Sound: Compression Waves, Velocity, Transmission, Echoes, Interference and Strings

ON THE CONNECTION OF THE PHYSICAL SCIENCES

Pgs. 122-125, 127-138

BY MARY SOMERVILLE

One of the most important uses of the atmosphere is the conveyance of sound. Without the air deathlike silence would prevail through nature, for in common with all substances it has a tendency to impart vibrations to bodies in contact with it. Therefore undulations received by the air, whether it be from a sudden impulse such as an explosion or the vibrations of a musical chord, are propagated in every direction, and produce the sensation of sound upon the auditory nerves. A bell rung under the exhausted receiver of an air-pump is inaudible, which shows that the atmosphere is really the medium of sound. In the small undulations of deep water in a calm, the vibrations of the liquid particles are made in the vertical plane, that is up and down, or at right angles to the direction of the transmission of the waves. But the vibrations of the particles of air which produce sound differ from these, being performed in the same direction in which the waves of sound travel. The propagation of sound has been illustrated by a field of corn agitated by the wind. However irregular the motion of the corn may seem on a superficial view, it will be found, if the velocity of the wind be constant, that the waves are all precisely similar and equal, and that all are separated by equal intervals and move in equal times.

A sudden blast depresses each ear equally and successively in the direction of the wind, but in consequence of the elasticity of the stalks and the force of the impulse, each ear not only rises again as soon as the pressure is removed, but bends back nearly as much in the contrary direction, and then continues to oscillate backward and forward in equal times, like a pendulum to a less and less extent, till the resistance of the air puts a stop to the motion. These vibrations are the same for every individual ear of corn. Yet as their oscillations do not all commence at the same time, but successively, the ears will have a variety of positions at any one instant. Some of the advancing ears will meet others in their returning vibrations, and as the times of oscillation are equal for all, they will be crowded together at regular intervals. Between these there will occur equal spaces, where the ears will be few, in consequence of being bent in opposite directions; and at other equal intervals they will be in their natural upright positions. So that over the whole field there will be a regular series of condensations and rarefactions among the ears of corn, separated by equal intervals where they will be in their natural state of density. In consequence of these changes the field will be marked by an alternation of bright and dark bands. Thus the successive waves which fly over the corn with the speed of the wind, are totally distinct from, and entirely independent of the extent of the oscillations of each individual ear, though both take place in the same direction. The length of a wave is equal to the space between two ears precisely in the same state of motion, or which are moving similarly, and the time of the vibration of each ear is equal to that which elapses between the arrival of two successive waves at the same point. The only difference between the undulations of a corn-field and those of the air which produce sound is, that each ear of corn is set in motion by an external cause and is uninfluenced by the motion of the rest; whereas in air, which is a compressible and elastic fluid, when one particle begins to oscillate, it communicates its vibrations to the surrounding particles, which transmit them to those adjacent, and so on continually. Hence from the successive vibrations of the particles of air the same regular condensations and rarefactions take place as in the field of corn, producing waves throughout the whole mass of air, though each molecule, like each individual ear of corn, never moves far from its state of rest. The small waves of a liquid and the undulations of the air like waves in the corn, are evidently not real masses moving in the direction in which they are advancing, but merely outlines, motions, or forms passing along, and comprehending all the particles of an undulating fluid which are at once in a vibratory state. It is thus that an impulse given to any one point of the atmosphere is successively propagated in all directions, in a wave diverging as from the center of a sphere to greater and greater distances, but with decreasing intensity, in consequence of the increasing number of particles of inert matter which the force has to move; like the waves formed in still water by a falling stone, which are propagated circularly all around the center of disturbance (N. 156).

The intensity of sound depends upon the violence and extent of the initial vibrations of air; but whatever they may be, each undulation when once formed can only be transmitted straight forward, and never returns back again unless when reflected by an opposing obstacle. The vibrations of the aerial molecules are always extremely small, whereas the waves of sound vary from a few inches to several feet. The various musical instruments, the human voice and that of animals, the singing of birds, the hum of insects, the roar of the cataract, the whistling of the wind, and the other nameless peculiarities of sound, show at once an infinite variety in the modes of aerial vibration, and the astonishing acuteness and delicacy of the ear, thus capable of appreciating the minutest differences in the laws of molecular oscillation. All mere noises are occasioned by irregular impulses communicated to the ear, and if they be short, sudden, and repeated beyond a certain degree of quickness, the ear loses the intervals of silence and the sound appears continuous. Still such sounds will be mere noise: in order to produce a musical sound, the impulses, and consequently the undulations of the air must be all exactly similar in duration and intensity, and must recur after exactly equal intervals of time. If a blow be given to the nearest of a series of broad, flat, and equidistant palisades set edgewise in a line direct from the ear, each palisade will repeat or echo the sound; and these echoes returning to the ear at successive equal intervals of time will produce a musical note. The quality of a musical note depends upon the abruptness, and its intensity upon the violence and extent of the original impulse. In the theory of harmony the only property of sound taken into consideration is the pitch, which varies with the rapidity of the vibrations. The grave or low tones are produced by very slow vibrations, which increase in frequency as the note becomes more acute.

