SOUND.

LECTURE I.

THE NERVES AND SENSATION—PRODUCTION AND PROPAGATION OF SONOROUS MOTION—EXPERIMENTS ON SOUNDING BODIES PLACED IN VACUO—ACTION OF HYDROGEN ON THE VOICE—PROPAGATION OF SOUND THROUGH AIR OF VARYING DENSITY — REFLECTION OF SOUND — ECHOES — REFRACTION OF SOUND—INFLECTION OF SOUND; CASE OF ERITH VILLAGE AND CHURCH —INFLUENCE OF TEMPERATURE ON VELOCITY — INFLUENCE OF DENSITY AND ELASTICITY—NEWTON'S CALCULATION OF VELOCITY—THERMAL CHANGES PRODUCED BY THE SONOROUS WAVE—LAPLACE'S CORRECTION OF NEWTON'S FORMULA—RATIO OF SPECIFIC HEATS AT CONSTANT PRESSURE AND AT CONSTANT VOLUME DEDUCED FROM VELOCITIES OF SOUND—MECHANICAL EQUIVALENT OF HEAT DEDUCED FROM THIS RATIO—INFERENCE THAT ATMOSPHERIC AIR POSSESSES NO SENSIBLE POWER TO RADIATE HEAT—VELOCITY OF SOUND IN DIFFERENT GASES — VELOCITY IN LIQUIDS AND SOLIDS—INFLUENCE OF MOLECULAR STRUCTURE ON THE VELOCITY OF SOUND.

THE various nerves of the human body have their origin in the brain, and the brain is the seat of sensation. When you wound your finger, the nerves which run from the finger to the brain convey intelligence of the injury, and if these nerves be severed, however serious the hurt may be, no pain is experienced. We have the strongest reason for believing that what the nerves convey to the brain is in all cases *motion*. It is the motion excited by sugar in the nerves of taste which, transmitted to the brain, produces the sensation of sweetness, while bitterness is the result of the motion produced by aloes. It is the motion excited in the olfactory nerves by the effluvium of a rose, which announces itself in the brain as the odour of the rose. It is the motion imparted by the sunbeams to the optic nerve which, when it reaches the brain, awakes the consciousness of light; while a similar motion imparted to other nerves resolves itself into heat in the same wonderful organ.*

The motion here meant is not that of the nerve as a whole; it is the vibration, or tremor, of its molecules or smallest particles.

Different nerves are appropriated to the transmission of different kinds of molecular motion. The nerves of taste, for example, are not competent to transmit the tremors of light, nor is the optic nerve competent to transmit sonorous vibration. For this latter a special nerve is necessary, which passes from the brain into one of the cavities of the ear, and there spreads out in a multitude of filaments. It is the motion imparted to this, the *auditory nerve*, which, in the brain, is translated into sound.

We have this day to examine how sonorous motion is produced and propagated. Applying a flame to this small collodion balloon, which contains a mixture of oxygen and hydrogen, the gases explode, and every ear in this room is conscious of a shock, to which the name of sound is given. How was this shock transmitted from the balloon to your organs of hearing? Have our exploding gases shot the air-particles against the auditory nerve as a gun shoots a ball against a target? No doubt, in the neighbourhood of the balloon, there is to some extent a propulsion of particles; but air shooting through air comes speedily to rest, and no particle of air from the vicinity of the balloon reached the ear of any person here present. The

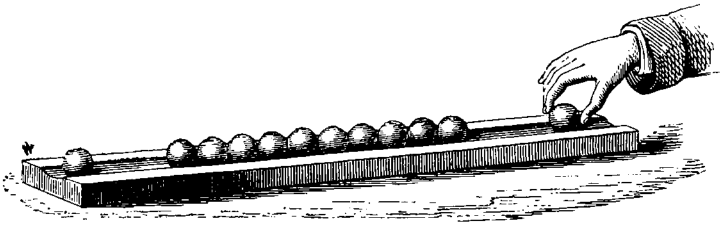
* The rapidity with which an impression is transmitted through the nerves, as first determined by Helmholtz and confirmed by Du Bois Raymond, is 93 feet a second.

