac{Fah^1}{Lah}=\frac{8}{5}=\frac{5}{3}\cdot\frac{24}{25}$	$\frac{Soh^1}{Lah}=\frac{9}{5}=\frac{15}{8}\cdot\frac{24}{25}$
$\frac{Fah^1}{Te}=\frac{3}{2}\cdot\frac{24}{25}\cdot\frac{80}{81}$	$\frac{Soh^1}{Te}=\frac{8}{5}=\frac{5}{3}\cdot\frac{24}{25}$	$\frac{Lah^1}{Te}=\frac{9}{5}\cdot\frac{80}{81}=\frac{15}{8}\cdot\frac{80}{81}\cdot\frac{24}{25}$

Looking at this table, we observe that the interval of a *second*—that is, of a note to the preceding one in the scale—has three different values. The first $\frac{9}{8}$ is called the interval of a full or **major tone**; the second $\frac{10}{9}$, which is $= \frac{9}{8} \cdot \frac{80}{81}$, is called a lesser or **minor tone**, which differs from the major tone by the small interval $\frac{80}{81}$, appreciable only to a practised ear, and called a musical **comma**; the other interval of a second is $= \frac{16}{15}$, which is $\frac{10}{9} \cdot \frac{24}{25}$, and is called the major semitone. Since $\frac{10}{9}$ is $\frac{16}{15} \times \frac{25}{24}$, the tone $\frac{10}{9}$ can be divided into two half-tones or semitones, or intervals of $\frac{16}{15}$ and $\frac{25}{24}$ respectively. The former is called the **major semitone**; and the latter, the **minor semitone**, is the smallest interval which is employed in music. The tones and semitones are dissonant intervals. From this column it will be seen that the musical scale consists of

Two tones, a semitone, three tones, and a semitone.

Thirds are of two sorts; the one interval of $\frac{5}{4}$ being the greater or major third; the other of $\frac{6}{5} = \frac{5}{4} \cdot \frac{24}{25}$, is the lesser or minor third; and differs from the former by a minor semitone. The interval $\frac{\text{Fah}}{\text{Ray}}$ is less than a minor third by a comma, which, however, is so small as to be neglected in practice.

The *fourths* are all perfect intervals of $\frac{4}{3}$, with the exception of $\frac{\text{Te}}{\text{Fah}}$, which is greater than a perfect fourth by a minor semitone and a comma ($\frac{25}{24} \cdot \frac{81}{80}$), and is a dissonant interval; and $\frac{\text{Ray}^1}{\text{Lah}}$, which is greater than a true fourth by a comma.

The *fifths* are perfect intervals of $\frac{3}{2}$, with the exception of $\frac{\text{Lah}}{\text{Ray}}$, which is less by a comma, and $\frac{\text{Fah}^1}{\text{Te}}$, which is less by a semitone.

The *sixths* are perfect intervals of $\frac{5}{3}$, with three exceptions, $\frac{\text{Doh}^1}{\text{Me}}$, $\frac{\text{Fah}^1}{\text{Lah}}$, and $\frac{\text{Soh}^1}{\text{Te}}$, which are *minor* sixths, or less than perfect sixths by a minor semitone.

The *sevenths* are perfect intervals of $\frac{15}{8}$ only in two instances, the other intervals being diminished by a minor semitone, or by a semitone and a comma.

44. **Harmonic Chords.**—If we sound all the different com-

binations of the seven musical tones, we find that the *first*, *third*, and *fifth* notes sounded together give an exceedingly agreeable harmony; now their ratios are as $1 : \frac{5}{4} : \frac{3}{2}$; or as $4 : 5 : 6$; and we find that any three notes having the same vibrational ratios give the same species of harmony. Three such notes are consequently said to form a **harmonic triad**; and if a fourth be sounded simultaneously, which is the octave of the first, the compound is a **major chord.**

If in this chord we substitute a minor third for the major one, we have four notes in the ratio of $1 : \frac{6}{5} : \frac{3}{2} : 2$, or of $10 : 12 : 15 : 20$, which constitute a **minor chord**, with a slightly dissonant effect, a peculiar, plaintive, though not unpleasant union of notes. It is to be observed, too, that the harmonic effect of a chord still remains if any of the notes be replaced by one which is one or two octaves above or below it. Hence the major chord C E G C^1 is reckoned harmonically the same as the combination C E^1 G^1 C^1. In examining the notes of the common scale, it will be remarked that there are three perfect major chords, in one or other of which every note of the scale occurs; namely:

First........$C : E : G : C^1 = 1 : \frac{5}{4} : \frac{3}{2} : 2 = 4 : 5 : 6 : 8.$
Second.....$G : B : D^1 : G^1 = \frac{3}{2} : \frac{15}{8} : \frac{9}{4} : \frac{6}{2} = 4 : 5 : 6 : 8.$
Third.......$F : A : C^1 : F^1 = \frac{4}{3} : \frac{5}{3} : 2 : \frac{8}{3} = 4 : 5 : 6 : 8.$

45. **SHARPS AND FLATS—KEYS.**—The range of musical instruments is vastly increased by a provision for raising or lowering the notes of the scale by a half-tone (a *minor* semitone). A note so increased or diminished is said to be *sharpened* or *flattened*. Now, if we consider any of the major consonances, such as a *third*, or *fourth*, or *fifth*, it will be seen that if we sharpen the lower note, or flatten the upper one, by a minor semitone, we multiply the ratio of the number of vibrations by $\frac{25}{24}$ or $\frac{24}{25}$; and from the table given above it will at once be seen that we reduce them to the corresponding minor intervals. A major tone $\frac{9}{8}$ becomes $\frac{9}{8} \times \frac{24}{25} = \frac{27}{25} = \frac{16}{15} \times \frac{81}{80}$, or a major semitone all but a comma; and a minor tone $\frac{10}{9}$ is reduced to $\frac{10}{9} \times \frac{24}{25} = \frac{16}{15}$, or a major semitone exactly. On the other hand, if we flatten the lower note or sharpen the upper note of any conso-

nance, we increase the interval by a semitone; and if it was minor, it now becomes major.

By this use of flats and sharps, we are enabled to transpose an air from one *key* to another; that is to say, to reproduce it with the same intervals, but with all the notes raised or lowered proportionally. Suppose, for instance, that we wish to transpose the ordinary notes of the scale two tones higher; if we were simply to replace doh, ray, me, fah, soh, lah, te, doh^1, by me, fah, soh, lah, te, doh^1, ray^1, me^1, we should have a new scale consisting of a semitone, three tones, a semitone, and two tones, instead of the ordinary succession of two tones, a semitone, three tones, and a semitone. In order to bring the two into agreement, so as not to alter the melody, we should have to raise or sharpen the second, third, sixth, and seventh of the new series; and we should then have practically the same sequence of tones as in the natural scale.

Considerations such as these lead to the following relations between the key of the scale and the sharpenings required:

Key.	Scale.
C (natural)	C D E F G A B C^1
D (two sharps)	D E F♯ G A B C♯ D^1
E (four sharps)	E F♯ G♯ A B C♯ D♯ E^1
F (one flat)	F G A B♭ C D E F^1
G (one sharp)	G A B C D E F♯ G^1
A (three sharps)	A B C♯ D E F♯ G♯ A^1
B (five sharps)	B C♯ D♯ E F♯ G♯ A♯ B^1

We cannot enter into details on this part of the subject, which relates to the theory of music; but we shall describe a simple contrivance whereby the sharps and flats necessitated by any change of the key-note of the scale may be exhibited to the eye. We may call it the

HARMONIC TRIANGLE.

The reader is asked to cut out a small strip of paper an exact copy of the strip QR shewn in the figure. Both QR and NP are reproductions of the sonometer-string represented in fig. 18, with the diatonic divisions marked for two octaves. To understand the meaning of the triangle ONP and its lines, we have only to know that if any point O be taken, and lines drawn from it to the divisions of C, D, E, F, &c. of the base-line NP, it is a well-known geometrical fact that these lines divide any parallel to NP, such as ST, in exactly the same proportions as NP is

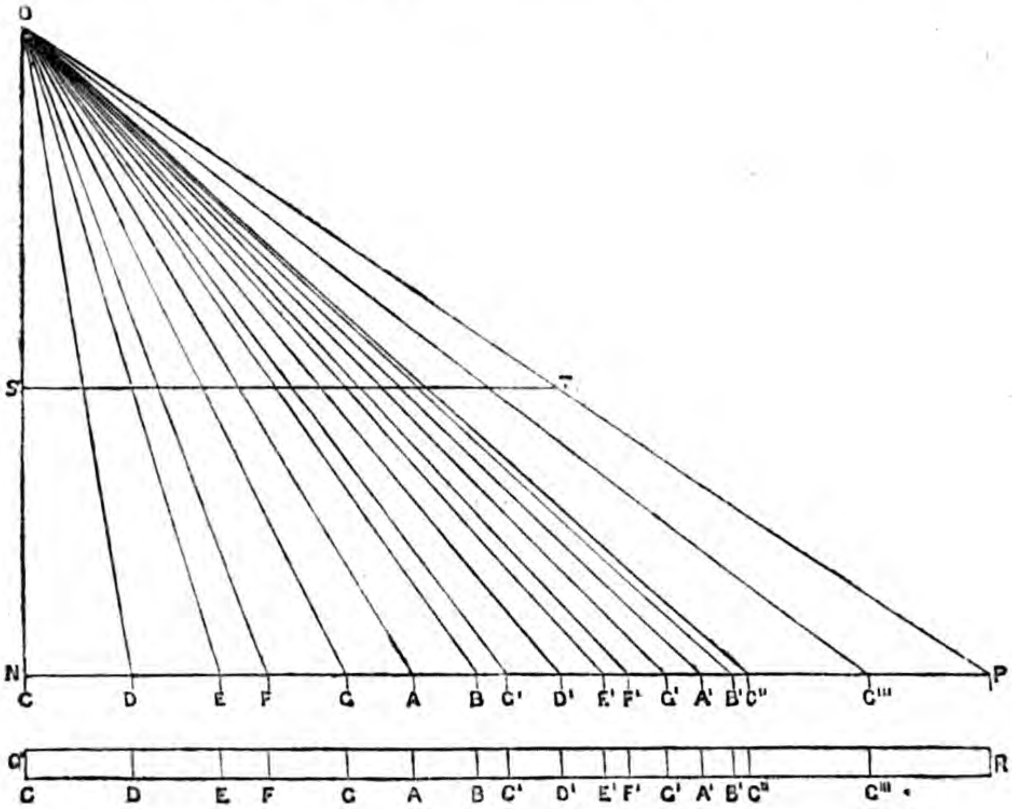


Fig. 19.—The Harmonic Triangle.

divided; that is to say, since if a string of length NP be shortened in succession to D, E, F, G, &c., and the parts CP, DP, EP, &c. sounded, we obtain the natural tones of the ordinary musical scale; so it follows that the musical division of a string, ST, will be indicated by the points of intersection of the lines OD, OE, OF, &c., with it.

Now, suppose we wish to find what notes should be altered if we change the key-note of our scale from C to say F. What does this really mean? Simply that if we start with FR instead of QR as our fundamental length of string (the tension remaining the same of course), then will the divisions G, A, B, C^1, D^1, &c., already marked on the string, remain correct for sounding the successive notes of the scale, as when we sounded them starting from the end Q? It is evident that we can find this out by lifting the movable strip QR and placing it across the harmonic lines of ONP, so that it remains parallel to NP, and so that we move it till the division F fall on the line ON, while the end R falls on the line OP. The harmonic lines of the triangle will at once shew where the divisions of the cord FR should fall to give the correct major scale with F as a fundamental tone—that is, with FR as the primary string. It will in this particular instance be found that the divisions already laid down on QR coincide practically with the harmonic lines of the triangle, except that the division marked B is nearer to the end R than it should be; hence we conclude that this tone should be flattened. This is a very instructive and simple method of studying key-relationships, which in music-books are often mixed up with a superfluity of technical terms; and if the whole be accurately drawn on a larger scale than we have space for here, the coincidence with the rules already quoted, page 50, will be found to be perfect.

46. **Temperament of the Scale.**—Since the number of new musical tones which would be introduced by changing the key-tone would be practically unmanageable for instrumental purposes, when only a limited number of tones can be commanded, some compromise must be adopted. This process is usually called **Temperament.** More or less imperfection must of necessity follow any such compromising in a field where all is subject to mathematical law, and many differences of opinion have prevailed and still prevail as to the proper scheme of *true* temperament. The mode usually adopted is that known as **Equal Temperament,** which neglects the difference between the semitones, and makes, for example, C sharp identical with D flat, by simply interposing a note midway between C and D to serve for both. From this it follows that the octave is divided into twelve equal intervals or semitones. Referring to our sonometer-string NP, we see that this means that in sounding these twelve equal musical intervals, we must shorten our string at each step by the *same fraction of its previous length.*

Now as the twelfth semitone is to be the octave of the primary tone, and the string therefore exactly *half* of the whole length, it is obvious that the fraction corresponding to the interval of a (tempered) semitone, when multiplied twelve times by itself, will be equal to $\frac{1}{2}$. By simple arithmetical calculation, then, this fraction is seen to be the twelfth root of $\frac{1}{2}$ or $= 1 \div \sqrt[12]{2} = \frac{1}{1{\cdot}060} = {\cdot}9434$ nearly. In other words, if we sound any string, and then that fraction of its length which is represented decimally by ·9434, and then that fraction of this second length which is represented by ·9434, and so on, we shall get the same musical succession of semitones as by sounding in order all the keys of a piano.

Conversely, the pulse-ratios of the successive tempered notes or semitones will be obtained from the fundamental taken as unity, as follows:

	Tempered Scale.	Natural Scale.	
C	$= 1{\cdot}000$	Fundamental tone......... =	1
C♯	$= \sqrt[12]{2} = 1{\cdot}060$	$\frac{25}{24}$ = Minor Semitone $\frac{16}{15}$ = Major Half-tone =	1·042 1·067
D	$= (1{\cdot}060)^2 = 1{\cdot}123$	Second, $\frac{9}{8}$.................. =	1·125
D♯	$= (1{\cdot}060)^3 = 1{\cdot}191$	Minor Third, $\frac{6}{5}$........... =	1·200
E	$= (1{\cdot}060)^4 = 1{\cdot}262$	Major Third, $\frac{5}{4}$........... =	1·250
F	$= (1{\cdot}060)^5 = 1{\cdot}338$	Fourth, $\frac{4}{3}$................... =	1·333
F♯	$= (1{\cdot}060)^6 = 1{\cdot}418$	$\frac{4}{3} \times \frac{25}{24}$.................... = $\frac{4}{3} \times \frac{16}{15}$.................... =	1·388 1·422
G	$= (1{\cdot}060)^7 = 1{\cdot}503$	Fifth, $\frac{3}{2}$...................... =	1·500
G♯	$= (1{\cdot}060)^8 = 1{\cdot}593$	Minor Sixth, $\frac{8}{5}$............ =	1·600
A	$= (1{\cdot}060)^9 = 1{\cdot}689$	Major Sixth, $\frac{5}{3}$............ =	1·666
A♯	$= (1{\cdot}060)^{10} = 1{\cdot}790$	$\frac{5}{3} \times \frac{25}{24}$.................... = $\frac{5}{3} \times \frac{16}{15}$.................... =	1·736 1·777
B	$= (1{\cdot}060)^{11} = 1{\cdot}898$	Seventh, $\frac{15}{8}$................ =	1·875
C^1	$= (1{\cdot}060)^{12} = 2{\cdot}000$	Octave, $\frac{2}{1}$................... =	2·000

From this it will be seen the *tempered* semitone is almost a mean between the major and minor semitones; and that the major *third* and perfect *fifth* coincide practically, though not perfectly, with the notes of the tempered scale.

Fig. 20.

These twelve semitones constitute what is called the **chromatic scale**, or scale which we obtain by sounding the *white and black* keys of the piano (fig. 20) in succession. When we sound the *white* keys alone, we get the natural major scale C, D, E, F, G, A, B, C^1.