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The velocity of sound is uniform and independent of the nature, extent, and intensity of the primitive disturbance. Consequently sounds of every quality and pitch travel with equal speed. The smallest difference in their velocity is incompatible either with harmony or melody, for notes of different pitches and intensities sounded together at a little distance, would arrive at the ear in different times. A rapid succession of notes would in this case produce confusion and discord. But as the rapidity with which sound is transmitted depends upon the elasticity of the medium through which it has to pass, whatever tends to increase the elasticity of the air must also accelerate the motion of sound. On that account its velocity is greater in warm than in cold weather, supposing the pressure of the atmosphere constant. In dry air at the freezing temperature, sound travels at the rate of 1090 feet in a second, and for any higher temperature one foot must be added for every degree of the thermometer above 32°; hence at 62° of Fahrenheit its speed in a second is 1120 feet, or 765 miles an hour, which is about three-fourths of the diurnal velocity of the earth's equator. Since all the phenomena of the transmission of sound are simple consequences of the physical properties of the air, they have been predicted and computed rigorously by the laws of mechanics. It was found, however, that the velocity of sound determined by observation, exceeded what it ought to have been theoretically by 173 feet, or about one-sixth of the whole amount. La Place suggested that this discrepancy might arise from the increased elasticity of the air in consequence of a development of latent heat (N. 173) during the undulations of sound, and calculation confirmed the accuracy of his views. The aerial molecules being suddenly compressed give out their latent heat; and as air is too bad a conductor to carry it rapidly off, it occasions a momentary and local rise of temperature which, increasing the elasticity of the air without at the same time increasing its inertia, causes the movement to be propagated more rapidly. Analysis gives the true velocity of sound in terms of the elevation If temperature that a mass of air is capable of communicating to itself, by the disengagement of its own latent heat when suddenly compressed in a given ratio. This change of temperature however could not be obtained directly by any experiments which had been made at that epoch; but by inverting the problem and assuming the velocity of sound as given by experiment, it was computed that the temperature of a mass of air is raised nine-tenths of a degree when the compression is equal to 1/116 of its volume.

Probably all liquids are elastic, though considerable force is required to compress them. Water suffers a condensation of nearly 0-0000496 for every atmosphere of pressure, and is consequently capable of conveying sound even more rapidly than air, the velocity in the former being 4708 feet in a second. A person under water hears sounds made in air feebly, but those produced in water very distinctly. According to the experiments of M. Colladon, the sound of a bell was conveyed under water through the Lake of Geneva to the distance of about nine miles. He also perceived that the progress of sound through water is greatly impeded by the interposition of any object, such as a projecting wall; consequently sound under water resembles light in having a distinct shadow. It has much less in air, being transmitted all round buildings or other obstacles, so as to be heard in every direction, though often with a considerable diminution of intensity, as when a carriage turns the corner of a street.

The velocity of sound in passing through solids is in proportion to their hardness, and is much greater than in air or water. A sound which takes some time in traveling through the air passes almost instantaneously along a wire six hundred feet long; consequently it is heard twice—first as communicated by the wire and afterward through the medium of the air. The facility with which the vibrations of sound are transmitted along the grain of a log of wood is well known. Indeed they pass through iron, glass, and some kinds of wood, at the rate of 18,530 feet in a second. The velocity of sound is obstructed by a variety of circumstances, such as falling snow, fog, rain, or any other cause which disturbs the homogeneity of the medium through which it has to pass. M. de Humboldt says that it is on account of the greater homogeneity of the atmosphere during the night that sounds are then better heard than during the day, when its density is perpetually changing from partial variations of temperature. His attention was called to this subject on the plain surrounding the Mission of the Apures by the rushing noise of the great cataracts of the Oronoco, which seemed to be three times as loud by night as by day. This he illustrated by experiment. A tall glass half full of champaigne cannot be made to ring as long as the effervescence lasts. In order to produce a musical note the glass together with the liquid it contains must vibrate in unison as a system, which it cannot do in consequence of the fixed air rising through the wine and disturbing its homogeneity, because the vibrations of the gas being much slower than those of the liquid the velocity of the sound is perpetually interrupted. For the same reason the transmission of sound as well as light is impeded in passing through an atmosphere of variable density. Sir John Herschel, in his admirable Treatise on Sound, thus explains the phenomenon:—"It is obvious," he says, "that sound as well as light must be obstructed, stifled, and dissipated from its original direction by the mixture of air of different temperatures, and consequently elasticities; and thus the same cause which produces that extreme transparency of the air at night, which astronomers alone fully appreciate, renders it also more favorable to sound. There is no doubt, however, that the universal and dead silence, generally prevalent at night, renders our auditory nerves sensible to impressions which would otherwise escape notice. The analogy between sound and light is perfect in this as in so many other respects. In the general light of day the stars disappear. In the continual hum of voices, which is always going on by day, and which reach us from all quarters and never leave the ear time to attain complete tranquillity, those feeble sounds which catch our attention at night make no impression. The ear, like the eye, requires long and perfect repose to attain its utmost sensibility."

Many instances maybe brought in proof of the strength and clearness with which sound passes over the surface of water or ice. Lieutenant Foster was able to carry on a conversation across Fort Bowen harbor, when frozen, a distance of a mile and a half.