process was this:—When the flame touched the mixed gases they combined chemically, and their union was accompanied by the development of intense heat. The air at this hot focus expanded suddenly, forcing the surrounding air violently away on all sides. This motion of the air close to the balloon was rapidly imparted to that a little further off, the air first set in motion coming at the same time to rest. The air, at a little distance, passed its motion on to the air at a greater distance, and came also in its turn to rest. Thus each shell of air, if I may use the term, surrounding the balloon, took up the motion of the shell next preceding, and transmitted it to the next succeeding shell, the motion being thus propagated as a *pulse* or *wave* through the air.

In air at the freezing temperature this pulse is propagated with a speed of 1,090 feet a second.

The motion of the pulse must not be confounded with the motion of the particles which at any moment constitute the pulse. For while the wave moves forward through considerable distances, each particular particle of air makes only a small excursion to and fro.

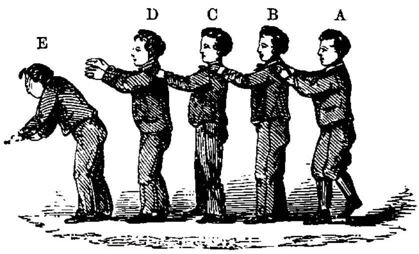
Fig. 1.



The process may be rudely represented by the propagation of motion through a row of glass balls, such as are employed in the game of *solitaire*. I place these balls along a groove thus, fig. 1, each of them touching its neighbours. Taking one of them in my hand, I urge it against the end of the row. The motion thus imparted to the first ball is delivered up to the second, the motion of the second is delivered up to the third, the motion of the third is imparted to the fourth; each ball, after having given up its motion, returning itself to rest. The last ball only of the row flies away. Thus is sound conveyed from particle to particle through the air. The particles which fill the cavity of the ear are finally driven against *the tympanic membrane*, which is stretched across the passage leading to the brain. This membrane, which closes the 'drum' of the ear, is thrown into vibration, its motion is transmitted to the ends of the auditory nerve, and afterwards along the nerve to the brain, where the vibrations are translated into sound. How it is that the motion of the nervous matter can thus excite the consciousness of sound is a mystery which we cannot fathom.

Let me endeavour to illustrate the propagation of sound by another homely but useful illustration. I have here

FIG. 2.



five young assistants, A, B, C, D, and E, fig. 2, placed in a row, one behind the other, each boy's hands resting against the back of the boy in front of him. E is now foremost, and A finishes the row behind. I suddenly push A; A pushes

B, and regains his upright position; B pushes C; C pushes D; D pushes E; each boy, after the transmission of the push, becoming himself erect. E, having nobody in front, is thrown forward. Had he been standing on the edge of a precipice, he would have fallen over; had he stood in contact with a window, he would have broken the glass; had he been close to a drum-head, he would have shaken the drum. We could thus transmit a push through a row of a hundred boys, each particular boy, however, only swaying to and fro. Thus, also, we send sound through the air, and shake the drum of a distant ear, while each particular particle of the air concerned in the transmission of the pulse makes only a small oscillation.

Scientific education ought to teach us to see the invisible as well as the visible in nature; to picture with the eye of the mind those operations which entirely elude the eye of the body; to look at the very atoms of matter in motion and at rest, and to follow them forth, without ever once losing sight of them, into the world of the senses, and see them there integrating themselves in natural phenomena. With regard to the point now under consideration, you will, I trust, endeavour to form a definite image of a wave of sound. You ought to see mentally the air particles when urged outwards by the explosion of our balloon crowding closely together; but immediately behind this condensation you ought to see the particles separated more widely apart. You ought, in short, to be able to seize the conception that a sonorous wave consists of two portions, in the one of which the air is more dense, and in the other of which it is less dense than usual. A condensation and a rarefaction, then, are the two constituents of a wave of sound.*

Let us turn once more to our row of boys, for we have

* A sonorous wave will be more strictly defined in Lecture II.