47. **The Graphic Study of Harmony.**—It may be asked, Why should certain tones *accord*, while others do not? We answer, doubtless the ultimate reason is an organic or physiological one; but the graphic representation of the aërial pulses with which a couple of concordant tones simultaneously beat upon our ear, will aid us in conceiving the proximate cause as the acoustic perception of similarities in the midst of differences. Fig. 21 shews, first, the pulses of a note and its octave; the latter being twice as

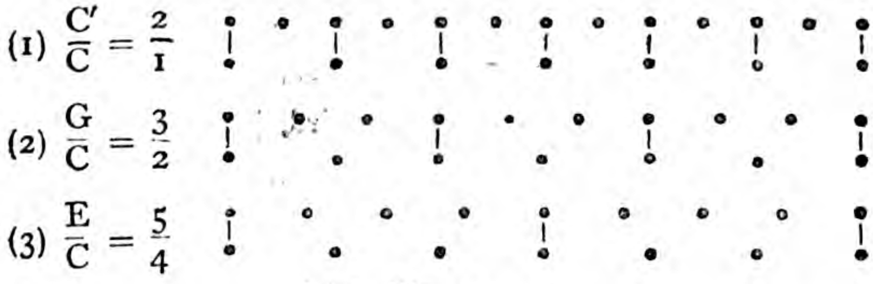


Fig. 21.

rapid as the former, and the coincidences of the pulses therefore as frequent as possible next to absolute coincidence or unison. Secondly, it shews the impulses of a note and its fifth where they occur in the ratio of three to two; the frequency of pulse-coincidence here is also very great, and next to that of the octave. This explains why the ear recognises so much of sameness in the harmony of a note and its fifth. Lastly, it shews the pulse-coincidences of a note and its major third. They are more frequent in this case than in that of a note and its minor third, corresponding to the æsthetical fact that the former accord is bold, distinct, and decided, while the latter is solemn and subdued in comparison.

It is instructive also to study the frequency of pulse-coincidence in *chords* by this graphic method. We can only afford space to exhibit the coincidences of a major chord, where the tone-pulses are as 4 : 5 : 6. Sir John Herschel has pointed out that if these pulse-dots be collected in one line, as in the lower line of fig. 22, we have a picture of the *rhythmic order* in which the pulses of each

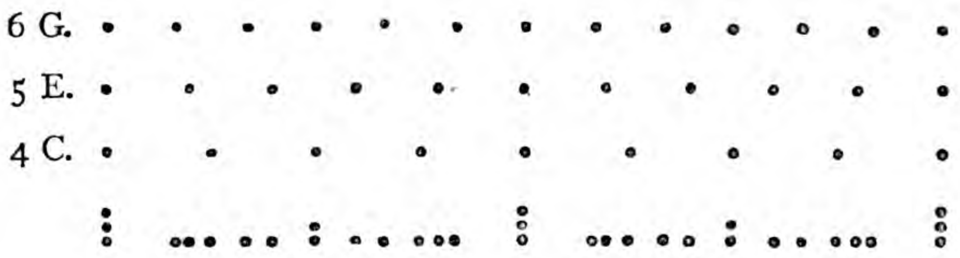


Fig. 22.—Pulses of a Major Chord.

tone fall upon the ear. If we compare with this the *pulse-resultant*, as we may call it, of a minor chord, we find the rhythm of the pulses quite different in *form*, the triple coincidences being more 'few and far between.' Portraying the pulse-dots in different colours for each different tone, and preserving the same colours in the resultant, we obtain graphic representations of striking beauty.*

48. **The Range of Musical Sounds.**—Having examined the relations of musical sounds, let us now examine the absolute estimate of their pitch. From the deepest bass of a large organ to its shrillest note is a compass of eight octaves; the deepest tone, emitted by the longest (32 feet) pipe of such an organ, is calculated to give about sixteen complete vibrations per second, while the highest note gives some 3400; but sounds many times higher than this are within

* For details as to the bearings of this on the theory of music, the reader is referred to *A Tract on Musical Statics*, by John Curwen (London: Tonic-Sol-Fa Agency, 1874).

the region of audibility, though not within that of musical discrimination : and this may fairly be taken as the range of musical sounds practically available. The absolute pitch of any of these notes being fixed, that of the whole series is of course determined by their mutual relations. It is usual to adopt for the *middle C* (a convenient standard of pitch, because within the compass of any voice or instrument) 256 complete vibrations per second ; this gives 16 vibrations per second for the fourth C below, and 2048 vibrations for the third C above, which begins the last octave of the series ; the last A having 3412 vibrations. The standard of pitch, however, varies somewhat with the age and country. In the time of Handel, it appears to have been considerably lower than it now is ; his C^1 having been about 500 vibrations, while that agreed to by the Stuttgart Musical Congress in 1834 was 528, and the C^1 of concert-pitch is 538, and the C^1 of the Italian Opera is 546.

The **wave-lengths** corresponding to these various notes may be easily calculated. Taking the velocity of sound at 1120 feet per second (sect. 9), we shall have this length of air thrown into as many waves as the number of vibrations in any tone. Thus the tones of an organ will give waves ranging from 1120 ÷ 16—that is, seventy feet in length, to 1120 ÷ 3400—that is, between three and four inches.

The musical range of an ordinary human voice is about two octaves, the range in the female starting an octave above that in the male, but reaching two octaves above in the higher notes. It is estimated that, in ordinary conversation, the aërial wave-length of a male voice is from eight to twelve feet, while that of the female voice is only from two to four feet. With comparatively rare exceptions, the whole compass of the human voice, male and female, is about four octaves.

49. **Timbre** or **Clang.**—The third quality of musical sounds is what is known as *timbre* by the French, or *klang-tint* by the Germans. It may be described as that peculiarity, colour, character, or feature of a sound by which, from experience, we identify its origin, and which enables us to distinguish

one instrument from another, or one human voice from another. It occupies, in the study of sound, a place whose importance has only been discovered in recent years. But it will be most profitably discussed after we have examined the modes of producing musical sounds, with their laws and peculiarities.

PART III.

DIFFERENT MODES OF EVOKING MUSICAL SOUNDS—MUSICAL INSTRUMENTS: THEIR LAWS, TIMBRE, AND ETHNOLOGY—THE VOICE AND THE EAR.

Stringed Instruments.

50. **Laws of Vibrating Strings.**—By means of the sonometer already introduced (sect. 39), we may study the relations between the rate of vibration or the note of a sounding-string, and its tension, length, and weight. Before stating these relations we may remark that a string may vibrate in two ways, either (1) *transversely*, or across its length, which is the case when plucked as in the guitar, or bowed as in the violin, or struck as in the piano ; or (2) *longitudinally*, or lengthwise, as when rubbed with the wet fingers or by a resined cloth, or when the fiddle-bow slips on the string. In the latter case the vibrations are very much more rapid, and the notes consequently much shriller than in the former case, because the force of cohesion tending to restore the particles of the string to their former position of equilibrium is very much greater than the mere force of tension in the former case. The former mode of vibration, however, is the one of chief musical interest.

The laws of transverse vibration are :

(1) *The rate of vibration is inversely proportional to the length of the string.* This has been already stated by anticipation (sect. 39), and the important musical inferences which are derived from it (sect. 41).

(2) *The rate of vibration is inversely proportional to the thickness of the string*, other things remaining the same. A string of double thickness is manifestly the same as two strings vibrating together, and hence will only vibrate half as fast. By increasing the thickness of a string, then, we have the same effect as by lengthening the string; use is made of this fact in the construction of the bass strings of a violin and pianoforte.

(3) *The rate of vibration is inversely proportional to the square root of the density*—that is, if we take a brass wire, and a catgut string, and an india-rubber string, if they be all of the same length and thickness and tension, but the wire be sixteen times more dense than the catgut, and the catgut four times more dense than the rubber; then the india-rubber string will vibrate twice as fast as the catgut, and the catgut four times as fast as the wire; the notes produced being in accordance with this law.

(4) *The rate of vibration is directly proportional to the square root of the tension of the string.* This is easily proved by giving tension to the sonometer-string by weights. We find that if a strain of fourteen pounds be required to sound any note, say C, of the scale, then not twenty-eight but fifty-six pounds weight is required to give the octave of this; and two hundredweights to give the second octave. This explains the enormous strain exerted by the strings of a piano. It is estimated that the strings of a grand-pianoforte exert a strain equal to six tons.

(5) *An elastic cord fixed at its two ends vibrates either as a whole, or divides itself into two, three, four, or some aliquot number of parts.*

This will require careful consideration, as much depends on it. Experimentally it may be illustrated with a long spiral of brass wire made by winding 'binding-wire' round a knitting-needle. If one end of such a wire be fixed to a peg in the wall, while the other is held in the hand, we may, by a sharp tilt of the hand, raise a loop on the chain which will pass along as a crested pulse to the end of the wire. By an up-and-down movement we may set up a complete wave, consisting of crest and hollow, which will pass along to the end. Arriving there, it will there be reflected or reversed in its direction of motion ; and what was crest will become hollow, and what was hollow crest. Thus an inverse wave will return to the hand.

The length of the wave will be less in proportion as the time taken to the jerk is less ; but the time of passage of the wave to the end of the line and back is independent of this, and depends only on the length, tension, weight, thickness, and density of the cord ; and is exactly the same as the time taken by the cord to swing as a whole. If now we keep tilting the end of the wire at *regular* intervals, which are an *aliquot part* of the time of vibration as a whole, it is clear that an exact number of waves will have been raised on the cord when the first one has just reached the extreme end N (fig. 23) ; also this first wave, being reflected at N, will just have returned to the point O at the same instant as an onward wave gets there. Now O, being solicited in two opposite directions, will remain at rest, and become a centre of reflection and of no vibration just as if it were absolutely fixed. Hence the part ON will vibrate as an independent string. Thus by the meetings of the onward and returning waves, the whole string will divide itself into vibrating parts separated by points of no vibration.

51. **Nodes and Ventral Segments.**—These parts ON, OP, &c., are usually termed *ventral segments ;* and the stationary

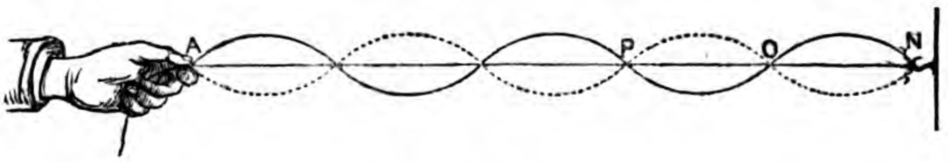


Fig. 23.

points O, P, &c., are called *nodes ;* the number of nodes is of course one less than the number of ventral segments ; and the latter number is a measure of the rate of vibration. When a string divides into two, three, four, &c. ventral segments, it is vibrating at two, three, four, &c. times the rate of its fundamental vibration.

This, then, is the complete explanation of the experiment referred to in sect. 6, as illustrating the conversion of back-and-fore pulsations into up-and-down waves. It is due to M. Melde of Marburg in Germany, and is an exceedingly instructive as well as exquisitely beautiful experiment. The prong of the tuning-fork takes the place of the hand as a more perfect governor of the jerks, and the result is a symmetry in the division of the string which could not be equalled by any other means. Tiny pieces of reflecting bead glued to the string we have found very suitable for illuminating the path of the vibrating string, which, in the words of Professor Tyndall, is sometimes 'of marvellous complication and indescribable splendour.'

52. **Spontaneous Subdivision of a Musical String.**—In a musical string stretched tightly between its two ends, the conditions are very much the same as in the cases just described. With the hand and spiral cord we have the means of varying the governing vibrator and the tension at pleasure; with a single tuning-fork and white silk string, in Melde's experiment (sect. 6 and fig. 5), the number of ventral segments can be varied only by changing the tension of the string. But in the case of the sonometer or any musical string, the tension is supposed to be fixed (for the time); hence the rate of vibration depends on alterations of the *length.* These changes of length in the sonometer we supposed to be made by a sliding-bridge (sect. 39); in the violin, they are made by using the fingers simply; in the pianoforte and other stringed instruments, by fixed differences of length.

The aliquot division of a string may be easily induced by simply touching it with the point of the finger, or with a pencil, or even with a feather at some exact fraction of its length from the end, as at O (fig. 23). If doing this, we draw the bow across the part ON, so as to sound it, the remainder of the string will *spontaneously* subdivide into parts of exactly the same length; and after this division is once started, we may remove the finger and keep up with the bow the same rate of vibration as that primarily induced. An exceedingly nice way of shewing these nodal divisions is to put light paper rings at different parts along the string. Those placed at the nodal points will remain undisturbed while we sound the string; while those intermediate to these points will be violently agitated, and will gradually make for the nearest haven of rest, until ultimately all the rings will be found collected at the points of no vibration.

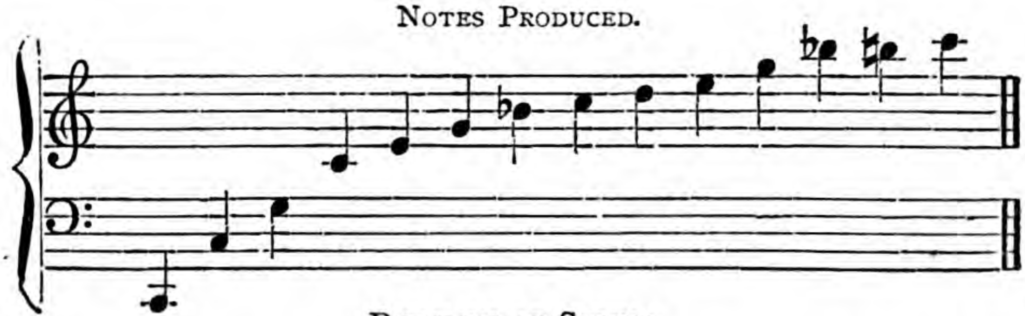
HARMONICS OF A SOUNDING-STRING—OVERTONES.

53. Let us examine the musical result of these laws of vibrating strings. Not only is it easy to induce a string to divide itself into an aliquot number of vibrating segments; but as a matter of fact it is found to be impossible to keep it from so doing. Overriding the vibration of the whole, we have always vibrations of its aliquot parts; and so, simultaneous with the fundamental tone given by a string, may be detected by the ear tones over and above the fundamental tone. These correspond to the vibrating subdivisions of the string; and are known as the **harmonics** of the fundamental tone. Now the harmonics attendant upon a tone of any given rate of vibration are not invariable in their individual intensities, when produced by different instruments, as, for example, a violin and a piano. Some ring out full and clear with the one instrument, which are practically suppressed in the other; and the resultant or combined effect of these harmonics or 'overtones' with the primary tone gives therefore a peculiar **colour, shade, quality, character, timbre** (as the French express it), or **clang** (as the Germans call it), to a tone which serves to distinguish the source of its production.

The law according to which these 'overtones' are formed was first given by Dr Thomas Young, and is accepted by Professor Tyndall as the true explanation of their origin. It is this: *When any point of a string is struck, all the aliquot divisions, which would require that point for a node, or point of rest, are necessarily prevented from forming, and the corresponding harmonics are of course absent.*

If, for example, we strike the string of our sonometer at the middle, that point is a place of maximum amplitude of vibration, and cannot possibly therefore admit of a division of the string into two, four, eight, &c. parts; consequently the whole train of harmonics corresponding to a twofold, fourfold, &c. vibration of the string is excluded from the accompaniment of the fundamental tone. If, again, we strike the string at a fourth of its length from the end, this is quite compatible with a division of the string into two parts; and the fact of such division of the string is proved by the ear, which detects the presence of the octave above the fundamental tone, and which will remain after the primary tone is stopped by touching the middle of the string. If, lastly, we strike or pluck the string at a third of its length from one end, then those subdivisions which would require the third point for a node are excluded. Hence none of the overtones corresponding to six, nine, twelve, &c. times, the primary rate of vibration, can be detected in such a case. In general, the harmonics attendant upon a fundamental tone of a free sounding-string are those corresponding to two, three, four, &c. times the fundamental rate of vibration of the sounding body; and the following is the order, according to musical notation, in which the harmonics arise, assuming that the string, at its full length, sounds the note C on the second ledger line below the bass staff, or lowest string on a violoncello:

NOTES PRODUCED.