The intensity of sound depends upon the extent of the excursions of the fluid molecules, on the energy of the transient condensations and dilatations, and on the greater or less number of particles wh;'Ji experience these effects. We estimate that intensity by the impetus of these fluid molecules on our organs, which is consequently as the square of the velocity, and not by their inertia, which is as the simple velocity. Were the latter the case there would be no sound, because the inertia of the receding waves of air would destroy the equal and opposite inertia of those advancing; whence it may be concluded that the intensity of sound diminishes inversely as the square of the distance from its origin. In a tube, however, the force of sound does not decay as in open air, unless perhaps by friction against the sides. M. Biot found from a number of highly interesting experiments made on the pipes of the aqueducts in Paris, that a continual conversation could be carried on in the lowest possible whisper, through a cylindrical tube about 3120 feet long, the time of transmission through that space being 2-79 seconds. In most cases sound diverges in all directions so as to occupy at any one time a spherical surface; but Dr. Young has shown that there are exceptions, as for example when a flat surface vibrates only in one direction. The sound is then most intense when the ear is at right angles to the surface, whereas it is scarcely audible in a direction precisely perpendicular to its edge. In this case it is impossible that the whole of the surrounding air can be affected in the same manner, since the particles behind the sounding surface must be moving toward it, whenever the particles before it are retreating. Hence in one half of the surrounding sphere of air its motions are retrogade, while in the other half they are direct; consequently at the edges where these two portions meet, the motions of the air will neither be retrograde nor direct, and therefore it must be at rest.

It appears from theory as well as daily experience, that sound is capable of reflection from surfaces (N. 174) according to the same laws as light. Indeed any one who has observed the reflection of the waves from a wall on the side of a river after the passage of a steamboat, will have a perfect idea of the reflection of sound and of light. As every substance in nature is more or less elastic, it may be agitated according to its own law by the impulse of a mass of undulating air; and reciprocally the surface by its reaction will communicate its undulations back again into the air. Such reflections produce echoes, and as a series of them may take place between two or more obstacles, each will cause an echo of the original sound, growing fainter and fainter till it dies away; because sound, like light, is weakened by reflection. Should the reflecting surface be concave toward a person, the sound will converge toward him with increased intensity, which will be greater still if the surface be spherical and concentric with him. Undulations of sound diverging from one focus of an elliptical shell (N. 175) converge in the other after reflection. Consequently a sound from the one will be heard in the other as if it were close to the ear. The rolling noise of thunder has been attributed to reverberation between different clouds, which may possibly be the case to a certain extent. Sir John Herschel is of opinion, that an intensely prolonged peal is probably owing to a combination of sounds because the velocity of electricity being incomparably greater than that of sound, the thunder may be regarded as originating in every point of a flash of lightning at the same instant. The sound from the nearest point will arrive first, and if the flash run in a direct line from a person, the noise will come later and later from the remote points of its path in a continued roar. Should the direction of the flash be inclined, the succession of sounds will be more rapid and intense, and if the lightning describe a circular curve round a person, the sound will arrive from every point at the same instant with a stunning crash. In like manner the subterranean noises heard during earthquakes like distant thunder, may arise from the consecutive arrival at the ear of undulations propagated at the same instant from nearer and more remote points; or if they originate in the same point, the sound may come by different routes through strata of different densities.

Sounds under water are heard very distinctly in the air immediately above; but the intensity decays with great rapidity as the observer goes farther off, and is altogether inaudible at the distance of two or three hundred yards. So that waves of sound, like those of light, in passing from a dense to a rare medium, are not only refracted, but suffer total reflection at very oblique incidences (N. 184).

The laws of interference extend also to sound. It is clear that two equal and similar musical strings will be in unison, if they communicate the same number of vibrations to the air in the same time. But if two such strings be so nearly in unison, that one performs a hundred vibrations in a second, and the other a hundred and one in the same period—during the first few vibrations, the two resulting sounds will combine to form one of double the intensity of either, because the aerial waves will sensibly coincide in time and place; but one will gradually gain on the other till at the fiftieth vibration it will be half an oscillation in advance. Then the waves of air which produce the sound being sensibly equal, but the receding part of the one coinciding with the advancing part of the other, they will destroy one another and occasion an instant of silence. The sound will be renewed immediately after, and will gradually increase till the hundredth vibration, when the two waves will combine to produce a sound double the intensity of either. These intervals of silence and greatest intensity, called beats, will recur every second; but if the notes differ much from one another the alternations will resemble a rattle; and if the strings be in perfect unison there will be no beats, since there will be no interference. Thus by interference is meant the coexistence of two undulations in which the lengths of the waves are the same. And as the magnitude of an undulation may be diminished by the addition of another transmitted in the same direction, it follows that one undulation may be absolutely destroyed by another when waves of the same length are transmitted in the same direction, provided that the maxima of the undulations are equal, and that one follows the other by half the length of a wave. A tuning-fork affords a good example of interference. When that instrument vibrates, its two branches alternately recede from and approach one another; each communicates its vibrations to the air, and a musical note is the consequence. If the fork be held upright, about a foot from the ear, and turned round its axis while vibrating, at every quarter revolution the sound will scarcely be heard, while at the intermediate points it will be strong and clear. This phenomenon arise from the interference of the undulations of air coming from the two branches of the fork. When the two branches coincide, or when they are at equal distances from the ear, the waves of air combine to reinforce each other; but at the quadrants, where the two branches are at unequal distances from the ear, the lengths of the waves differ by half an undulation, and consequently destroy one another.