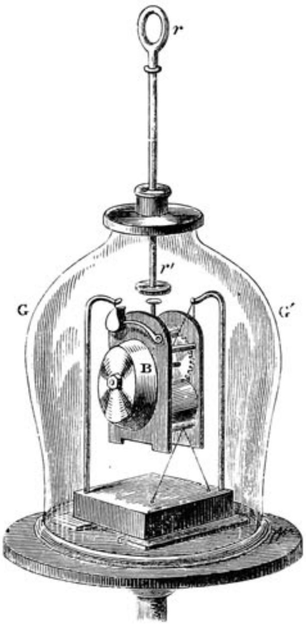
not yet extracted from them all that they can teach us. When I push A, he may yield languidly, and thus tardily deliver up the motion to his neighbour B. B may do the same to C, C to D, and D to E. In this way the motion may be transmitted with comparative slowness along the line. But A, when I push him, may, by a sharp muscular effort and sudden recoil, deliver up promptly his motion to B, and come himself to rest; B may do the same to C, C to D, and D to E, the motion being thus transmitted rapidly along the line. Now this sharp muscular effort and sudden recoil is analogous to the *elasticity* of the air in the case of sound. In a wave of sound, a lamina of air, when urged against its neighbour lamina, delivers up its motion and recoils, in virtue of the elastic force exerted between them; and the more rapid this delivery and recoil, or in other words the greater the elasticity of the air, the greater is the velocity of the sound.

But if air be thus necessary to the propagation of sound, what must occur when a sonorous body, a ringing bell for example, is placed in a space perfectly void of air? Out of that space the sound could never come. The hammer might strike, but it would strike silently. A celebrated experiment which proved this was made by a philosopher named Hawksbee, before the Royal Society in 1705.* He so fixed a bell within the receiver of an air-pump, that he could ring the bell when the receiver was exhausted. Before the air was withdrawn the sound of the bell was heard within the receiver; after the air was withdrawn the sound became so faint as to be hardly perceptible. I have here an arrangement which enables me to repeat, in a very perfect manner, the experiment of Hawksbee. Within this jar, G G′, fig. 3, resting on the plate of an air-pump is a bell, B, associated with

* Philosophical Transactions, 1705.

clockwork.* I exhaust the jar as perfectly as possible, and now, by means of a rod, $r\,r'$, which passes air-tight through the top of the vessel, I loose the detent which holds the hammer. It strikes, and you see it striking, but only those close to the bell can hear the sound. I now allow hydrogen gas, which you know is fourteen times lighter than air, to enter the vessel. The sound of the bell is not sensibly augmented by the presence of this attenuated gas, though the receiver is now full of it.† By working the pump, the atmosphere round the bell is rendered still more attenuated. In this way we obtain a vacuum more perfect than that of Hawksbee, and this is important, for it is the last traces of air that are chiefly effective in this experiment. You now see the hammer pounding the bell, but you hear no sound. Even when I place my ear against the exhausted receiver, I am unable to hear the faintest tinkle. Observe also that the bell is suspended by strings, for if it were allowed to rest upon the plate of the air-pump, the vibrations would communicate themselves to the plate, and be transmitted

FIG. 3.



* A very effective instrument presented to the Royal Institution by Mr. Warren De la Rue.

† Leslie, I believe, was the first to notice this. Air, it may be stated, reduced to the specific gravity of hydrogen, transmits the sound of the bell vastly better than hydrogen. A whole atmosphere of this gas has no sensible effect in restoring the sound of the bell, while the fifteenth of an atmosphere of air renders its ringing very audible.

to the air outside. All that I can hear by the most concentrated attention, with my ear placed against the receiver, is a feeble thud, due to the transmission of the shock of the hammer through the strings which support the bell. I now permit air to enter the jar with as little noise as possible. You immediately hear a feeble sound, which grows louder as the air becomes more dense; and now every person in this large assembly distinctly hears the ringing of the bell.*