DIVISIONS OF STRING.

1	2	3	4	5	6	7	8	9	10	12	14	15	16
C	C	G	C	E	G	B♭	C	D	E	G	B♭	B♮	C

A variety of circumstances, such as the smartness of the stroke, the nature of the striking hammer, and even, as we have seen, the place of the stroke, influences the development of the harmonics: sometimes they may be so fully developed as effectually to mask the primary tone; and sometimes so feebly developed as to be almost imperceptible.

VIBRATIONS OF RODS.

54. **Transverse Vibrations of Rods.—The Kaleidophone.—** If a rod of glass, wood, or any elastic metal, especially of tempered steel, be *fixed at both ends*, and sounded by striking or by bowing, it behaves very much as a string similarly fixed; it may vibrate as a whole, or it may subdivide into two, three, or more aliquot parts. It is found by experiment, what may also be confirmed by analysis, that the rate of vibration of such a rod does not follow the same law as that of an elastic string, but increases at the *square* of the rate that the length diminishes. Also the series of overtones have their vibrations inversely as the squares of the natural odd numbers—that is, as 9 : 25 : 49, &c. Thus the notes corresponding to the division of the rod into two, three, &c. segments do not follow the same simple relation as in the case of strings.

If the rod be *fixed at one end only*, it similarly subdivides into segments, the free end, however, always forming a place of maximum vibration instead of a node: and in this case also the rate of vibration is inversely proportional to the square of the length of the rod—that is, if a steel wire one inch long be fixed in a vice, and vibrate one hundred times per second, then one half an inch long will vibrate four hundred times per second.

While such a rod vibrates in segments it also usually vibrates as a whole; the compound vibration of such a rod may be prettily exhibited by **Wheatstone's Kaleidophone.** This is a steel knitting-wire firmly fixed in a stand, and having a reflecting bead fixed on its free end; light is allowed to fall from a lamp or window on the bead, so that the eye sees a bright spot when all is at rest. When the wire is sounded or struck, and made to vibrate, the path of the end of the wire is seen as a luminous curve of exquisite symmetry and marvellous complexity, which may be varied almost indefinitely by changing the length of the wire or the spot where it is struck.

A rod *free at both ends*, such as we have in the musical toy called the **harmonica**, may also vibrate either as a whole or sectionally. Its simplest mode of vibration is when it has two nodes, as in fig. 24; but it may also divide so as to have three, four, &c. nodes, with correspondingly high harmonic tones. Professor Tyndall finds that if the numbers of nodes are two, three, four, &c., the corresponding vibrations are proportional to nine, twenty-five, forty-nine, &c. in this case: while the *fundamental tone* of a rod free at *both* ends, as in the common glass harmonica, bears to the *fundamental tone* of a similar rod fixed at *one* end the ratio of twenty-five to four.

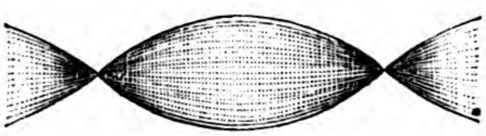


Fig. 24.

55. **The Tuning-Fork.**—The chief interest in this law of vibration of a rod free at both ends lies in the fact that a tuning-fork is merely such a rod bent into a **U** shape. Hence a tuning-fork sounding its fundamental note may be regarded as having two nodal points A, B (fig. 25) near the base of its prongs. No tone is obtained corresponding to a three-node division of the fork, but the first harmonic results from four nodes, as may be found by trial with a violin bow. Also with a C tuning-fork, of 256 vibrations per second, we jump at once to a tone having $\frac{25}{4}$ of this number, or 1600 vibrations per second: the subsequent harmonics rising above this in vibration as 25, 49, 81, &c., rise above 9. It is because the overtones of a tuning-fork are so completely above those of the fundamental, and because they vanish more quickly than in the case of a vibrating string, that they affect the fundamental tone less, and that a tuning-fork in consequence is considered as giving a *practically pure tone.*

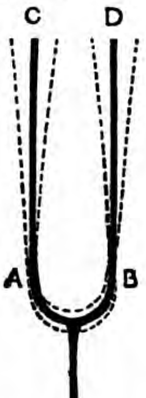


Fig. 25.

56. **Longitudinal Vibration of Rods—Indirect Method of estimating the Velocity of Sound in Solids.**—If a rod of wood or glass or metal fixed at its two ends be rubbed lengthwise with a resined cloth, it will emit a much shriller sound than if

it be bowed transversely. Just as in the case of a wire, the force of molecular elasticity tending to restore the particles to their position of rest is much greater than that of mere tension which operates transversely, and hence the rate of vibration is all the more rapid. Experimentally, it may easily be shewn that the rate of longitudinal, like that of transverse, vibration is inversely proportional to the length of the rod or wire; that a rod has a fundamental longitudinal note; that it may subdivide into two or more segments separated by nodes, between which the pulses play backwards and forwards. If one end of a rod be connected with a sounding-board, then it is obvious that each backward and each forward vibration of the board corresponds to the passage of a single pulse to the extreme end of the rod and back; *hence if we knew the absolute rate of vibration of this board, we should only have to multiply it by four times the length of the rod to get the velocity of sound through the rod.*

On this principle, then, the relative velocity of sound in different materials, such as wood and metal, may easily be found, by simply finding the relative lengths of rods of wood and metal which, sounded longitudinally, give the same note. Professor Tyndall by this means finds that a brass wire or rod 15½ feet long gives the same note as an iron one 23 feet long; hence he concludes their velocities are as 15½ to 23, or as 11 to 17 nearly. He finds also that a rod of mahogany 4 feet long gives the same note as a rod of deal 6 feet long; hence their conductibilities of sound are as 4:6. Rods free at one end and fixed at the other, or free at both ends and fixed in the middle, may also be made to vibrate longitudinally; and to divide segmentally according to much the same laws. The vibrations of a glass rod free at both ends and clamped in the middle, may easily be made visible by hanging a tiny pendulum to rest against one end, while we draw a resined cloth lengthways over the other half of the rod: the pendulum will be violently kicked away.

57. **Kundt's Experiments on the Velocity of Sound.**—Advantage has been taken of the foregoing laws by M.

Kundt of Berlin to determine the velocity of sound. We shall briefly explain his mode of experimenting. A glass tube corked at both ends may be regarded as a compound rod—an air rod inclosed within a hollow glass rod. Now, if the velocity of sound were the same in air as in glass, the vibrations of the aërial core would be coincident with those of the cylindrical shell. The velocity in glass is, however, enormously greater than in air, as we have already stated (sect. 13); hence the column of air which will vibrate longitudinally at the same rate as the glass tube will be as much shorter as the velocity in air is less. M. Kundt reveals these correspondent air-columns by strewing a little lycopodium powder inside the glass tube.

Fig. 26.

Fixing the tube in a clamp at its middle, and drawing a wet or resined cloth sharply along one of the halves, we find that the powder inside dances into regular heaps or waves, collecting in quantity between the points of no vibration or nodes (see fig. 26).

Counting the dust-heaps, we should find them to be about sixteen, shewing that the velocity in glass is sixteen times as great as in air. With different gases, such as hydrogen or carbonic acid, inside the tube, the number of lycopodium heaps would be different, about ten in the former case and twenty in the latter: hence the velocity in hydrogen is to that in air as 16 to 10; and the velocity in carbonic acid

Fig. 27.

to that in air as 16 to 20. The results which have been obtained by this method of M. Kundt are of surprising agreement with those obtained by totally different means.

M. Kundt has also, by an extension of the same principle, been able to calculate readily the sound-conductibility of different substances. He simply fits a rod of the material into a glass tube as BD is in AC; so that BD is equal in length to AC, and B is the middle of AC (fig. 27). On sounding CD in the ordinary way with a wet cloth, we shall find *half* as many dust-heaps in AB as the number which represents the velocity in BD compared with that in air.

VIBRATIONS OF SOUNDING PLATES.

58. **Chladni's Sand-figures—Laws of their Formation.**—As the vibrations of an elastic strip would be practically the same as those of an elastic rod, and subject to the same laws, so, a plate being but an extended strip, is subject in its vibration to laws which may be deduced from those already given for rods. Like rods, plates vibrate either as a whole, or they subdivide into multiple segments, separated not by nodal points, but by nodal lines, or lines of no vibration, which lie between parts vibrating in opposite phase. Chladni, towards the end of last century, discovered the elegant mode of studying these vibrations of plates, which still bears his name. It consists of strewing some fine sand over a plate of glass or metal, placed horizontally, and clamped by some suitable contrivance either at the centre or near the edge. Drawing a well-resined fiddle-bow down the edge, we find that the sand starts into a symmetrical form or figure sometimes of remarkable beauty; it is tossed off the vibrating parts, as the paper rings were in the case of our sonometer string (sect. 52), and collects at the parts of no vibration, which by the nature of the case are necessarily lines. Fig. 28 shews some of the figures so obtained; but the number of figures that may be got from a single square plate may be multiplied almost infinitely by varying the position of the clamp

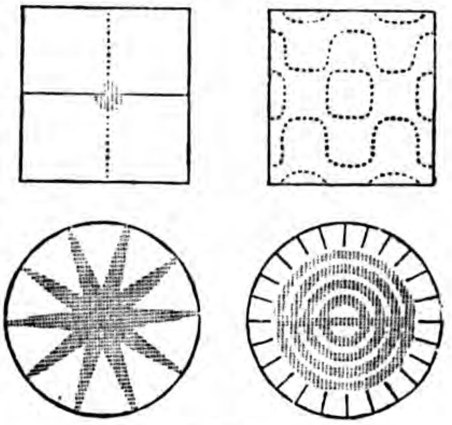


Fig. 28.

&c. They can be readily transferred to gummed paper, and kept for any length of time.

The laws according to which these figures are formed may be thus briefly summarised: (1) As the nodal lines always separate parts of the plate in opposite states of vibration, the number of segments is necessarily even. (2) The same figure will always be given by the same note with the same form of plate; but the moment the note is changed by any means, the figure changes with startling sensitiveness; and the higher the note the more numerous will be the divisions of the plate; the fundamental note corresponding to a four-fold division of the plate by a simple cross figure. (3) Square plates present two different types of figures, one with the nodal lines parallel to the sides, the other with these lines diagonally disposed. If we wish to change the figure, we have only to touch one or more points on the edge of the plate with one hand, while with the other we draw the bow briskly down the edge; the points touched by the finger are necessarily nodal points, and dictate the nodal lines. (4) When the plates are circular and clamped at the centre, we have also two types of lines; in the first type the nodal lines are radii of the plate; four corresponding to its fundamental tone, six to the first harmonic, eight to the second harmonic note, and so on. In the second type we have one or more nodal lines forming circles concentric with the plate; they may be produced by soldering a circular metal plate on the end of a metal rod, and stripping the rod longitudinally with resined fingers. (5) Bells, cymbals, and such-like being really only curved plates, execute their vibrations in accordance with the same laws as plates. Their deepest note corresponds to a division of the surface into four, as may easily be shewn by mounting a small clock-bell face up, and strewing some fine sand inside. A common drinking-glass provided with a foot and partly filled with water, shews in the same way tiny ripples corresponding to the vibrating segments. These instruments are specially remarkable for the number and intensity of their overtones. (6) The general law for two plates of similar figure but different size is that, for the same vibration figure, the number of their vibrations is proportional to their thickness, and inversely proportional to their surface.

SOUNDING AIR-COLUMNS IN TUBES AND PIPES.

59. A column of air within a pipe or tube of any sort may be regarded as an elastic rod, whose play of elasticity is only very much greater than that of a solid rod, and whose mode of vibration is, from the nature of the case, *longitudinal* only, but which in its vibration is subject to laws very much the same as those already given for elastic solid rods. Like a rod or a string, a column of air of a given length has its particular time of vibration ; in other words, every column of air, when vibrating as a whole, has its own fundamental note, identical with that produced by any other sounding body vibrating at the same rate. Like a rod, too, an air-column may be made to vibrate segmentally, producing the harmonics of its fundamental tone.

We cannot of course draw our fiddle-bow across an air-column to set it in vibration ; we might indeed, as is done in M. Kundt's experiments (sect. 57), set up the vibrations in the air-column in a pipe by sounding *longitudinally* the inclosing tube; practically, however, a much simpler means is at hand. The mere approach of a body, sounding at its own peculiar rate, to the mouth of a pipe, suffices to stir up its pulsations. Thus, if we make a few tubes of pasteboard, by simply rolling sheets of paper round a ruler, and have them of different lengths, we shall find, on bringing a sounding tuning-fork near to the mouth of the tubes, that only one of them will resound to its vibrations—that one, namely, whose periodic time is in sympathy with that of the fork. An elegant variety of the same experiment is to hold a sounding tuning-fork over a tall glass jar: by pouring water slowly into the jar we find at length that the note rings out full and clear ; but, if we pour more water in, we deaden the sound again. And if we had eight tuning-forks corresponding to an octave of the diatonic scale, we should find that eight air-columns or jars would be required to resound in sympathy with these notes ; also we should find that similar relations would hold between the lengths of these columns as hold between the vibration-rates of the notes of the scale—that is to say, their successive lengths would be as $1 : \frac{8}{9} : \frac{4}{5} : \frac{3}{4} : \frac{2}{3} : \frac{3}{5} : \frac{8}{15} : \frac{1}{2}$.

60. **Theory of Stopped Pipes and their Harmonics.**—In considering the relation between the length of an air-column, or of its containing pipe, and the corresponding note to which it answers, we must remember that a stopped pipe—that is, a pipe closed at one end and open at the other—exactly resembles a rod fixed at one end and free at the other, and sounded *longitudinally* (see sect. 56). First of all, we observe that the rate of vibration increases exactly in proportion as the length of the pipe diminishes; so that, with a pipe of ten feet (or inches, for the actual dimensions are of no consequence), we get the octave of the note produced by one twenty feet (or inches) long; and with one five feet long the second octave to the first, and so on. Secondly, for each complete vibration of the note, a condensed pulse and a rarefied pulse have *each* to run down to the bottom of the tube and back, hence *the length of the tube will be one-fourth of the aërial wave-length of the note which the tube resounds.* Now the wave-length of any note (sect. 48) is obtained by simply dividing the velocity of sound, 1120 feet per second, by the vibration-rate of the note per second. Thus a C tuning-fork of 256 vibrations per second will give 1120÷256, or four and a half feet of a wave; hence a closed pipe sounding this note, or resounding to it, will be one-fourth of this length, or 13½ inches. Also the nodes, for higher rates of vibration, will be formed according to the same law as in a rod fixed at one end—namely: (1) if the fundamental note of the tube is sounded, the pulses will simply play backwards and forwards between the mouth and bottom of the tube; (2) the first harmonic will correspond to a node at D such that CD $= \frac{1}{2}$ of DE, or at a point one-third down the tube; (3)

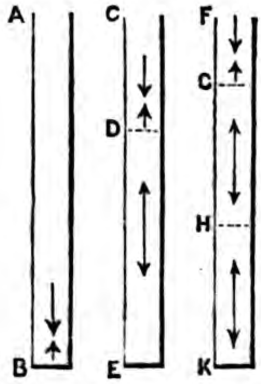


Fig. 29.

the second harmonic will correspond to two nodes at G, H (fig. 29, 3), such that FG = $\frac{1}{2}$ GH or $\frac{1}{2}$ HK, or such that FG = $\frac{1}{5}$ of the length of the tube. A little consideration will shew that the rates of vibration corresponding to these nodal divisions must be proportional to the numbers of half-segments; that is, will be as 1 : 3 : 5, &c. For the air-pulses travel at a uniform rate; hence, since CD is only $\frac{1}{3}$ of AB, the pulses in CE must have played three times back and fore while those in AB have only played once.