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When the particles of elastic bodies are suddenly disturbed by an impulse, they return to their natural position by a series of isochronous vibrations, whose rapidity, force, and permanency depend upon the elasticity, the form, and the mode of aggregation which unites the particles of the body. These oscillations are communicated to the air, and on account of its elasticity they excite alternate condensations and dilatations in the strata of the fluid nearest to the vibrating body: from thence they are propagated to a distance. A string or wire stretched between two pins, when drawn aside and suddenly let go, will vibrate till its own rigidity and the resistance of the air reduce it to rest. These oscillations may be rotatory in every plane, or confined to one plane, according as the motion is communicated. In the piano-forte, where the strings are struck by a hammer at one extremity, the vibrations probably consist of a bulge running to and fro from end to end. Different modes of vibration may be obtained from the same sonorous body. Suppose a vibrating string to give the lowest C of the piano-forte, which is the fundamental note of the string; if it be lightly touched exactly in the middle so as to retain that point at rest, each half will then vibrate twice as fast as the whole, but in opposite directions; the ventral or bulging segments will be alternately above and below the natural position of the string, and the resulting note will be the octave above C. When a point at a third of the length of the string is kept at rest, the vibrations will be three times as fast as those of the whole string, and will give the twelfth above C. When the point of rest is one fourth of the whole, the oscillations will be four times as fast as those of the fundamental note, and will give the double octave; and so on. These acute sounds are called the harmonics of the fundamental note. It is clear from what has been stated, that the string thus vibrating could not give these harmonics spontaneously unless it divided itself at its aliquot parts into two, three, four, or more segments in opposite states of vibration separated by points actually at rest. In proof of this, pieces of paper placed on the string at the half, third, fourth, or other aliquot points according to the corresponding harmonic sound, will remain on it during its vibration, but will instantly fly off from any of the intermediate points. The points of rest called the nodal points of the string, are a mere consequence of the law of interferences. For if a rope fastened at one end be moved to and fro at the other extremity so as to transmit a succession of equal waves along it, they will be successively reflected when they arrive at the other end of the rope by the fixed point, and in returning they will occasionally interfere with the advancing waves; and as these opposite undulations will at certain points destroy one another, the point of the rope in which this happens will remain at rest. Thus a series of nodes and ventral segments will be produced, whose number will depend upon the tension and the frequency of the alternate motions communicated to the movable end. So when a string fixed at both ends is put in motion by a sudden blow at any point of it, the primitive impulse divides itself into two pulses running opposite ways, which are each totally reflected at the extremities, and running back again along the whole length are again reflected at the other ends. And thus they will continue to run backward and forward, crossing one another at each traverse, and occasionally interfering, so as to produce nodes; so that the motion of a string fastened at both ends consists of a wave or pulse, continually doubled back on itself by reflection at the fixed extremities.

Harmonics generally coexist with the fundamental sound in the same vibrating body. If one of the lowest strings of the piano-forte be struck, an attentive ear will not only hear the fundamental note, but will detect all the others sounding along with it, though with less and less intensity as their pitch becomes higher. According to the law of coexisting undulations, the whole string and each of its aliquot parts are in different and independent states of vibration at the same time; and as all the resulting notes are heard simultaneously, not only the air but the ear also vibrates in unison with each at the same instant (N. 176).

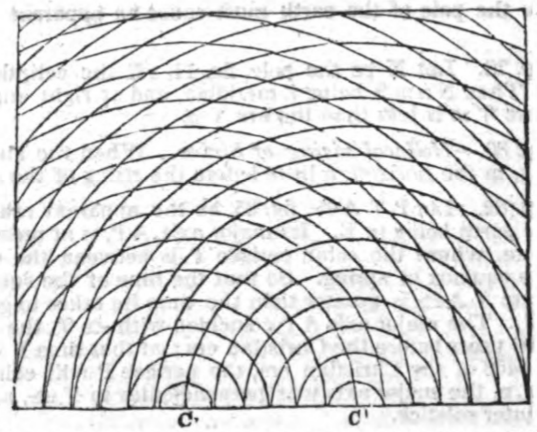
Harmony consists in an agreeable combination of sounds. When two chords perform their vibrations in the same time, they are in unison. But when their vibrations are so related as to have a common period after a few oscillations they produce concord. Thus when the vibrations of two strings bear a very simple relation to each other, as where one of them makes two, three, four, &c. vibrations in the time the other makes one; or if it accomplishes three, four, &c. vibrations while the other makes two, the result is a concord which is the more perfect the shorter the common period. In discords, on the contrary, the beats are distinctly audible, which produces a disagreeable and harsh effect, because the vibrations do not bear a simple relation to one another, as where one of two strings makes eight vibrations while the other accomplishes fifteen. The pleasure afforded by harmony is attributed by Dr. Young to the love of order, and to a predilection for a regular repetition of sensations natural to the human mind, which is gratified by the perfect regularity and rapid recurrence of the vibrations. The love of poetry and dancing he conceives to arise in some degree from the rhythm of the one and the regularity of the motions in the other.

A blast of air passing over the open end of a tube, as over the reeds in Pan's pipes; over a hole in one side. as in the flute; or through the aperture called a reed with a flexible tongue, as in the clarinet, puts the internal column of air into longitudinal vibrations by the alternate condensations and rarefactions of its particles. At the same time the column spontaneously divides itself into nodes between which the air also vibrates longitudinally, but with a rapidity inversely proportional to the length of the divisions, giving the fundamental note or one of its harmonics. The nodes are produced on the principle of interferences by the reflection of the longitudinal undulations of the air at the ends of the pipe, as in the musical string, only that in one case the undulations are longitudinal, and in the other transverse.