At great elevations in the atmosphere sound is sensibly diminished in loudness. De Saussure thought the explosion of a pistol at the summit of Mont Blanc to be about equal to that of a common cracker below. I have several times repeated this experiment: first, in default of anything better, with a little tin cannon, the torn remnants of which are now before you, and afterwards with pistols. What struck me was the absence of that density and sharpness in the sound which characterise it at lower elevations. The pistol-shot resembled the explosion of a champagne bottle, but it was still loud. The withdrawal of half an atmosphere does not very materially affect our ringing bell, and air of the density found at the top of Mont Blanc is still capable of powerfully affecting the auditory nerve. That highly attenuated air is able to convey sound of great intensity, is forcibly illustrated by the explosion of meteorites at great elevations above the earth. Here, however, the initial disturbance must be exceedingly violent.

The motion of sound, like all other motion, is enfeebled by its transference from a light body to a heavy one. I remove the receiver which has hitherto covered our bell;

* By directing the beam of an electric lamp on glass bulbs filled with a mixture of equal volumes of chlorine and hydrogen, I have caused the bulbs to explode in vacuo and in air. The difference, though not so striking as I at first expected, was perfectly distinct.

you hear how much more loudly it rings in the open air. When the bell was covered the aerial vibrations were first communicated to the heavy glass jar, and afterwards by the jar to the air outside; a great diminution of intensity being the consequence. The action of hydrogen gas upon the voice is an illustration of the same kind. The voice is formed by urging air from the lungs through an organ called the larynx. In its passage it is thrown into vibration by the vocal chords which thus generate sound. But when I fill my lungs with hydrogen, and endeavour to speak, the vocal chords impart their motion to the hydrogen, which transfers it to the outer air. By this transference from a light gas to a heavy one, the sound is weakened in a remarkable degree.* The consequence is very curious. You have already formed a notion of the strength and quality of my voice. I now empty my lungs of air, and inflate them with hydrogen from this gasholder. I try to speak vigorously, but my voice has lost wonderfully in power, and changed wonderfully in quality. You hear it, hollow, harsh, and unearthly: I cannot otherwise describe it.

The intensity of a sound depends on the density of the air in which the sound is generated, and not on that of the air in which it is heard.† Supposing the summit of Mont Blanc to be equally distant from the top of the Aiguille Verte and the bridge at Chamouni; and supposing two observers stationed, the one upon the bridge and the other upon the Aiguille: the sound of a cannon fired on Mont Blanc would reach both observers with the same intensity, though in the one case the sound would pursue its way through the rare air above, while in the other it would descend through the denser air below. Again, let a

* It may be that the gas fails to throw the vocal chords into sufficiently strong vibration. The *laryngoscope* might decide this question.

† Poisson Mécanique, vol. ii. p. 707.

straight line equal to that from the bridge of Chamouni to the summit of Mont Blanc, be measured along the earth's surface in the valley of Chamouni, and let two observers be stationed, the one on the summit and the other at the end of the line; the sound of a cannon fired on the bridge would reach both observers with the same intensity, though in the one case the sound would be propagated through the dense air of the valley, and in the other case would ascend through the rarer air of the mountain. Charge two cannon equally, and fire one of them at Chamouni, and the other at the top of Mont Blanc, the one fired in the heavy air below may be heard above, while the one fired in the light air above is unheard below; because, at its origin, the sound generated in the denser air is louder than that generated in the rarer.

You have, I doubt not, a clear mental picture of the propagation of the sound from our exploding balloon through the surrounding air. The wave of sound expands on all sides, the motion produced by the explosion being thus diffused over a continually augmenting mass of air. It is perfectly manifest that this cannot occur without an enfeeblement of the motion. Take the case of a shell of air of a certain thickness, with a radius of one foot, reckoned from the centre of explosion. A shell of air of the same thickness, but of two feet radius, will contain four times the quantity of matter; if its radius be three feet, it will contain nine times the quantity of matter; if four feet, it will contain sixteen times the quantity of matter, and so on. Thus the quantity of matter set in motion augments as the square of the distance from the centre of explosion. The *intensity* or loudness of the sound diminishes in the same proportion. We express this law by saying that the intensity of the sound varies inversely as the square of the distance.

Let us look at the matter in another light. The me-