61. **Theory of Open Pipes and their Harmonics.**—A pipe open at both ends, and sounding its fundamental tone, is exactly like a rod free at both ends and clamped at its middle, and sounded longitudinally. There is a node at the centre, and consequently the open pipe AC (fig. 30) sounds the same note as a closed one equal to AB—that is, the octave above the note sounded by a closed one of the same length as the open one. This law is general: *Any open pipe sounds an octave lower, if it be stopped at one end.* The first harmonic corresponds to the formation of two nodes, E, F, in the pipe; such that DE = GF = $\frac{1}{2}$ EF; or DE = $\frac{1}{4}$ of the length of the tube: and the second harmonic to nodal divisions, such that KL = $\frac{1}{2}$ LM or = $\frac{1}{6}$ the length of the tube. Hence the fundamental and its harmonics have their pulsations in the ratio of 2 : 4 : 6, &c.; or of 1 : 2 : 3, &c.

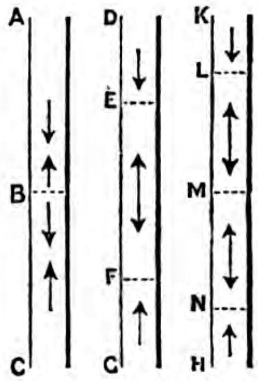


Fig. 30.

Thus in the case of open pipes the harmonics do not rise so rapidly as in closed pipes: the first in an open pipe is simply the octave to the fundamental, while in a closed pipe it is a fifth higher than this.

62. **ORGAN PIPES.**—There are various modes of inducing sonorous pulsation in pipes for musical purposes. The primitive method, employed in Pan's pipes or in the flute, consists in directing a blast of air across the mouth of the pipe, or an aperture near the end; the air current grazing the aperture is broken up into a rhythmic flutter sufficiently

regular to induce musical vibration of the air inside the pipe. In the organ, which is the most important of wind-instruments, two different sorts of mouth-pieces are fitted to the ends of the pipes to evoke their tones. The first class of pipes is called **Flue-pipes** or **Mouth-pipes**, and is represented in fig. 31, by A, a section of square wooden flue-pipe, and by B, a section of a cylindrical metal one. The principle is very much the same as that of the common whistle. The air from the bellows entering by *a* issues in a thin sheet at *e*, and its course being divided by the wedge-shaped *lip*, *e*, between the external air and the pipe, an alternately condensed and rarefied pulse may be supposed to act on the air in the pipe, according as the puff passes inside or escapes outside.

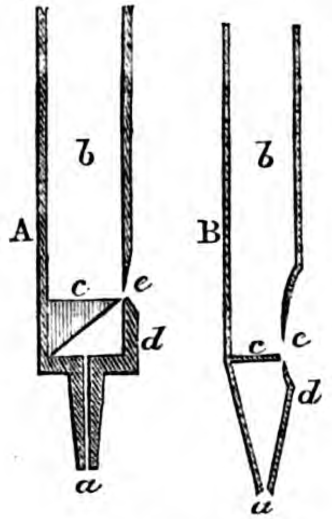


Fig. 31.

All the parts of such a pipe are fixed, and as they may be of metal or wood, cylindrical or prismatic in shape, they are the least liable to injury, and of most importance from a practical point of view. The *pitch* of the resulting note depends, according to the principles already laid down, on the length of the pipe; but the *purity* and *quality* of the tone depend on the relations between its various parts, as well as, to a certain extent, on the quality of the material composing the pipe. For instance, if the diameter of the pipe be too small in comparison with its length, it will sound its first harmonic, the octave of its fundamental tone.

Fig. 32 shews a mouth-piece of the second class of organ pipes, known as **Reed-pipes.** Here the governor of the vibrations is the reed R, an elastic strip of brass fixed over a corresponding opening in the end, M, of a small tube

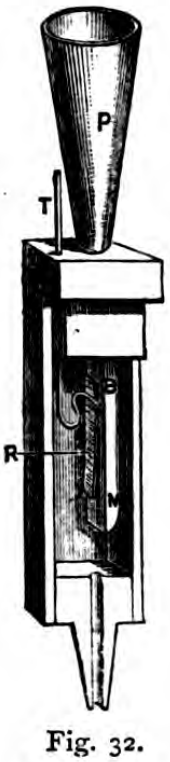


Fig. 32.

leading to the body of the pipe. The pitch of the tone depends on the density, length, and elasticity of the vibrating reed, and hence an elastic wire, T, pressing on the reed is moved up or down to tune the pipe; but the *quality* and *purity* of the tone depend on the relations of the parts of the pipe. Among reeds there are again two varieties, one called the **free-reed**, which vibrates *through* the opening, and the other the **beating-reed**, which vibrates *over* the opening, closing it like a flap, and giving a rougher quality of tone than the free-reed. In the harmonium, accordion, concertina, and other instruments of that class, the reed is also employed as the pulsation-generator.

It is perhaps worthy of remark here that while (in sect. 60) we estimated the length of the C pipe whose aërial pulsations would be 256 per second, to be 13½ inches, it is in practice always referred to as the one-foot pipe; the lower octaves being given by the two, four, eight, sixteen, and thirty-two feet pipe respectively. We have no experimental evidence as yet on the subject, but it is probable that the discrepancy between theory and practice in this instance may be due to frictional retardation of the internal air-vibrations by the sides of the pipe.

63. **Nodes in Organ Pipes.**—The disposition of nodes and ventral segments, theoretically stated in sect. 61, may be beautifully exhibited by a contrivance due to M. König of Paris, and consisting of the application of a manometric flame (sect. 28) to openings in the side of a pipe.

We take an organ pipe and drill three holes in one side, so as to divide the length of the pipe into four equal parts; we next fasten over each a conical gutta-percha capsule with a glass jet and a pipe to admit the gas, the base of each capsule being covered with an oiled-silk membrane. It is obvious that this membrane will be pressed outwards by increase of the air-density in the pipe. If now we sound the fundamental note of the pipe, we find that all the flames are agitated, but that at the centre is most violently affected. This corresponds to the single nodal division of the pipe. If by blowing more strongly we sound the first harmonic—that is, the octave to the fundamental tone—we find the other two flames most strongly agitated and the central one at rest, corresponding to the nodal division of the pipe shewn by DEFG (fig. 30). Instead of looking at the flames with the eye simply, we may view them in our rotating mirror-box, and we shall have the appearance of luminous tongues already described (fig. 15).

It must be noted that the nodal points of an organ pipe, being the meeting-places of waves of condensation and rarefaction, are points of no *vibration* of the air-particles, but are points of greatest changes of *pressure*. At the open ends of the pipe there can be of course no sensible compression or rarefaction, but there is a maximum amplitude of vibration of the particles.

64. The **Chemical Harmonicon** or **Singing Flame** is an old experiment illustrating this subject. If a tiny flame of hydrogen or common coal-gas be introduced within a long glass or pasteboard tube held vertically, in a certain position of the flame the air within the tube assumes rhythmic pulsations which swell into a powerful tone. The size of the flame, its position in the tube, and the length of the tube, determine the tone. It would be easy to have a set of tubes and jets to give the different notes of the scale, so that we might play a tune with them, were it not that the notes do not start with sufficient expertness. The vibration of the air inside reacts upon the gas flame, so that when it is viewed in our rotating mirror-box, a band of luminous tongues is displayed.

We may also easily exhibit the nodal divisions of a sounding-pipe by means of this simple tube and flame. Having taken a lid of a pill-box, we replace the end of it by a piece of tracing-paper, which we gum on so as to make a tiny tambourine; three threads are then fixed to it, so that it may easily be lowered into the pipe. On putting in a pinch of sand, and lowering the whole, we find that the sand dances with a burring sound, shewing that the interior air is in violent agitation. With a little care we can easily find a spot where the sand remains quiescent; this of course indicates the place of a node.

TIMBRE, OR QUALITY OF MUSICAL SOUNDS.

65. We are now prepared to understand the modern theory of *timbre*, or that peculiarity of sound by which we recognise the tone of a familiar voice, or distinguish an air played on a violin from the same air played on a harmonium, or even discriminate the tone of one piano from that of another.

Two voices singing together, or two instruments played in concert, may be similar in every note as far as pitch (or frequency of vibration) is concerned, and they may be similar as regards loudness or amplitude of tone-vibration; and yet there may be a vague difference of some sort which we instinctively recognise, but which is occult in its nature. The cause is, however, now well established. *No tone either sung or played is absolutely pure or simple, but is always more or less compound;* in fact, a very pure musical tone sounds bare and lacking in richness. We have seen (sect. 53) that it is not possible to sound a string as a whole, without at the same time starting its sectional vibrations; and the same thing is true of the vibrations of an elastic rod or of an organ pipe, of the human voice, or of any musical instrument whatsoever. Now the series of sectional tones, or harmonics, which accompany the fundamental tone, is, as we have already explained, formed according to one law in the case of strings, and according to another in the case of vibrating springs or reeds; hence the *resultant-tones* of a stringed instrument will differ in character from the resultant-tones of a reed-instrument. None can mistake the music of a harmonium for that of a piano. We might compare tones of the same fundamental pitch, but sounded on different instruments, to wall-paperings having the same ground colour, but whose superimprinted patterns are all different. As we might even have two paperings with exactly the same ground colour and the same pattern, but with different depths of the pattern colours, and we should have no difficulty in discriminating them; so the same musical note may be sounded on two different violins, an old Cremona and a modern fiddle such as may be had for a few shillings, and it will have a totally different *quality:* the former will have all the lower and harmonious overtones well developed, with the higher and discordant ones faint or practically suppressed; while the latter has these discordant superposed tones in too strong relief, and the resultant effect is unpleasant.

The general laws connecting the dimensions of a string or of a rod with the pitch of its ground-tone are perfectly well understood, and have been already discussed ; but the conditions which dictate the individual strength of the harmonics attendant on the fundamental tone are due to more recondite molecular structure, and cannot be so readily analysed. No doubt the conditions favourable to the development or suppression of particular harmonics in the case of a sounding-string are easily stated, and are familiar to pianoforte-makers, who, for instance, know that the hammer should strike the string at about one-seventh from the end, so that the harmonious overtones below the seventh are admitted, while the discordant seventh is extinguished. But the quality of a stringed instrument does not depend on the string alone or even chiefly; the material of the sound-board, the manner of sounding the string, and even the material of the hammer, all have most important influence on the *timbre.* The catgut strings are not all that is required to make a violin a musical instrument; inferior finish of the body, shape and disposition of the sound-holes, imperfect elasticity of the wood, and a score of little points not to be detected even by experts, all go to mould the judgment which a cultivated ear will pass on the quality of the violin.

66. **Experimental Study of Timbre.**—The truth of this theory of timbre can be experimentally proved by the methods already given (sects. 27 to 34) for examining the vibrations of sounding bodies. One of the readiest and most striking is the flame-manometer and revolving mirror-box (sect. 28). If, for example, we sing a note of a definite pitch, say the first A of the treble, into the mouth of the manometer funnel (fig. 14), we shall see in the mirror-

box, not a row of regular simple luminous teeth, but side by side with the *large pitch-determining* teeth we shall have two, three, or even more *secondary* teeth corresponding to the accompanying overtones. If next we sound, by means of an organ flue-pipe, the same musical note, we should find the prominent or principal teeth at the same interval, but the attendants varied in size, disposition, and even number ; and if, lastly, we were to sound a strong A tuning-fork, we should find the dominant teeth seemingly unattended by any smaller ones.

The tracings of the phonautograph (sect. 34) would shew precisely parallel differences in the representative curves. In the case of the tuning-fork, the curves would be smooth and simple ; in the case of the voice, over-riding waves of greater or less complexity will appear on the simple waves. Different voices sounding the same note, or even the same voice sounding the same note so as to pronounce the different vowel sounds, *a*, *e*, *i*, *o*, *u*, would trace phonautograph curves of totally different *form*, though identical in amplitude and pitch, and would produce correspondingly varied manometric figures.

67. **Helmholtz's Resonators.**—By a beautifully simple contrivance, Helmholtz shewed, in 1863, how the most complex sound or noise may be analysed into its component

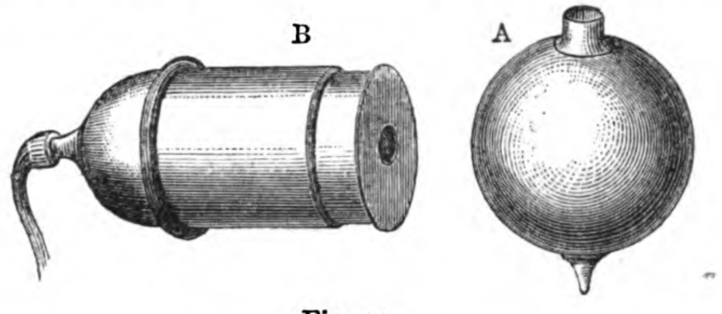


Fig. 33.

tones. The principle is an application of the laws of sounding air-columns. We have seen (sect. 59) that an air column enclosed in a tube, or cavity, has a definite period of pulsation, and (sects. 59 and 62) that any body vibrating at the rate peculiar to this column will induce sympathetically its vibration. Now Helmholtz constructs a series of spherical or cylindrical cavities (fig. 33), with a small tube for insertion in the ear, each carefully adjusted to answer or resound to one of the set of harmonics developed by a sounding-string—that is, to resound to a series of notes whose vibrations are proportional to the natural numbers 1, 2, 3, 4, 5, &c. In this way we can *test* any tone or sound for the presence of each individual of this series: the ear is deaf to all other tones but that particular one reinforced by its artificial cavity. It is as it were called aside from its companions, and privately examined in the inner chamber of the ear. The delicacy of this mode of scrutiny is marvellous, tones otherwise lost in the crowd being thus distinctly recognised.

König, the renowned acoustician of Paris, has adapted the same principle to optical exhibition with the manometer-flame; he simply replaces the funnel-mouth of the tube (fig. 14) by a cylindrical resonator, such as B, fig. 33; it will be easily understood that the vibroscopic flame connected with B will remain unaffected except by the particular note reinforced by B. König arranges a series of fourteen such resonators, harmonically adjusted, and extending over four and a half octaves; each resonator is connected by a tube with its own vibroscopic flame, and the whole set of flames is arranged in a vertical column, the mirror box being lengthened so as to exhibit the whole column of jets, which of course remain lighted simultaneously. If any note be sounded in front of the apparatus, and if it be simple or pure, only that resonator will answer it whose pitch is the same or sympathetic with it: but if it be, as it usually is, compound or accompanied by harmonics, the whole set of corresponding resonators will 'speak,' as will be shewn by the serration of their vibroscopic bands. This ingenious instrument thus exhibits to a whole audience at once the component tones of any composite sound.

INTERFERENCE OF SOUND—BEATS.

68. Closely connected with this part of our subject is the theory of *beats*, which are heard when two notes *nearly in unison* are sounded together. These are due to

the mutual interference of the aërial vibrations, which the analogy of water-waves will help us to understand. If we had a **Y**-shaped water-channel with centres of similar liquid disturbance at the ends of the prongs of the **Y**, it is clear that the combined effect in the united channel will depend on the relative lengths of the conveying channels; if equal, and if the waves meet crest with crest, and hollow with hollow, the resultant waves in the united channel will have twice the amplitude of the original ones; but if the crests from the left-hand channel just meet the hollows from the right-hand one, they will destroy each other, and there will be no waves at all: if, lastly, from inequality in the lengths of the converging channels or other cause, the waves meet at intermediate phases, the resultant waves will have a different period and amplitude from the original ones.

A precisely similar acoustical experiment may be performed: We take a wooden or pasteboard tube like an inverted *y*, **ʎ**, and gum over the upper end of it a piece of oiled silk or tracing-paper. Now, we hold this over a square plate, such as we employ for Chladni's figures (sect. 58); we know that when we sound the plate its adjacent segments are in opposite phases of vibration, while its diametrically opposite segments are in similar phases. What do we find, then, if we put a pinch of sand on the membrane? That the sand is violently agitated if we hold the prongs *diametrically* over the plate; but quiescent if we hold them *parallel* to the sides. In the latter case the vibrations passing up one prong just counteract those passing up the other, because they are in exactly opposite phases.