A pipe either open or shut at both ends when sounded vibrates entire, or divides itself spontaneously into two, three, four, &c. segments separated by nodes. The whole column gives the fundamental note by waves or vibrations of the same length with the pipe The first harmonic is produced by waves half as long as the tube, the second harmonic by waves a third as long, and so on. The harmonic segments in an open and shut pipe are the same in number, but differently placed. In a shut pipe the two ends are nodes, but in an open pipe there is half a segment at each extremity, because the air at these points is neither rarefied nor condensed, being in contact with that which is external. If one of the ends of the open pipe be closed, its fundamental note will be an octave lower, the air will now divide itself into three, five, seven, &c. segments; and the wave producing its fundamental note will be twice as long as the pipe, so that it will be doubled back (N. 177). All these notes may be produced separately, by varying the intensity of the blast. Blowing steadily and gently, the fundamental note will sound; when the force of the blast is increased, the note will all at once start up an octave; when the intensity of the wind is augmented, the twelfth will be heard, and by continuing to increase the force of the blast the other harmonics may be obtained, but no force of wind will produce a note intermediate between these. The harmonics of a flute may be obtained in this manner, from the lowest C or D upward, without altering the fingering, merely by increasing the intensity of the blast, and altering the form of the lips. Pipes of the same dimensions, whether of lead, glass, or wood, give the same tone as to pitch under the same circumstances, which shows that the air alone produces the sound.

NOTE 156, pp. 93, 124.—Fig. 37 shows the propagation of waves from

Fig. 37.



two points C and C′, where stones are supposed to have fallen. Those points in which the waves cross each other, are the places where they counteract each other's effects, so that the water is smooth there, while it is agitated in the intermediate spaces.

NOTE 174, p. 131.—*Reflected waves.* A series of waves of light, sound,

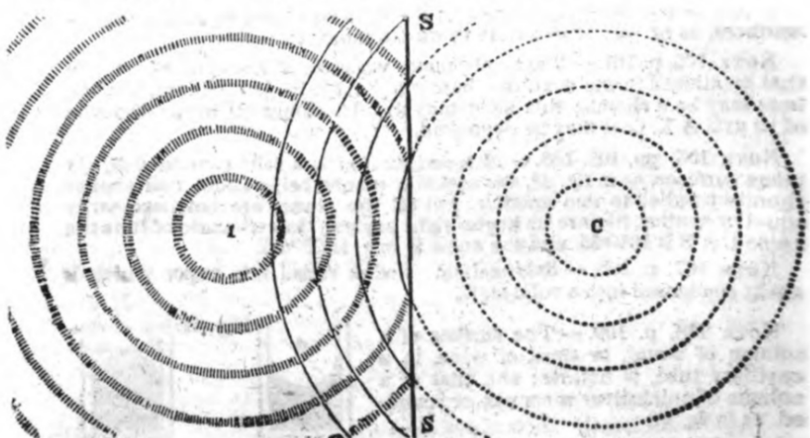


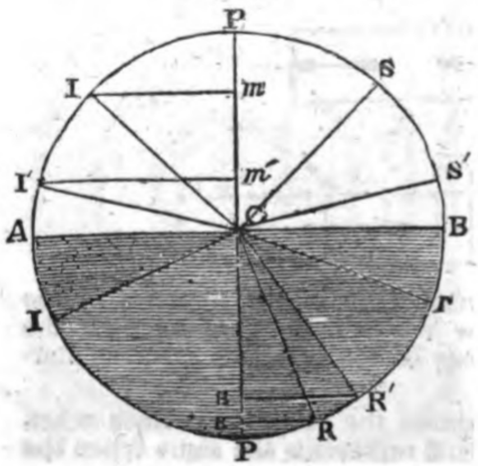
Fig. 43.

or water, diverge in all directions from their origin I, fig. 43, as from a center. When they meet with an obstacle S S, they strike against it, and are reflected or turned back by it in the same form, as if they had proceeded from the center C, at an equal distance on the other side of the surface S S.

NOTE 175, p. 132.—*Elliptical shell.* If fig. 6 be a section of an elliptical shell, then all sounds coming from the focus S to different points on the surface, as *m*, are reflected back to F, because the angle T *m* S is equal to *t m* F. In a spherical hollow shell, a sound diverging from the center is reflected back to the center again.