Confirmatory of the same fact is the following experiment with such a plate. Cut an **X**-shaped piece of cardboard, and hold over the diametrical segments of the plate while it is sounded with the bow: the effect is a remarkable increase in the loudness of the sound, owing to the damping of the aërial pulsations of those segments, which being opposite in phase to the others, diminish their intensity: if we turn it quarter round, we lessen the sound; half round, we again increase it.

A simple experiment, illustrating the interference of sound, is to strike a tuning-fork, and holding it at some distance from the ear, to turn it slowly round; we shall hear the sound rise and fall remarkably in intensity. The explanation is evidently the want of perfect coincidence in phase of the pulsations sent on by each prong to the ear. If the legs of the tuning-fork were separated by exactly *half* the wave-length corresponding to its note, the ear placed in line with the two prongs would not hear them sounding at all, or very very feebly.

Take again the illustration of our Y-shaped water-channel, and imagine waves to be travelling along the legs at the same rate, say a mile per minute; but that they were of slightly different length, say such that there were 500 waves in a mile of the left channel, and 501 in a mile of the right channel: then 500 of the longer waves would enter the common channel per minute, and 501 of the shorter waves. Suppose that at the beginning of the minute the two sets of waves coincide crest with crest, the resultant wave will be of double size: at the end of half a minute 250 waves from the left and 250½ waves from the right will have entered the united channel; thus the component waves will be in opposite phase, and the resultant wave will vanish. At the end of a minute the phases will be again coincident: and in the same way, if there were 520 waves per minute from the right channel, there would be twenty prominent waves, with twenty vanishings in the course of the minute.

Apply this to the analogous case of aërial pulsation. If two notes not quite in unison are sounded together, the wave-lengths of the pulses they set up will be slightly different; but the rate of sonorous motion is the same in both: hence, at certain parts of the course the pulses will coincide, and at others they will oppose each other. The result will be an alternate swelling and falling, or *beating* of the sound, which is more distinct as the notes are near together. If the one note make 256 (C) vibrations per second, while the other only makes 250, there will be six of these beats per second: as the difference in the notes increases, their number will increase, until a **Differential tone** resulting from these beats is fused together: the relation between the vibrational number of this differential tone and those of the two primary tones will determine, in accordance with the before-mentioned laws of harmony, whether their conjoint effect is consonant or dissonant.

Beats may be easily heard by striking two adjacent lower bass keys of the piano or harmonium; or by having two tuning-forks of exactly the same pitch, and then loading one of them with a little wax. If we make the mouth of our vibroscope (sect. 28) **Y** shaped, and hold the two slightly dissonant tuning-forks in front of the openings, we shall see the effect of the beats presented in an objective manner in the luminous band. With two organ pipes slightly out of unison, the effect on the vibroscope or on the ear is remarkably striking. Beats are very powerfully produced with a large bell, if the ear be properly placed with respect to the vibrating segments into which it divides itself. If we put our ear to a telegraph pole, we often hear well-developed beats when the wind acts strongly on the wires. The unpleasantness of the effect due to beats is supposed to bear an analogy to that of a flickering flame, or the joltings of a carriage on a paved street, or the interrupted shocks of a galvanic coil.

69. **HELMHOLTZ'S DOUBLE SYREN.**—The great German physicist has employed a modification of the syren already described (sect. 23) to verify the different laws of concord, discord, harmony, and interference. It is shewn in fig. 34, and consists of two syrens, one inverted over the other; their movable discs having a common axle and turning together. One or both of the discs may be sounded by urging a strong blast of air through one or both of the tubes A, B. The discs are, as improved by Dove, adapted to give each four separate tones by simple pressure of the spring buttons; and the numbers of holes are, in the upper disc, 9, 12, 15, 16 (D, G, B, C^1); in the under disc, 8, 10, 12, 18 (C, E, G, D^1). A registering apparatus is connected with the endless screw as in the ordinary syren, but is not shewn in the figure. The experimenter is thus enabled

to study the harmony of a very large number of combinations of tone, with absolute certainty as to their numerical ratios. All the different relations of the major and minor scale can be obtained at once; and as the nature of any harmony is independent of the actual velocity of rotation of the discs, it follows that it depends only on the numerical ratio of the tones. We may study the harmony of a note

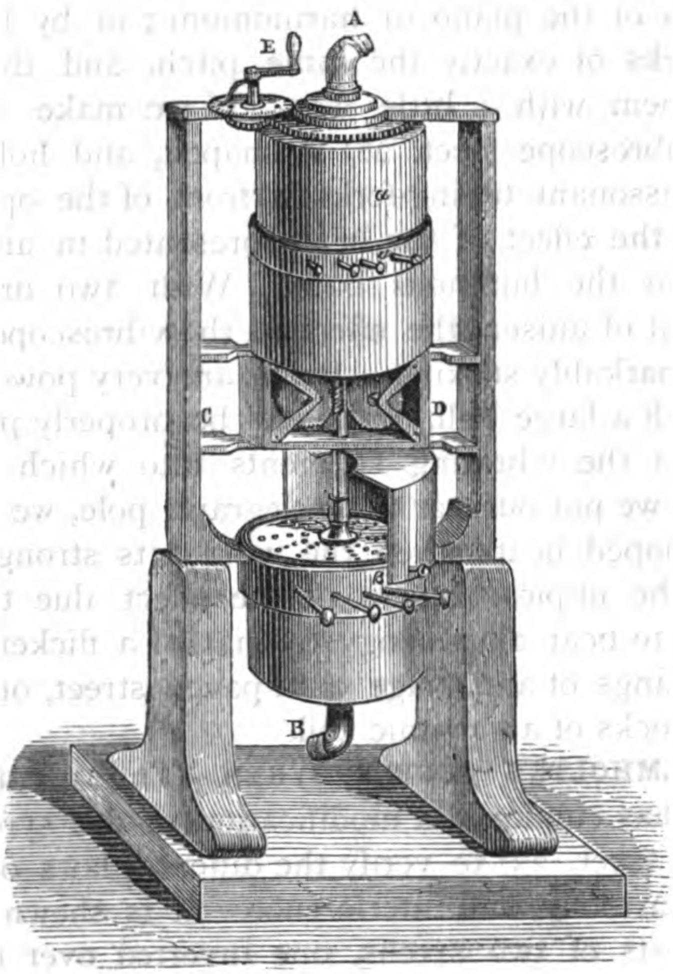


Fig. 34.

and its fifth by using the keys 8 and 12, or 10 and 15, or 12 and 18, any of these ratios being equivalent to that of $\frac{2}{3}$. By using the keys 8, 10, 12, 16, we obtain the major chord C E G C[1], whose harmony remains identical whatever the velocity of the discs—that is to say, whatever be the key-tone of the scale.

This instrument is specially useful in studying the theory of beats. By means of a handle, E, and toothed wheels, the air-box, *a*, of the upper syren can be turned either in the same or in the opposite direction to that in which the discs are turning: thus the rate of pulsation of the upper disc can be varied with extreme precision, being increased if we turn the box opposite to the direction of the disc motion, and diminished if we turn in the same direction. If we press the two keys 12 (G), we get two notes in perfect unison, whatever be the rate of rotation; but if we turn the box of the upper syren in either direction, we hear powerful beats whose number per second is the difference between the pulse-rate of the two tones.

MUSICAL INSTRUMENTS.

70. As even the most barbarous race has some apology for a musical instrument, we can hardly imagine a people so primitive but that they had some instrumental contrivance to accompany their songs and dances. The historical and ethnological specimens of musical art collected in museums or depicted on ancient monuments, comprise every imaginable shape and every possible elastic material. Hide and horn, wood and bone, glass and stone, and the various metals, have all been in requisition for musical purposes. We shall very briefly sketch, under the classes of *stringed instruments*, *instruments of percussion*, and *wind-instruments*, some of the more important national features of the practical embodiment of those principles we have been examining.

(1) Stringed Musical Instruments.

71. In some form or other, these have been found from the earliest ages, among all nations having any pretension to musical acquirements. Very rude, indeed, were the ancestors of our ornate instruments of the present day. The string of the bow, when not used in war, was twanged to evoke a few musical tones; and a simple wooden board with a few strings stretched over it, had to serve as a primitive piano. These are, however, pre-historic types of instruments, though representatives of them were found by

Livingstone actually in use among the savage tribes of Africa.

With the Egyptians, the Assyrians, and the Hebrews, stringed instruments of the **harp** and **lyre** type were universally known and in great repute. There have been discovered paintings of Egyptian harps in use fifteen hundred years before the Christian era, so elegant in form that Bruce, the famous traveller, was not credited when he first announced his discovery, in a royal tomb at Thebes, of such evidence of high musical art among the ancient Egyptians. They had also instruments of the **guitar** type, with two, three, four, or five strings, indicating a knowledge of producing, by means of a finger-board, a greater number of tones than were obtainable even on harps.

The Greeks and Romans had very much the same forms of stringed instruments, which in all likelihood were but importations or modifications of those used in Egypt. Among both these nations the universal favourite was the **lyre**, of which there were a great many varieties known by different names. The *kithara* had a square base, and was held against the breast. It had three, five, or seven strings, which were more usually twanged with an ivory or metal plectrum than with the fingers. There were also the *phormingx*, the *trigonon*, the *pektis*, the *barbiton*, the *nabla*, the *pandoura*, &c., but much uncertainty attaches to their exact forms.

The Hindus have still in popular use stringed instruments of great antiquity; among which may be mentioned the *vina*, with seven wire strings and movable frets, and having hollowed gourds attached for resonating effects. In olden times they had also the harp, *chang*, identical with that of Assyria, but now fallen into disuse. The Hindus claim to have invented the *fiddle-bow*, and with much show of reason, for there are said to be names for it in Sanskrit works more than two thousand years old. It is worthy of remark that the Hindus employed a scale with smaller intervals than our semitone; having indeed as many as twenty-two intervals to the octave.

The Persians and Arabians also had stringed instruments of the harp and lyre type in great variety; but most probably identical in construction with those of the Hebrews and Assyrians. In Arabian works on music we have, it is believed, a reproduction of the older Persian system; we find the octave divided into seventeen intervals, or *third-tones*, and these are still commonly employed in the East.

An instrument prominent in mediæval concerts was the **organistrum**, a large hurdy-gurdy, requiring two persons to play it. One turned a handle at the end, and so worked a wheel near the middle of the strings, which sounded them. The other managed the keys for lengthening and shortening the strings at the other end. It is most distinctly figured in a sculpture on the famous Pilgrimage Church of Santiago in Spain, which dates from the end of the twelfth century. A cast of the sculpture is to be found in the South Kensington Museum.

In more modern times the **lute** and the **theorbo or arch-lute**, a stringed instrument somewhat like a guitar, was three hundred years ago as great a favourite as the pianoforte is now. It consisted of a pear-shaped *body* or *belly*, with a long *neck*, which served as the finger-board, and which had nine marks or *frets* of catgut to indicate the position of the fingers for different notes. It had at first six strings, but they gradually increased in number, till in the arch-lute there were twenty-four.

It is worthy of notice here that the **guitar** (supposed to represent the ancient word **kithara**) represents a whole class of instruments, those, namely, with a neck and finger-board; the lyre and harp, on the other hand, are the typical names for all stringed instruments having merely a body without a neck.

The *lute* was succeeded by the **violin** family of instruments, which have kept their popularity for centuries, and which, at the present day, retain unimproved the very same features as two hundred years ago. Instruments of the violin type are mentioned as early as 1200 A.D.; they were probably introduced into Europe on the irruption of the Saracens and Moors into Spain. The *viol* was the direct parent of the violin; it was a fretted instrument of three sorts, treble, tenor, and bass, each provided with six strings. The viol-da-gamba (that is, *viola di gamma*, or *leg-viol*) was held between the legs, and remained in use till the end of last century, when it was supplanted by the violoncello. The modern violin, as is well known, has four strings of catgut, the lowest being covered with silver wire; they are tuned in fifths, E^1, A, D, G_1, and have a compass of fully three octaves. The finest violins now in use came from the hands of one family, *Amati*, living in Cremona from the beginning to the end of the seventeenth century. Two rival makers, Straduarius and Guarnerius, appeared to the Amatis towards the end of the seventeenth and beginning of the eighteenth centuries. Be the acoustical explanation what it may, the curved form seems essential to any satisfactory tone in the case of the violin. Yet Savart, the renowned French acoustician, demonstrated about a century ago that a very excellent violin might be constructed with straight sides, and at the cost of only a few shillings.* The violin used by the Esquimaux is of this simple construction.

The modern **pianoforte** may be regarded as the perfection of a series of keyed modifications of the ancient harp; the transition was represented by the **virginal**, the **clavichord**, the **spinet**, the **harpsichord**, and others — all somewhat resembling a diminutive pianoforte—but of much smaller compass, of more insignificant tone, and of inferior action. The virginal and the clavichord had a compass of *three octaves*, and the harpsichord latterly of *five octaves*. Though now utterly unknown, except as musical curiosities, they were much esteemed in their day. The pianoforte was invented about 1714 almost simultaneously by a French, a German, and an Italian maker; the first seen in England was made by Father Wood, an English monk settled in Rome. All the really important later inventions have, however, been introduced by the English.

Though every one is familiar with its general features, it may not be amiss to give a diagram of the action of a grand pianoforte. Different makers, it is to

* See the *Annales de Chimie et de Physique*, tome xii.

be remembered, have great differences of detail in the mechanism or action, some being very much more complicated than that here figured. A is the key; B, the lever which raises the hammer; C, the hammer; D, the string; and E, the damper, which stops the vibration of the string the instant the finger is lifted off the key; F is the button which catches the lever after it has struck the hammer; G, the check; H, the damper pedal-lifter; I, the spring; and K, K, K are rails and sockets.

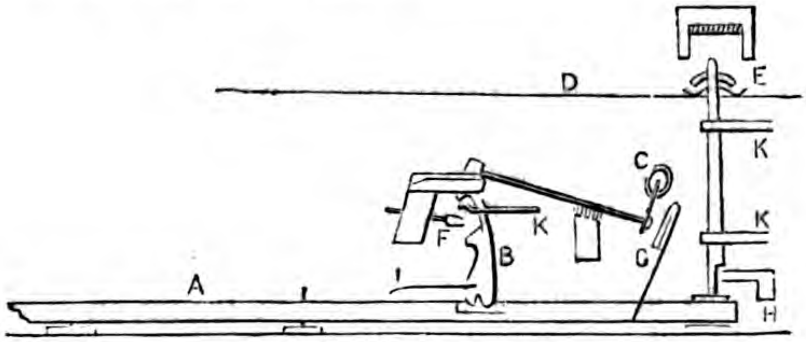


Fig. 35.

Formerly, the strings of the pianoforte were all of thin wire; now, the bass strings are very thick, and coated with a fine coil of copper wire; and the thickness, strength, and tension of the strings all diminish from the lower to the upper notes. A grand pianoforte has three strings to each of the upper and middle notes, and now, generally, only two to the lower notes, and one to the lowest octave. When the soft pedal is pressed down, the hammers are shifted sideways, so as to strike only two strings instead of three, or one string instead of two.

Besides the grand, the kinds of pianoforte in use are the square, in which the strings are placed in a horizontal position, but obliquely to the keys; and the upright, in which the strings run vertically from top to bottom of the instrument. The difference in form necessitates alterations in the details of the action, but the general principle is the same.

(2) Pulsatile Musical Instruments.

72. We need only very briefly sketch these, as their use generally is rather to produce mere volume or intensity of

sound than to give musically artistic effects. The *drum*, the *tambourine*, the *sistrum*, *cymbals*, and *bells* were all in use very much in their modern shape, among the ancient Egyptians, Assyrians, Hebrews, Greeks, and Romans.

It is to the eccentric ingenuity of the Chinese that we must turn to find the artistic cultivation of this class of sounds. Their sacred musical instrument is called **king**, and is very highly esteemed on account of its antiquity, which is said to reach back two thousand years before our Christian era. The *king* is a sort of harmonicon, constructed of slabs of hard and heavy sonorous stone of the agate species. Its musical value is ascribed by the Chinese to its constancy of pitch; neither cold nor heat, dryness nor moisture affecting its tones; and, curiously enough, twelve stones or intervals are found in the compass of an octave. They have also a wood harmonicon consisting of sixteen wooden slabs suspended in a wooden frame, in two tiers, one over the other.

Drums of various sizes and forms they also employ in profusion; the half-drum or *gong* being peculiarly Chinese; its powerful sounds are however used chiefly for signalling, for marking time, and for martial purposes. Among the ancient Chinese, bells were also used in sets of sixteen or more, so as to constitute a musical scale.

It is probable that musical sets of bells were employed by the ancient Romans on a small scale; but it is in modern Europe, especially in England, that we find a *penchant* for peals of bells. There are two modes of bell-ringing: the first is by *chimes*, where a set of bells have their hammers acted on by a pinned cylinder like that used in a music-box; the second is by *carillons*, where the hammers are acted on by a set of keys struck by the hand.

(3) Wind-Instruments.

73. Next to pulsatile instruments, which are universally found in some form or other, come wind-instruments, specimens of which have reached us from prehistoric times, and have been found among the most savage tribes of the old and new worlds.

The most primitive of this class of musical relics are perforated bones and even teeth of animals; these may have been used as whistles or calls in hunting.

Among the ancient Egyptians, Assyrians, and Hebrews, there were many varieties of the **pipe**, **flute**, and **trumpet** species. One Egyptian flute, in the British Museum, has seven finger-holes burnt in the side, and appears to have been sounded with a reed after the manner of our clarionet. A flute concert, painted on one of the tombs in the pyramids of Gizeh, dates prior to 2000 B.C. Like the Egyptians, the Hebrews had also both single and double pipes. It is worthy of notice that the wind-instrument *ugab*, which is translated 'organ' in our version of the Bible, was more probably a species of Pandean pipe or syrinx. They had also a kind of *bagpipe*, which some suppose to be referred to in Daniel, under the name *sumphonia*. Much has been written concerning the *magrepha* of the Hebrews, which is not mentioned in Scripture, but is carefully described in the Talmud. It is generally described as an organ, but modern investigators conclude that it was rather a species of bagpipe, or a combination of a syrinx with bellows. Lastly the Hebrews had several kinds of trumpet—curved ones of ram's horn, still used by the Jews in their religious services; and straight ones of silver, which are distinctly represented on the Arch of Titus, in the famous triumphal procession after the fall of Jerusalem.

Among the Greeks and Romans we find the same types of wind-instruments, probably importations from the East. Among both, the **flute** was a favourite instrument; it was similarly made and played by both—being about fifteen inches long, of wood or bone, and having six finger-holes, five above and one underneath. Both had the **syrinx** or **Pandean pipe**, the number of tubes being variable, and ranging from three to nine, but most commonly seven. Both had trumpets straight and curved, made of bronze and chiefly used in war. Their only other wind-instrument of importance was the **hydraulos** or **water-flute** of the Greeks, corresponding apparently with the

organum hydraulicum or hydraulic organ of the Romans. We are not to imagine that this corresponded at all in size or ingenuity with the organ of our day. Probably it was nothing more than a huge set of Pandean pipes, sounded by reed mouth-pieces below, the air-current being produced by a flow of water, and the pipes sounded by a sort of stops, for there does not appear to have been anything approaching to a key-board. This rude instrument is said to have been used in the churches during the first six centuries of our era; but it was not till the hydraulic organ was transformed into the pneumatic or wind organ that the history of the modern splendid instrument began. There are some illustrations, dating about the twelfth century, of the organ as then in use: it took four men at the bellows to get sufficient strength of wind up, and two more to play the instrument, which had only about a dozen pipes. Side by side with this let us look at any of the magnificent organs of the present day, such as that of York Cathedral, or of Birmingham town hall, or of continental towns. 'The York organ has 4200 pipes, with 56 stops, besides 6 copula-stops; the largest metal pipe is 32 feet long and 20 inches in diameter. The Birmingham organ has about 3000 pipes, 40 real stops, 4 rows of keys, and $2\frac{1}{3}$ octaves of pedals; the largest metal pipe is 35 feet long and 21 inches diameter; the whole measures 35 feet wide, 15 deep, and 48 high, and weighs about 40 tons.' Several continental organs have over 5000 pipes.

THE HUMAN VOICE.

74. **The Larynx, Vocal Reeds, and Glottis.**—Here will come in appropriately a sketch of the oldest, but the most perfect of all wind-instruments—the Voice. In the human being we have first of all the lungs for bellows, with the muscles of the thorax for blowers: from these the wind passes up through the **trachea** or windpipe to the **larynx** or wind-chest as it were; stretched over this wind-chest are the **vocal cords**, or reeds—for the voice is a *reed* rather than a *string* instrument—whose great expansile and contractile power makes them equivalent to a multiplicity of reeds; and lastly, over

and above the reeds, we have the **pharynx** or throat leading to the resonant air-cavity of the mouth.

Fig. 36 shews the larynx or cartilaginous box, whose parts are exceedingly mobile in order that the tension of the vocal cords may be increased or diminished at will. These cartilages are five in number, and are sufficiently indicated below the engraving. The various cartilages are connected

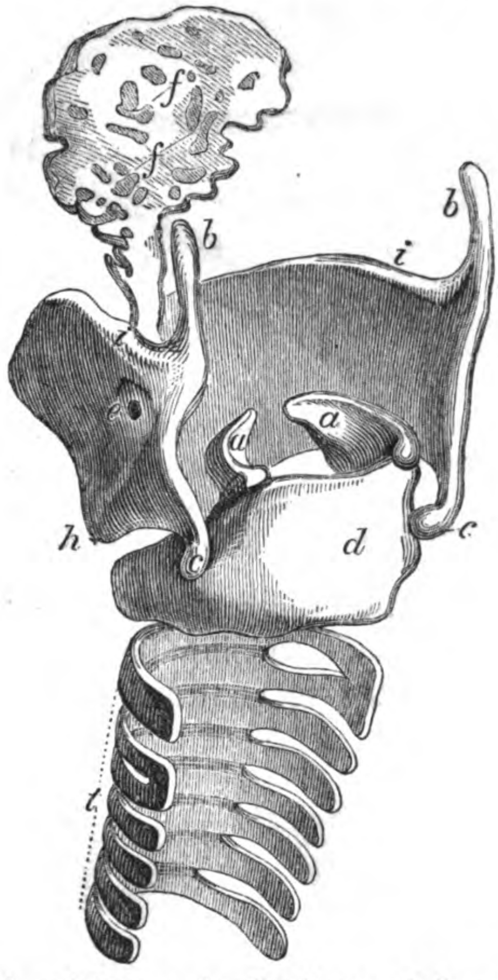


Fig. 36 (from Todd and Bowman).—Cartilages of Larynx and Epiglottis, and upper rings of Trachea, seen from behind : *a*, arytenoid cartilages; *b*, superior cornua of thyroid cartilage; *c*, its inferior cornua; *d*, posterior surface of cricoid; *f*, epiglottis, with its perforations; *i*, upper margin of thyroid; *h*, its left inferior tubercle; *t*, trachea.

together by ligaments, the chief of which are those known as the **true** and the **false vocal cords.** Fig. 37 will give an idea of the position of the vocal cords in a state of rest. In this position, there is a wide opening between the vocal ligaments, and the air passes freely through between them.

There are two opposing sets of muscles which act on the cords to stretch or relax them ; and other two sets of muscles which act on the aperture of the glottis to *open* or *close* it. As soon as we wish to utter a sound, the two

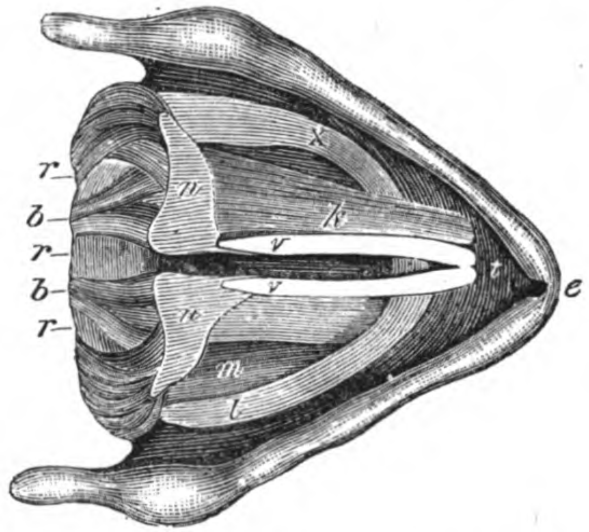


Fig. 37.—View of Larynx from above, after Willis : *b*, ligaments uniting arytenoid and cricoid cartilages ; *e*, thyroid cartilage in front ; *k*, left thyro-arytenoid muscle, right removed ; *l*, *r*, *x*, cricoid cartilage ; *m*, right crico-arytenoid muscle ; *n*, arytenoid cartilage ; *t*, *v*, vocal cord.

arytenoid cartilages raise themselves in the fold of mucous membrane, and approach, causing the vocal cords also to approach, and the glottis to contract as in fig. 38 ; which

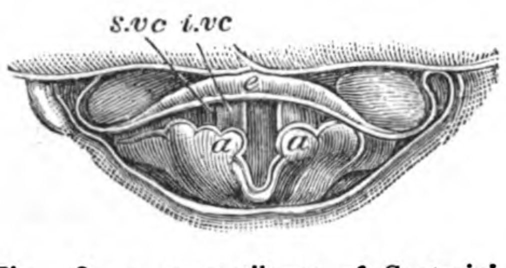


Fig. 38.—*a*, *a*, cartilages of Santorini, surmounting the arytenoid cartilages ; *e*, epiglottis ; *ivc*, inferior or true vocal cord ; *svc*, superior or false vocal cord of left side.

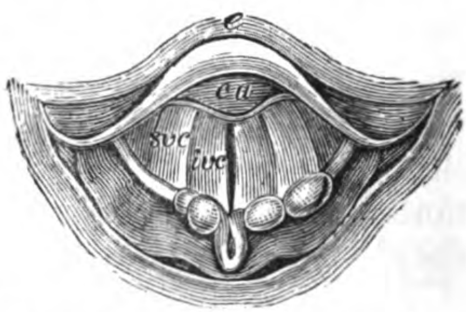


Fig. 39.—*e*, epiglottis ; *cu*, cushion of epiglottis ; *ivc*, true vocal cord ; *svc*, false vocal cord.

represents the larynx during the emission of the broad vowel sound *ah*. By means of the beautifully simple invention known as the *Laryngoscope*, all these movements may be readily studied. Fig. 39 shews the condition of the larynx during the emission of a high or acute sound; the glottis, it will be seen, is contracted almost to a line. By the vibration of the vocal reeds, the issuing blast escapes in a series of puffs, which will be more massive in the case of fig. 38 than in that of fig. 39. The greatest sounding distance for the vocal cords does not exceed one-tenth of an inch. In the adult male, the length of the cords is about ·73 of an inch, and half as long again as in the average adult female; hence a woman's voice is more than an octave higher than a man's voice.

75. **Delicacy of Vocal Muscular Action.**—The sounds produced by the vocal apparatus are quite in accordance with the ordinary laws of vibrating reeds or membranes; depending for pitch on the strength of the blast, the tension, and degree of approximation of the ligaments. There is no difficulty in understanding all this; in fact, a rough mechanical model of the voice can easily be made with a simple tube and two elastic bands or pieces of leather stretched across the end, so as to be parallel or slightly inclined. But what is most marvellous is the extreme precision with which the muscular contractions are adapted to the desired effects. The natural compass of a male voice is about two octaves, or twenty-four semitones; now if a singer can produce ten distinct intervals in each semitone, which is a very ordinary accomplishment, this corresponds to 240 distinct adjustments of length of the vocal cords. In a state of rest, the length of the cords is $\frac{73}{100}$ of an inch; for their greatest tension, it is about $\frac{93}{100}$, the difference being one-fifth of an inch. Thus it is nothing extraordinary to have the power of adjusting the vocal cords to $\frac{1}{240}$ of $\frac{1}{5}$ of an inch—that is, to one twelve-hundredth part of an inch.

These surprisingly delicate adjustments have been acquired and continue to be effected under the guidance of the ear; tones once heard seem to establish a mutual understanding between the nerves which stimulate the action of the larynx and corresponding nerve-fibres of the ear. Persons born deaf are also dumb, not that they have any malformation of the vocal organs, or are powerless to produce the sounds; but that, having never heard them, they have no stimulus to produce them, and no umpire of any vocal effects produced.

76. **Timbre of the Voice.**—The sounds produced simply by modifications of the tension of the vocal cords may be considered the prime factors of *musical tones;* but when we come to analyse the *articulate sounds of language*, there are other factors to be clearly separated, such as the use of the lips, teeth, and tongue, and the adjustment of the cavity of the fauces and palate, &c. To take the simplest case, the sounding of the different *vowels:* we may of course pronounce them all equally loud, or at the same pitch — that is, with the same vibration-rate and therefore tension of the vocal cords; but a single trial of the different vowel-sounds shews that the shape of the mouth cannot be retained unaltered for any two. Though the pitch of the vocal reeds remain unaltered, the *timbre* of the sounds must be different, and must correspond to the change of the resonant cavity, the mouth. We shall give very briefly the results of the splendid researches of Helmholtz on this subject. The vocal tones are exceedingly rich in harmonics or overtones; now, different adjustments of the elastic resonator will, according to the explanations already given (sect. 59), reinforce different individuals of this harmonic series, sometimes the primary harmonics, sometimes the higher harmonics. Upon the union with the fundamental tone of the special harmonics, thus reinforced, depends the *resultant vowel-sound.* Thus, in sounding *ōō* (foot), the mouth cavity reinforces the fundamental tone of the vocal reeds; in sounding *ō* (note), some of the overtones are reinforced; in sounding *ah* (far), harmonics above the last set are reinforced, and so on.

The flame-manometer of M. König, already mentioned, illustrates this subject very beautifully. If holding the flame before our rotating mirror (fig. 13), we sound at the mouthpiece of our vibroscope the different vowels, *ah, ā, ē, ī, ō, ōō*, we shall find in our rotating mirror not a succession of perfectly equal and similar luminous teeth, as we do when a single pure tone is sung or sounded, but *groups* of unequal teeth recurring regularly; also the *individual character* of the luminous group is quite different in each case.

77. **Helmholtz's Vowel Apparatus.**—Not satisfied with mere analysis, Helmholtz put this theory to the crucial test of synthesis, and actually succeeded in building up the different vowel-sounds out of a set of mechanically sounded pure tones. We shall endeavour to explain the principle of his vowel apparatus without a diagram. It consists of ten large tuning-forks fixed upright on a table, each having a brass resonance box immediately behind it to reinforce its fundamental tone. The prongs of each fork are placed between the poles of an electro-magnet, so that whenever the current from a neighbouring battery is sent through any magnet, its fork is instantly set in vibration. There is a keyboard at the end of the table, so that by pressing down one or more keys, one or more tuning-forks may be sounded.* The forks are all tuned so as to stand to each other in the relations of a fundamental tone and its first nine harmonics or overtones. In this way it is easy to understand that any group of harmonically related tones may be associated. The results are perfectly confirmatory of the analytical theory.

We have not space to enter upon the superposition of the mechanical actions of the lips, tongue, teeth, &c. over the resonance of the mouth, whereby *consonants* are formed, and the vowel-sounds *articulated*, or jointed together. For a complete discussion of all these points reference may be made to Max Müller's *Lectures on the Science of Language*, and to Ellis's translation of Helmholtz's great work.

THE EAR AND THE SENSE OF HEARING.