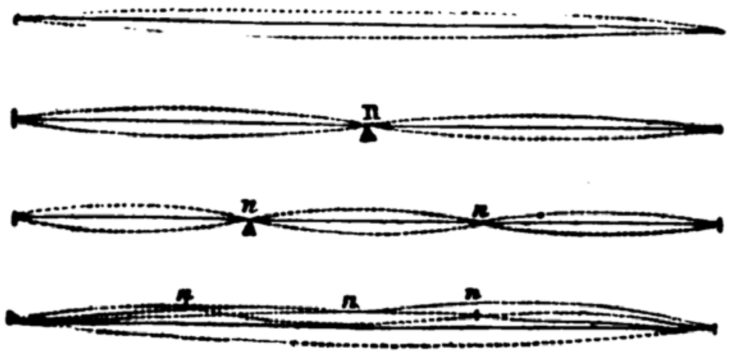
NOTE 184, pp. 133, 148, 149.—*Reflection and refraction.* Let P C p, fig. 48, be perpendicular to a surface of glass or water A B. When a ray of light, passing through the air, falls on this surface in any direction I C, part of it is reflected in the direction C S, and the other part is bent at C, and passes through the glass or water in the direction C R. I C is called the incident ray, and I C P the angle of incidence; C S is the reflected ray, and P C S the angle of reflection: C R is the refracted ray, and p C R the angle of refraction. The plane passing through S C and I C is the plane of reflection, and the plane passing through I C and C R is the plane of refraction. In ordinary cases, C I, C S, C R, are all in the same plane. We see the surface by means of the reflected light, which would otherwise be invisible. Whatever the reflecting surface may be, and however obliquely the light may fall upon it, the angle of reflection is always equal to the angle of incidence. Thus I C, I′ C, being rays incident on the surface at C, they will be reflected into C S, C S′, so that the angle S C P will be equal to the angle I C P, and S′ C P equal to I′ C P. That is by no means the case with the refracted rays. The incident rays I C, I′ C, are bent at C, toward the perpendicular, in the direction C R, C R′; and the law of refraction is such, that the sine of the angle of incidence has a constant ratio to the sine of the angle of refraction; that is to say, the number expressing the length of I m, the sine of I C P, divided by the number expressing the length of R n, the sine of R C p, is the same for all the rays of light that can fall upon the surface of any one substance, and is called its Index of refraction. Though the index of refraction be the same for any one substance, it is not the same for all substances. For water it is 1·336; for crown-glass it is 1·535; for flint-glass, 1·6; for diamond, 2·487; and for chromate of lead it is 3, which substance has a higher refractive power than any other known. Light falling perpendicularly on a surface, passes through it without being refracted. If the light be now supposed to pass from a dense into a rare medium, as from glass or water into air, then R C, R′ C, become the incident rays; and in this case the refracted rays, C I, C I′ are bent from the perpendicular instead of toward it. When the incidence is very oblique, as r C, the light never passes into the air at all, but it is *totally* reflected in the direction C r', so that the angle p C r is equal to p C r': that frequently happens at the second surface of glass. When a ray I C falls from air upon a piece of glass A B, it is in general refracted at each surface. At C it is bent toward the perpendicular, and at R from it, and the ray emerges parallel to I C; but when the ray is very oblique to the second surface, it is totally reflected. An object seen by total reflection is nearly as vivid as when seen by direct vision, because no part of the light is refracted.

Fig. 48.



NOTE 176, p. 136. Fig. 44 represents musical strings in vibration; the

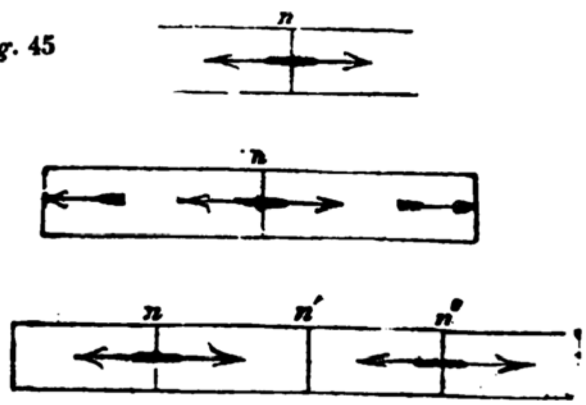
Fig. 44.



straight lines are the strings when at rest. The first figure of the four would give the fundamental note, as, for example, the low C. The second and third figures would give the first and second harmonics; that is, the octave and the 12th above C, *n n n* being the points of rest; the fourth figure shows the real motion when compounded of all three.

NOTE 177, p. 137. Fig. 45 represents sections of an open and of a shut pipe, and of a pipe open at one end. When sounded, the air spontaneously divides itself into segments. It remains at rest in the divisions

Fig. 45



or nodes *n n'*, &c., but vibrates between them in the direction of the arrow-heads. The undulations of the whole column of air give the fundamental note, while the vibrations of the divisions give the harmonics.

Center for History of Physics

Sound: Compression Waves, Velocity, Transmission, Echoes, Interference and Strings

CONVERSATIONS ON NATURAL PHILOSOPHY

Pgs. 176-183

BY JANE MARCET

Mrs. B. I shall first explain to you the nature of sound, which is intimately connected with that of air; and I think at our next meeting we may enter upon the subject of opticks. We have now considered the effects produced by the wide and extended agitation of the air; but there is another kind of agitation of which the air is susceptible—a sort of vibratory, trembling motion, which, striking on the drum of the ear, produces sounds

Caroline. Is not sound produced by solid bodies? The voice of animals, the ringing of bells, musical instruments, are all solid bodies. I know of no sound but that of the wind which is produced by the air.

Mrs. B. Sound, I assure you, results from a tremulous motion of the air; and the sonorous bodies you enumerate, are merely the instruments by which that peculiar species of motion is communicated to the air.

Caroline. What! when I ring this little bell, is it the air that sounds, and not the bell?

Mrs. B. Both the bell and the air are concerned in the production of sound. But sound, strictly speaking, is a perception excited in the mind by the motion of the air on the nerves of the ear; the air, therefore, as well as the sonorous bodies which put it in motion, is only the cause of sound, the immediate effect is produced by the sense of hearing: for, without this sense, there would be no sound

Emily. I can with difficulty conceive that. A person born deaf, it is true, has no idea of sound, because he hears none; yet that does not prevent the real existence of sound, as all those who are not deaf can testify.

Mrs. B. I do not doubt the existence of sound to all those who possess the sense of hearing; but it exists neither in the sonorous body nor in the air, but in the mind of the person whose ear is struck by the vibratory motion of the air, produced by a sonorous body. To convince you that sound does not exist in sonorous bodies, but that air or some other vehicle is necessary to its production, endeavour to ring the little bell, after I have suspended it under a receiver in the air-pump, from which I shall exhaust the air

Caroline. This is indeed very strange: though I agitate it so violently, it does not produce the least sound.

Mrs. B. By exhausting the receiver, I have cut off the communication between the air and the bell; the latter, therefore, cannot impart its motion to the air.

Caroline. Are you sure that it is not the glass, which covers the bell, that prevents our hearing it?

Mrs. B. That you may easily ascertain by letting the air into the receiver, and then ringing the bell.

Caroline. Very true: I can hear it now almost as loud as if the glass did not cover it; and I can no longer doubt but that air is necessary to the production of sound.

Mrs. B. Not absolutely necessary, though by far the most common vehicle of sound. Liquids, as well as air, are capable of conveying the vibratory motion of a sonorous body to the organ of hearing; as sound can be heard under water. Solid bodies also convey sound, as I can soon convince you by a very simple experiment. I shall fasten this string by the middle round the poker; now raise the poker from the ground by the two ends of the string, and hold one to each of your ears:—I shall now strike the poker with a key, and you will find that the sound is conveyed to the ear by means of the strings, in a much more perfect manner than if it had no other vehicle than the air.

Caroline. That it is, certainly, for I am almost stunned by the noise. But what is a sonorous body, Mrs. B.? for all bodies are capable of producing some kind of sound by the motion they communicate to the air.

Mrs. B. Those bodies are called sonorous, which produce clear, distinct, regular, and durable sounds, such as a bell, a drum, musical strings, wind instruments, &c. They owe this property to their elasticity; for an elastic body, after having been struck, not only returns to its former situation, but having acquired momentum by its velocity, like the pendulum, it springs out on the opposite side. If I draw the string A B, which is made fast at both ends, to C, it will not only return to its original position, but proceed onwards to D. This is its first vibration, at the end of which it will retain sufficient velocity to bring it to E, and back again to F, which constitutes its second vibration; the third vibration will carry it only to G and H, and so on till the resistance of the air destroys its motion. The vibration of a sonorous body gives a tremulous motion to the air around it, very similar to the motion communicated to smooth water when a stone is thrown into it. This first produces a small circular wave around the spot in which the stone falls; the wave spreads, and gradually communicates its motion to the adjacent waters, producing similar waves to a considerable extent. The same kind of waves is produced in the air by the motion of a sonorous body, but with this difference, that as air is an elastick fluid, the motion does not consist of regularly extending waves, but of vibrations, and are composed of a motion forwards and backwards, similar to those of the sonorous body. They differ also in the one taking place in a plane, the other in all directions. The aerial undulations being spherical.

Emily. But if the air moves backwards as well as forwards, how can its motion extend so as to convey sound to a distance.

Mrs. B. The first sphere of undulations which are produced immediately around the sonorous body, by pressing against the contiguous air, condenses it. The condensed air, though impelled forward by the pressure, re-acts on the first set of undulations, driving them back again. The second set of undulations which have been put in motion, in their turn communicate their motion, and are themselves driven back by re-action. Thus there is a succession of waves in the air, corresponding with the succession of waves in the water.

Caroline. The vibrations of sound must extend much further than the circular waves in water, since sound is conveyed to a great distance.

Mrs. B. The air is a fluid so much less dense than water, that motion is more easily communicated to it.
The report of a cannon produces vibrations of the air which extend to several miles around.

Emily. Distant sound takes some time to reach us, since it is produced at the moment the cannon is fired; and we see the light of the flash long before we hear the report.

Mrs. B. The air is immediately put in motion by the firing of a cannon; but it requires time for the vibrations to extend to any distant spot. The velocity of sound is computed to be at the rate of 1142 feet in a second.

Caroline. With what astonishing rapidity the vibrations must be communicated! But the velocity of sound varies, I suppose, with that of the air which conveys it. If the wind sets towards us from the cannon, we must hear the report sooner than if it set the other way.

Mrs. B. The direction of the wind makes less difference in the velocity of sound than you would imagine. If the wind sets from us, it bears most of the aerial waves away, and renders the sound fainter; but it is not very considerably longer in reaching the ear than if the wind blew towards us. This uniform velocity of sound enables us to determine the distance of the object from which it proceeds; as that of a vessel at sea firing a cannon, or that of a thunder cloud. If we do not hear the thunder till half a minute after we see the lightning, we conclude the cloud to be at the distance of six miles and a half.

Emily. Pray how is the sound of an echo produced?

Mrs. B. When the aerial vibrations meet with an obstacle, having a hard and regular surface, such as a wall, or rock, they are reflected back to the ear and produce the same sound a second time; but the sound will then appear to proceed from the object by which it is reflected. If the vibrations fall perpendicularly on the obstacle, they are reflected back in the same line; if obliquely, the sound returns obliquely in the opposite direction, the angle of reflection being equal to the angle of incidence.

Caroline. Oh, then, Emily, I now understand why the echo of my voice behind our house is heard so much plainer by you than it is by me, when we stand at opposite ends of the gravel walk. My voice, or rather, I should say, the vibrations of air it occasions, fall obliquely on the wall of the house, and are reflected by it to the opposite end of the gravel walk.

Emily. Very true; and we have observed that when we stand in the middle of the walk, opposite the house, the echo returns to the person who spoke.

Mrs. B. Speaking-trumpets are constructed on the principle of the reflection of sound. The voice, instead of being diffused in the open air, is confined within the trumpet; and the vibrations which spread and fall against the sides of the instrument, are reflected according to the angle of incidence, and fall into the direction of the vibrations which proceed straight forwards. The whole of the vibrations are thus collected into a focus; and if the ear be situated in or near that spot, the sound is prodigiously increased. Figure 7, plate XIV. will give you a clearer idea of the speaking-trumpet: the reflected rays are distinguished, from those of incidence, by being dotted; and they are brought to a focus at F. The trumpet used by deaf persons acts on the same principle; but as the voice enters the trumpet at the large instead of the small end of the instrument, it is not so much confined, nor the sound so much increased.