78. Across the gulf which separates the outer region of physical vibrations from the inner one of sense or consciousness, stands a bridge of splendid architecture, the human ear. We descry trains of sonorous pulses

* We purposely omit details of the electrical break and other arrangements, as with the apparatus before one, they are easily understood, and without a good drawing they would only bewilder.

enter upon the bridge at one end, we can follow the trains over a good few piers, but finally we lose them in a tubular portion of the bridge, and only identify them as they emerge at the nearer end. Fig. 40 is a general

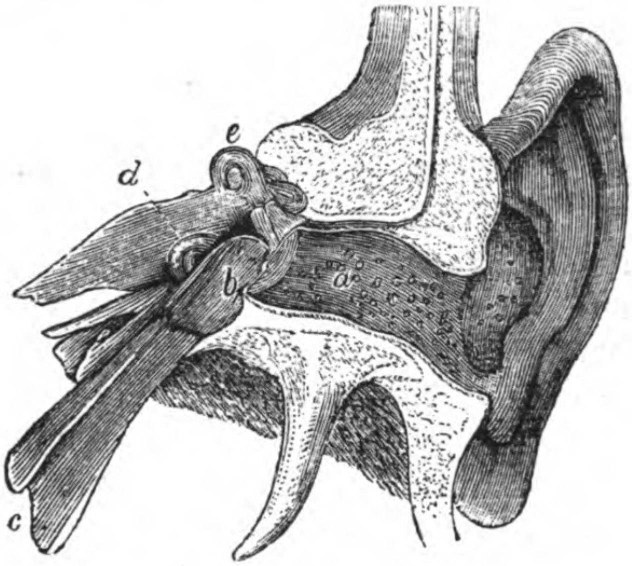


Fig. 40.

view of the external, middle, and internal ear. The outer ear acts as a sort of collector of the air-pulses, which pass thence along the *auditory canal*, *a*, to the **tympanum** or *drum*, *b*, on which they beat. The interior of the tympanic cavity is connected by a passage, *c*, called the *Eustachian tube*, with the throat; *d* is the **cochlea** or *shell-like* organ, and *e* the **semicircular canals**, whose exact functions are still veiled in obscurity. It is even matter of dispute what is the special use of the external ear; in man, at all events, it is no mere trumpet; for a less elaborate and a more conical shape would have better fulfilled this function. Doubtless its disposition is to a certain extent protective of the delicate mechanism within. But apart from all this it seems probable that the position and shape of the ears in man are intimately connected with the discrimination of *direction of sounds*. Placed at an inclination, such as they are, they will obviously reflect a sound in front more powerfully than one from behind; and this differential of intensity comes by experience to indicate the directions of *behind* and *before*. A single ear would suffice for this; but with a couple of them it is probable that the same principle explains the perception of sound-direction generally.

The auditory canal leads to the circular membrane of the **tympanum**, which closes it obliquely. Within this membrane is an air-cavity called the tympanic cavity, whose walls are of a bony structure, and which contains within it three small bones, or ossicles, called the **ear-bones**, represented in fig. 41, and named from their shape *malleus* (the hammer), *incus* (the anvil), and *stapes* (the stirrup). The handle of the hammer is firmly attached to the tympanic membrane, and these bones are generally regarded as a sort of stepping-stones for the passage of the sound across the cavity. This air-cavity is connected by the Eustachian tube with the external air; and thus the pressure of air within is kept the same as that of the outside air. But for such a provision, the cavity would act like an aneroid barometer under changes of air-pressure. It is worthy of remark, however, that the tube is opened only during the act of swallowing; at other times it is shut; and but for this provision the sounds of one's self breathing and speaking would be conveyed direct to the sentient ear, and be intolerable.

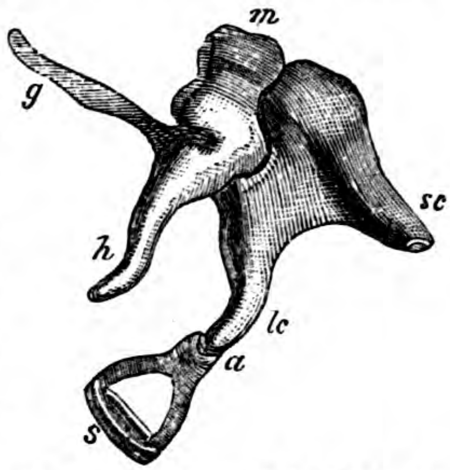


Fig. 41.—Ossicles of the Left Ear, as seen from the outside and below: *m*, head of the malleus; *g*, the slender process, or *processus gracilis*; *h*, the manubrium or handle; *sc*, the short crus, and *lc* the long crus of the incus; *a*, the position of the lenticular process, through the medium of which it articulates with the head of the stapes; *s*, the base of the stapes. Magnified three diameters.

The tympanum is hollowed from without inwards, and this fact, together with the damping effect of the attached ear-bones, is given by Helmholtz as explaining the great range of tones which this membrane is capable of transmitting. Were it a plane-stretched membrane or plate, it would only vibrate its fundamental tone or some of its harmonics; but a funnel-shaped membrane, as he proves experimentally, has no peculiar tone, and is not thus limited in its vibration range. The ear-bones seem also to play the part of *dampers* of the vibrations of the drum, extinguishing them almost the moment they are received.

Somewhat after the manner of the pianoforte action, the ear-bones transmit the vibrations of the tympanum to the membrane of the **fenestra ovalis**, which is the oval opening leading to the inner ear or **labyrinth** (represented in fig. 42). This opening leads first of all to the **vestibule**, or entrance

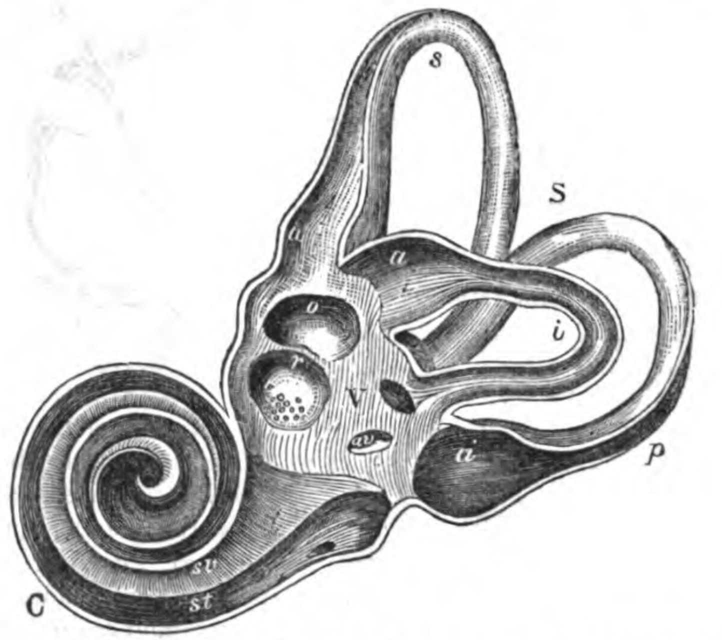


Fig. 42.—Interior of the Osseous Labyrinth: V, vestibule; *av*, aqueduct of the vestibule; *o*, fovea semi-elliptica; *r*, fovea hemispherica; S, semicircular canals; *s*, superior; *p*, posterior; *i*, inferior; *a*, *a*, *a*, the ampullar extremity of each; C, the cochlea; *sv*, osseous zone of the lamina spiralis, above which is the scala vestibuli, communicating with the vestibule; *st*, scala tympani, below the spiral lamina. Magnified three and a half diameters.

chamber, which has the passages of the cochlea on the one side, and of the semicircular canals on the other. Within these winding corridors the secrets of the transference from matter to mind are concealed. There is within the cochlea a compound spiral passage to its apex, a bony partition separating the two passages. The osseous structures of the labyrinth and semicircular canals are each lined throughout with a membrane, so as to form two complete irregular sacs, filled with a liquid which is nearly pure water. Upon this membrane are spread filaments of the auditory nerve. Near the wall of the membranous labyrinth are attached by fine filaments, small stones, which have been long known as the **otoliths** or **ear-stones**; they are supposed to have some vibratory function, but nothing is known definitely. The surface of the wall is studded with cells, which have fine hairs on their surface; from the bottom of the hairs fine nerve-fibres pass to the wall, and thence join the ramifications of the auditory nerve.

79. **The Organs of Corti.**—The most remarkable organs, however, are those within the cochlea discovered by Corti, and known as the *fibres of Corti.* It is difficult to describe their situation and structure without large and fine diagrams. We shall try to indicate these roughly. Fig. 43 shews a section of the spiral passage of the cochlea, perpendicular to the section in the last figure. L*s* is the *lamina spiralis* or

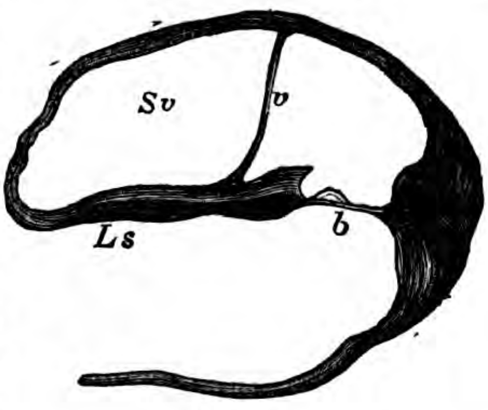


Fig. 43.

spiral partition which divides the canal into two; *v* being a membrane which subdivides the one canal again into two longitudinal passages. Now the partition L*s* is not osseous all the way across, but is completed by a membrane *b*, which stretches between it and the outer wall of the cochlea. Over this membrane are **V**-shaped fibres, *b*, spanning it like a bow, and resting on it as a base. They cover the membrane all the way up to the apex, and are in countless numbers: as many as three thousand have been counted in a small space. The fibres are not all uniform in size or shape, but vary with the varying breadth of the membrane, which increases from about $\frac{1}{500}$ of an inch at the base to $\frac{1}{50}$ inch at the apex. Indeed, the whole formation is so striking and so delicately formed, that it forces on us the idea of a microscopic musical instrument—a collection of vibrating strings over a sounding-board. It would be foolish to jump at once to the conclusion that the mystery of hearing is, by this discovery, fully dispelled; for many difficulties still remain to be explained, and much of what has been written on this subject is merely speculative. Nevertheless it seems highly probable, from the researches of Corti, Helmholtz, and others, that this organ within the cochlea is the seat of the musical sense; that it may be regarded as a *sympathetic vibratory apparatus*, whose fibres are individually tuned to accept, and announce to headquarters, specific tones or rates of vibration: and their extraordinary number is only correspondent to the great range and sensibility of the human ear.

80. **THE TELEPHONE.**—This remarkable electro-acoustic apparatus illustrates the action of the tympanic membrane, and may be conveniently described in this connection. By its means, musical tones, a musical air, or even a conversation in any ordinary tone of voice, may be transmitted to any distance along a telegraph wire. It is not an instance of actual sound-conduction by the wire, as described in sect. 12 or sect. 38, but is the reproduction at a distance, by means of electricity, of sound-vibrations.

Like the ordinary telegraph, it consists of (1) a *transmitter* with its *local battery*, and (2) a *receiving* or *interpreting* apparatus at the far end. The transmitter is something like the half of our vibroscopic apparatus (fig. 14), having a funnel-mouth, an air-cavity or box, and an elastic membrane. A strip of tin-foil or gold-leaf is pasted from the centre to the circumference of the membrane where it is in metallic connection with one pole of the local battery. Pressing lightly on the tin-foil at the centre is the tip of an elastic metal spring, whose other end is fixed to the box and is in metallic connection with the telegraph wire, and through it with the other pole of the battery.* It is clear then, that if we sound any note into this apparatus, the membrane will vibrate and cause interruptions of the electric current at the same rate as it vibrates. These interruptions are audibly reproduced at the distant station in a very simple manner. It is well known to electricians that a momentary current sent through a coil of wire

* See the Manual on *Electricity* in this series.

surrounding an iron rod causes a click by the momentary magnetisation of the iron. The receiving apparatus is based on this fact, and consists of a small coil with a soft-iron core enclosed in a sounding-box with elastic wooden sides. Whatever number of vibrations, then, the transmitting membrane makes per second, just as many clicks per second will be reproduced at the far end; these are strengthened by the resonating box, so that the tones sung at the one end can be distinctly recognised at the other. And the analogy to the tympanum lies specially in the fact that the spring pressing on the centre of the membrane resembles the ear bones attached to the middle of the tympanum, and prevents the membrane from merely vibrating in sympathy with its fundamental tone or its harmonics. Consequently the telephone, like the ear, is adapted to transmit a great range of tones, and is thus capable of transmitting a melody. Recently this instrument has been considerably improved in its construction by an American professor (Professor A. Graham Bell, of Boston), who was the first to accomplish the transmission of telephonic messages so as to be distinctly audible to a large audience. He not only sent well-known melodies from a distance of eighteen miles, but he kept up a conversation in ordinary tones of voice with his assistant at that distance. Coughing, laughing, and even the tone of a familiar voice could be distinctly recognised. Thus Electricity and Acoustics have united to achieve another of the many scientific marvels of the present age.

QUESTIONS.

Section 1. Is there any reason to believe that the study of Acoustics has been auxiliary to the art of music?

2. How would you reveal to the eye the minute motion of a sounding body?

3. Sound cannot pass through a vacuum: what experiment proves this? What change on a piece of music might we expect if we could hear it first in air, then in an atmosphere of hydrogen?

4. Explain clearly the nature of the air-motion in the transmission of sound. How does an air-*pulse* differ from an air-*puff?* What is meant by a sonorous *wave?* Distinguish the wave or pulse-motion, and the motion of the aërial particles.

5. How do liquid or chain waves differ from sonorous air-waves? Sketch waves of different length but the same amplitude; also waves of the same length but different amplitudes.

6. Shew experimentally that chain-waves may readily be taken as the representatives of pulses of condensation and rarefaction.

7. Give any illustrations of the mechanical effect of powerful sounds.

8. What are *sensitive flames*, and the acoustical facts they illustrate? Describe any method of exhibiting these.

9. How would you calculate the distance of a thunder-cloud by the interval between the lightning and the thunder? Describe the experiments by which the velocity of sound in air has been ascertained. What are the effects of atmospheric pressure, moisture, temperature, and motion on the rate of propagation of sound in it? Give the velocity at the temperature of the freezing point and also at that of 50°.

10. What remarkable omission was made by Sir Isaac Newton in his theoretical calculation of sound-velocity? Give the velocity of sound in air, oxygen, hydrogen, and carbonic acid, and state the relation between velocity and gaseous density.

11. Describe the experiment of Colladon and Sturm, on the Lake of Geneva, for determining the velocity of sound in water. Why is it greater than in air?

12. Do solids conduct sound better or worse than gases? How would you shew this by experiment? What reason can you give for the fact?

13. What are the best conductors of sound? How do the molecular structure, density, and elasticity of a solid affect its conductibility?

14. State the law of reflection of sound. Describe any experiments to illustrate its analogy to the reflection of light.

15. Explain briefly the action of the ear-trumpet, the speaking-trumpet, and the stethoscope.

16. In speaking-tubes care must be taken to have no sudden bend. Why so?

17. What are the conditions of hearing an echo? How may an echo be taken advantage of to find the distance of an inaccessible rock? On what does the number of syllables echoed depend?

18. Explain the cause of multiple echoes.

19. What unexpected results were brought out by Professor Tyndall's experiments on the aërial transmission of sound? What does he mean by *acoustic clouds* and *aërial echoes?*

20. What is the fundamental distinction between *noise* and *tone?*

21. Explain what condition is necessary to the production of a musical sound.

22. What are the superior and inferior musical limits? Describe some simple means of ascertaining these.

23. Sketch the principle of the syren disc: also of the improved form of syren due to Cagniard de la Tour, explaining how the number of pulsations per second of any note is calculated by its means.

24. How is the isochronism of a vibrating string connected with its adaptation to musical use?

25. State the different modes of analysing a musical sound.

26. In what simple way may the motion of a sounding tuning-fork be exhibited to the eye?

27, 28. Describe fully the principle of the flame-vibroscope or manometer, and sketch the luminous appearances produced.

29. Explain the principle of Lissajous' experiments: stating clearly the connection between the mechanical conditions and the acoustical results.

30. What is Helmholtz's simple mode of examining the motions of a sounding-string microscopically?

31. What is Melde's mechanical illustration of the composition of vibrations?

32. Blackburn's pendulum illustrates the same subject. Sketch its principle and the mode of using the apparatus.

33. Explain how the vibrations of a tuning-fork may be made to register themselves permanently.

34. Give a short account of the Phonautograph, and some idea of its acoustical purpose.

35. How has it been found possible to *photograph* a *sound?* Explain the arrangement.

36. What are the three elements of a musical sound?

37. Detail the circumstances which modify the intensity of a sound.

38. Explain clearly the purpose served by the sounding-board of a musical instrument, such as a piano or a violin. What experiment of Wheatstone's illustrates this point?

39. Sketch a sonometer as now usually made; and give an idea of how it is to be used experimentally. What law connects the length of a string with the rate of its vibration?

40. When are two musical tones called consonant or dissonnant? How does the acoustic basis of consonance differ from the common or emotional one?

41. Give details as to the experimental proof of the numerical relation between consonances—such as a note and its third, a note and its fourth, &c. What is the general arithmetical connection between two concordant tones?

42. What are the numerical relations between the notes of the musical scale? Is there any connection between these relations and the names of the notes, *third*, *fourth*, *fifth*, &c.? Explain clearly how you would divide a string forty-eight inches long, so as to give the successive notes of the major and minor scales.

43. How is the musical interval between one note and another estimated? Hence shew how there are different intervals going by one name, such as *seconds*, *thirds*, &c. Express the intervals of a musical comma, a major semitone, and a minor semitone by their arithmetical ratios.

44. What is a harmonic *triad?* and a harmonic *chord?* Shew that by octave transpositions the common major chord, C E G C^1, may be made to include every note of the scale.

45. What is meant by the sharp or flat of any note? Give the numerical ratio which converts a note into its sharp or flat. Explain the meaning of a key-note; and the effect on the scale of changing the key-note, which necessitates the use of flats and sharps. Describe the simple geometrical contrivance (Harmonic Triangle) by which we may shew the position of the flats and sharps for any change of key.

46. Explain the meaning of the terms *Temperament of the Scale*, and *Equal Temperament*. Are the two notes C sharp and D flat absolutely identical? Go through the arithmetical calculations connecting the successive notes of the tempered scale, and compare them with the ratios of the natural scale already referred to. What is the chromatic scale?

47. What is the graphic mode of exhibiting the pulse coincidences of two concordant tones, or of a major or minor chord?

48. It is said that the standard of musical pitch has been rising since the time of Handel. Give some idea of the extent of this pitch variation. What is concert-pitch? How is it calculated that the wave-lengths in the tones of an organ vary from three or four inches to seventy feet?

49. Describe generally the meaning of the term *Timbre* or *Clang*.

50. If we rub a string lengthwise, and then crosswise, the note is higher in the former case. How do you explain this? What are the different laws connecting the vibration-rate of a string with (1) its length, (2) its thickness, (3) its density, and (4) its tension? How may they be proved experimentally?

51. Explain the aliquot division of a sounding-string. What is the relation connecting the note, the number of aliquot parts, and the rate of vibration of the string as a whole? Describe any experiment for shewing readily the nodes of a sounding-string.

52. How may the aliquot subdivision of a string be spontaneously induced?

53. What is meant by the *harmonics* of a sounding-string? How do you account for their existence? Enunciate Young's law as to the production of overtones in a string. State any circumstances which influence the development of overtones. Express in the musical notation the normal harmonics in the case of a free sounding-string.

54. Sketch briefly the mode of vibration of an elastic rod (1) fixed at both ends; (2) fixed only at one end; and (3) free at both ends. According to what law do the successive harmonics arise? What is illustrated by Wheatstone's kaleidophone?

55. What are the nodal divisions of a tuning-fork corresponding to its fundamental tone? Why is its tone practically pure?

56. What do you know of the laws of longitudinal vibration of rods? How can the velocity of sound be deduced from the note of a rod sounded lengthwise?

57. Give a short account of Kundt's experiments on the velocity of sound. What is the relation between the number of dust-heaps and the velocity of sound in the glass tube?

58. How would you shew Chladni's sand-figures? What are the laws according to which the figures are formed?

59. Trace the analogy between the vibration of a sounding air-column and of a sounding-string. How would you shew this experimentally?

60. Picture the aërial motion within a sounding-pipe stopped at one end. What are the nodes corresponding to the first three harmonics? What relation does the length of the pipe bear to the note it yields?

61. If we open the end of a stopped pipe, how is its tone affected? What law does the harmonic-development now follow?

62. What are the two leading classes of organ pipes? On what do the pitch and the quality of an organ pipe depend?

63. Sketch König's manometric mode of shewing the nodal divisions of an organ pipe.

64. Describe the chemical harmonicon experiment. What may it be used to illustrate?

65. State the fundamental principle of the modern theory of *timbre.* Wherein does the tone of one violin differ from that of another? Explain why the pianoforte-maker adjusts the hammer to strike the string at a particular place.

66. Describe König's experimental mode of illustrating this theory of *timbre.* How does the phonautograph support the theory?

67. What are Helmholtz's resonators, and what important facts do they serve to establish?

68. Explain the general principle of wave-interference. How may two sounds conspire to produce silence? Apply this to explain the theory of *Beats*. What is the *differential* tone arising from beats in certain instances?

69. Give an outline of Helmholtz's Double Syren. How is it used to illustrate the laws of concord, harmony, and beats?

70. Name the three classes under which musical instruments fall.

71. State what you know of the stringed instruments of the ancients. Do you know whether any nation has at any time used smaller musical intervals than our semitone? What were the *organistrum*, the *lute*, the *theorbo*, the *viol?* Wherein does the value of an old Cremona violin lie? Describe the general action of a pianoforte. What keyed instruments paved the way for its introduction?

72. What do you know of the Chinese *king*, the *gong*, musical *chimes* and *carillons?*

73. Give an account of the chief wind-instruments of the ancients. What was the water-organ of the Romans? Compare it with the modern organ.

74. Describe clearly the principal parts of the vocal apparatus. What reason is there for saying it is not a stringed instrument? What are the changes in the vocal chords in uttering first a low note and then a shrill one?

75. Give some idea of the delicate adjustments of the vocal chords of which a good singer has the command.

76. Sketch briefly Helmholtz's theory as to the pronunciation of the different vowel-sounds. How does König's manometric flame illustrate this? What acoustic difference of character is there between the consonants and the vowels?

77. Describe Helmholtz's synthetic vowel apparatus.

78. What are the functions, so far as known, of the following parts of the ear—the outer-ear, the auditory-canal, the tympanum, the semicircular canals, the ear bones, the labyrinth, the cochlea?

79. Give an account of the famous Organs of Corti, with his theory as to their function.

80. How is it possible to transmit sounds to any distance by electricity? What analogy does the Telephone transmitter bear to the human tympanum?

SPECIMEN ANSWERS

TO

SOUTH KENSINGTON SCIENCE QUESTIONS IN ACOUSTICS.

1874—ELEMENTARY.

Q. 1. On a day when the temperature of the air was 32° F., I saw the flash of a gun and heard the report half a minute afterwards: what was the distance of the gun, and why do I mention a particular temperature?

ANS. It has been found by the French and other experimenters that at 32° F., or the freezing temperature of water, the velocity of sound in air is 1090 feet per second; and that at a higher temperature the velocity is increased, owing to the increased *elasticity* of the air. Obviously, therefore, as the flash may be supposed to pass to the eye in an instant (for ordinary distances), the gun will be distant 1090×30 feet $= 10{,}900$ yards $= 6\frac{1}{5}$ miles nearly. (See sect. 9.)

Q. 2. A musical string vibrates 400 times in a second: state what occurs when you shorten or lengthen the string without altering its tension, and also what occurs when you increase or lessen its tension without altering its length.

ANS. The tension of a string remaining unaltered, its rate of vibration increases exactly as its length decreases; so that half, third, double of the string will vibrate 800, 1200, 200 times a second. This is the mechanical result. The musical effect is that the pitch of note given by the string rises or falls as it is shortened or lengthened; and by sounding parts of the string which are aliquot parts or simple fractions of the whole string, we get tones harmonically related to that of the whole string. Thus we get the successive notes of the common scale by sounding first the whole string, then $\frac{8}{9}$, $\frac{4}{5}$, $\frac{3}{4}$, $\frac{2}{3}$, $\frac{3}{5}$, $\frac{8}{15}$, and $\frac{1}{2}$ of it. Again, if keeping the length constant we increase the tension, we increase the rate of vibration, and with that the pitch of the resulting note; not, however, in a simple ratio, for we must increase the tension 4, 9, &c. times to raise the vibration 2, 3, &c. times. (See sects. 39 and 50.)

Q. 3. What is the cause of the variations of pitch produced by the fingering of the common flute? In other words, explain the action of the flute as a musical instrument.

ANS. A flute is an open pipe sounded by blowing with the lips at a side-hole near one end. If there were no finger-holes, or if we stop them all, we simply sound the fundamental note (or any of the harmonics by varying the blast). There is a node, or place of maximum condensation of the air within, at the centre of the pipe. (Sketch figure.) If now we open a hole at the middle, the aërial pressure within is there reduced to that of the atmosphere outside, and a new arrangement of nodes, with of course a new note, is the result. So by opening the different finger-holes we have so many new lengths of pipe, as it were, with corresponding new nodal divisions, and new notes. (See sects. 61 and 63.)

Q. 4. How are the musical sounds of an accordion, concertina, or mouth harmonica produced? State, if you know, the similarity between the production of these sounds and that of the human voice.

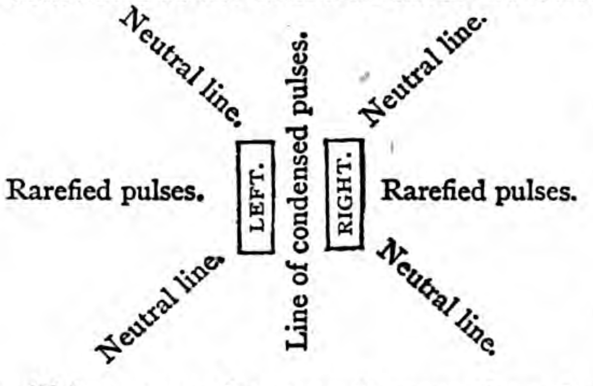
ANS. The musical tones of the accordion, concertina, or mouth harmonica are due to pulsations of the column or body of air enclosed in the instrument; and these are induced by the vibrations of elastic metal strips called *reeds*, which are placed over a series of embouchures or openings to the air-cavity. The pitch depends on the size, weight, and elasticity of these governing metal tongues. The human voice is an analogous reed-instrument, the tones being induced by successive openings and closings of the glottis by the vocal membrane, the breath escaping in a rapid series of puffs, which act on the resonant air-cavity of the mouth. (See sects. 62 and 75.)

1874—ADVANCED.

Q. 1. A syren with twelve apertures rotates 2400 times in a minute: what is the length of the sonorous waves it produces in air of the freezing temperature?

ANS. Each aperture at each revolution allows a puff of air to escape: hence in this case there will be 12 × 2400 puffs per minute, or 12 × 2400 ÷ 60 per second, that is 480 per second. The first puff will have reached 1120 feet when the last is escaping, hence this interval will be divided into 480 equal pulses, and each will be 1120 ÷ 480 feet long, or 2 feet 4 inches. (See sects. 9, 23, and 48.)

Q. 2. Along four directions round a vibrating tuning fork no sound is heard. Draw a horizontal section of the two prongs of the fork, mark the four directions referred to, and explain the extinction of the sound in those directions.



ANS. The legs of a tuning-fork move in opposite directions, so that while the one motion tends to produce condensations of the air all round, the other tends to produce rarefactions. Now the pulses of condensation will be *squeezed out*, as it were, from between the legs and propagated *across* the line of vibration of the prongs, while the pulses of rarefaction will be propagated in the same line. A little consideration shews that there will be four intermediate lines in which the air pressure will be everywhere normal, and consequently along which no sound will be heard. (See sect. 55.)

Q. 3. A number of tuning-forks stood silent upon a table, and at a distance from them a fork was sounded. On stopping the vibrations of the latter, one fork, and one only, of those upon the table was found sounding: explain the observation.

ANS. When a tuning-fork or any musical instrument sounds any note, it stirs up pulsations in the air all round; these act sympathetically, as it is termed, on any vibrating body *of the same vibration-period or pitch*, and set it sounding, but have no influence on a body of different tone or period. The feeble vibrations of the air keeping time with those of the heavier elastic body, gradually accumulate vibration in it, or accelerate any vibration it already has; but by mutual interference the vibrations of the air set up by the fork would only tend to stop or deaden any vibrations of a different period. (See sects. 59, 67, 68.)

Q. 4. Two open organ pipes are in perfect unison, being of the same length. I shorten one of them slightly: what will be the effect upon the ear when both of them are now sounded together? Explain the effect.

ANS. Shortening the pipe, we lower its tone, or lengthen the air-waves which the pipe emits. If then we sound the two pipes of slightly different pitch, and they emit waves of slightly different lengths, the consequence will be an alternate coincidence and opposition of these wave pulses; and the production of what is known as *beats*. Their number will depend on the numerical difference of the vibration-rates of the notes. (See sects. 67, 68.)

1875—ELEMENTARY.

Q. 1. Three observers are stationed, the first at a mile, the second at two miles, and the third at three miles from a gun. At twelve o'clock precisely the gun is fired; state the times at which the explosion will be heard by the three observers. If anything be wanting in this question necessary to the completeness of your calculation, state what it is.

ANS. For the calculation we require to know the velocity of sound per second, and for this *accurately* we should further know the atmospheric temperature at the time of observation. Taking the velocity for an ordinary temperature (50° F.) at 1120 feet per second; we find the first observer would hear the gun $5760 \div 1120$ seconds, that is, about 5·14 seconds past twelve. The other times will obviously be $2 \times 5{\cdot}14$ or 10·28 seconds, and $3 \times 5{\cdot}14$ or 15·42 seconds past twelve o'clock. (See sect. 9.)

Q. 2. Describe, as distinctly as you can, the condition of the air in the neighbourhood of each observer, at the moment he hears the sound.

ANS. The shot announces itself to the ear of the observer as a powerful rap against its tympanum or drum: a condensed pulse or crowded condition of the air has spread in all directions from the mouth of the gun, much as the water-circles spread out from the spot where a stone has fallen into the water. There has been no projection of the air-particles from the mouth of the gun; the distance to which the puff of smoke goes shews how small a way such a puff would reach; but there has been an impact-transmission, much of the same kind as when we strike with a hammer the end of a long plank or rod, while the other end just touches a pane of glass or a person's head. (See sect. 4.)

Q. 3. You frequently hear musical sounds proceeding from telegraph wires. How are these sounds produced; and why do you hear them so much louder when you approach the posts that support the wires?

ANS. The sounds heard from telegraph wires are simply due to vibration set up in them by the wind. As they are long wires, their fundamental vibration would be too slow to be audible; but they divide segmentally, and vibrate with corresponding increase of rapidity, so that we have a sort of long Æolian harp. The posts play the part of sounding-boards; they pick up the vibration of the wire and give volume to the sound which otherwise were too feeble. (See sects. 38, 50–53.)

Q. 4. Describe an experiment which shall prove that sound cannot be propagated through a vacuum.

ANS. If an alarum clock or a music-box, wound up and fit to go on for some time, be laid on pads of india-rubber or cotton-wool on the plate of an air-pump, and covered with the receiver, we find as we exhaust the air that the sound gets fainter and fainter, till if our air-pump be good it may become quite inaudible. On readmitting the air, however, we instantly hear the sound as if approaching us from a great distance. (See sect. 3.)

THE END.

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