Emily. Are the trumpets used as musical instruments also constructed on this principle?

Mrs. B. So far as their form tends to increase the sound, they are; but, as a musical instrument, the trumpet becomes itself the sonorous body, which is made to vibrate by blowing into it, and communicates its vibrations to the air. I will attempt to give you in a few words, some notion of the nature of musical sounds, which as you are fond of musick must be interesting to you. If a sonorous body be struck in such a manner, that its vibrations are all performed in regular times, the vibrations of the air will correspond with them; and striking in the same regular manner on the drum of the ear, will produce the same uniform sensation on the auditory nerve and excite the same uniform idea in the mind; or, in other words, we shall hear one musical tone. But if the vibrations of the sonorous body are irregular, there will necessarily follow a confusion of aerial vibrations; for a second vibration may commence before the first is finished, meet it half way on its return, interrupt it in its course, and produce harsh jarring sounds which are called discords.

Emily. But each set of these irregular vibrations, if repeated at equal intervals, would, I suppose, produce a musical tone. It is only their irregular succession which makes them interfere, and occasions discord.

Mrs. B. Certainly. The quicker a sonorous body vibrates, the more acute, or sharp, is the sound produced.

Caroline. But if I strike any one note of the piano-forte repeatedly, whether quickly or slowly, it always gives the same tone.

Mrs. B. Because the vibrations of the same string, at the same degree of tension, are always of a similar duration. The quickness or slowness of the vibrations relate to the single tones, not to the various sounds which they may compose by succeeding each other. Striking the note in quick succession, produces a more frequent repetition of the tone, but does not increase the velocity of the vibrations of the string. The duration of the vibrations of strings or chords depends upon their length, their thickness, or weight, and their degree of tension: thus, you find, the low bass notes are produced by long, thick, loose strings; and the high treble notes by short, small, and tight strings.

Caroline. Then the different length and size of the strings of musical instruments, serve to vary the duration of the vibrations, and consequently, the acuteness of gravity of the notes?

Mrs. B. Yes. Among the variety of tones, there are some which, sounded together, please the ear, producing what we call harmony, or concord. This arises from the agreement of the vibrations of the two sonorous bodies; so that some of the vibrations of each strike upon the ear at the same time. Thus, if the vibrations of two strings are performed in equal times, the same tone is produced by both, and they are said to be in unison.

Emily. Now, then, I understand why, when I tune my harp in unison with the piano-forte, I draw the strings tighter if it is too low, or loosen them if it is at too high a pitch; it is in order to bring them to vibrate, in equal times, with the strings of the piano-forte.

Mrs. B. But concord, you know, is not confined to unison; for two different tones harmonize in a variety of cases. If the vibrations of one string (or sonorous body whatever) vibrate in double the time of another, the second vibration of the latter will strike upon the ear at the same instant as the first vibration of the former; and this is the concord of an octave. If the vibrations of two strings are as two to three, the second vibration of the first corresponds with the third vibration of the latter, producing the harmony called a fifth.

Caroline. So, then, when I strike the key-note with its fifth, I hear every second vibration of one, and every third of the other at the same time?

Mrs. B. Yes; and the key-note struck with the fourth is likewise a concord, because the vibrations are as three to four. The vibrations of a major third with the key-note, are as four to five; and those of a minor third, as five to six. There are other tones which, though they cannot be struck together without producing discord, if struck successively, give us the pleasure which is called melody. Upon these general principles the science of musick is founded; but I am not sufficiently acquainted with it to enter any further into it.

721. By what is the quality of winds affected? 722. What facts are stated in the notes illustrating the effects thus produced on the wind?? 723. How is sound produced? 724. What is sound, strictly speaking? 725. How can it be shown that air is necessary in the production of sound? 726. Why cannot a bell be heard in an exhausted receiver? 727. Is the atmosphere the only conductor of sound? 728 What besides air convey the vibratory motion of sonorous bodies? 729. What bodies are called sonorous? 730. To what do they owe their sonorous property? 731. How would you explain Fig. 6, plate XIV. as illustrating the production of sound? 732. To what is the tremulous motion, given to the air by a sonorous body, compared? 733 If the air reverberate, how can its motion extend so as to convey sound to a distance? 734. Why is motion more easily communicated to air than to water? 735. Why do we see the flash of a cannon, at a distance, before we hear the report? 736. What is the computed velocity of sound? 737. What effect has the direction of the wind on the velocity of sound? 738. To what practical purpose can we apply the uniform velocity of sound? 739. How is the sound of an echo produced? 740. On what principle are speaking-trumpets constructed? 741. What does Figure 7, Plate XIV. represent? 742. Where must the ear be situated in regard to the speaking-trumpet so as to receive an increased sound? 743. How do the speaking-trumpets used by deaf persons differ from that in the figure? 744. How far is a trumpet used for a musical instrument constructed on the above principle? 745. How must a sonorous body be struck so that its vibrations produce in the mind the same uniform idea, or one musical tone? 746. How are harsh jarring sounds or discords produced? 747. On what does the acuteness or sharpness of a musical sound depend? 748. On what does the duration of vibrations of strings or chords in musical instruments depend? 749. How is harmony or concord in sounds produced? 750. How is an octave concord produced? 751. How is that species of harmony, called a fifth, produced?*