sation and rarefaction from one end of the series of balls to the other. This is exactly what takes place in every sonorous wave, and we could have no better illustration of the character of sonorous vibrations than that here given. It gives us in a moment a more exact idea of the nature of condensed and rarefied pulses than could be obtained by hours of the best-directed efforts of the unaided imagination. Indeed, we could scarcely desire a better instance than this of the capability which a well-devised and well-executed experiment possesses of furnishing us with a clear mental picture of certain physical processes that otherwise would remain quite obscure, if not unintelligible.

The motion of each ball in the experiment just made is like that of the bob of a pendulum. The motion of each particle of air agitated by the ball is the same. Such motions are accordingly called *pendular motions*. They are also known as *simple harmonic motions*. We shall use either term indifferently. The motions of each particle of a medium, transmitting a sonorous wave, are always in a direction parallel to the line of propagation of sound. In this respect they differ from the motions of the individual particles of a water wave, which are always at right angles to the direction of the wave itself. Sound-vibrations are likewise different from light-vibrations, for the latter, like vibratory motions of particles of water, are always transverse to the line of propagation of luminous rays.

What has been said of the mode of the propagation of sound in air applies with equal truth to all other media, whether gaseous, liquid, or solid. Sound is transmitted in pulses. Whatever the media, then, by which sonorous vibrations are carried from one point to another, we must regard the molecules of this media as being the active agents in the transfer of the motion impressed on it. While conveying sound the molecules are in a state of invisible, but most energetic tremor, and when this tremor ceases, the sensation of sound ceases also.

How wonderfully the mechanical action of these infinitesimal molecules, the physiological action of the organ of

hearing, and the psychological action of the brain are related to each other! Who can tell us how they are connected, or how one gives rise to, or influences, the other? No one. Such questions are "above the reach and ken of mortal apprehension." They bring home to us with telling force the fact that there are mysteries in the natural as well as in the supernatural order, — mysteries that only an angelic, possibly only the Divine, mind can fathom.

CHAPTER II.

LOUDNESS AND PITCH.

MUSICAL sounds differ from each other in three ways, — in loudness, in pitch, and in quality. To-day we shall discuss the subjects of loudness and pitch, and reserve that of quality for a subsequent lecture.

In speaking of the loudness of sound we must carefully distinguish between the sensation of loudness and the mechanical action that gives rise to it. Generally speaking, there is no measure for the loudness of sounds, so far as sensation is concerned. Acute sounds, even when of the same mechanical intensity as grave sounds, seem louder than the grave ones. A bass note, therefore, to sound as loud as a treble note, must be executed with proportionally much more force. The reason of this is that the ear is not equally sensitive to all sounds.

Mechanically considered, the loudness of sound depends upon the energy of vibration of the sonorous body. I draw a bow across the prong of a tuning-fork, and you hear a loud, clear note. At the same time those of you who are sufficiently near can see that the prongs are actually in motion. Gradually, however, the sound dies away, and simultaneously, and at the same rate, the vibratory motion of the fork disappears. From this experiment we learn that the loudness of sound for any given note depends upon the amplitude of vibration of the sonorous body. The greater the amplitude, the louder the sound. As the result of many careful experiments, it has been found that the intensity or loudness of sound varies as the square of the amplitude of the oscillations of the vibrating body.

Here are two tuning-forks, A and B, that are made to give exactly the same note. If A could be caused to vibrate with an amplitude of exactly one fifth of an inch, and B with an amplitude of one tenth of an inch, A would have twice the width of swing of B, and would give rise to a sound just four times as loud as B.

The loudness of sound varies also with the distance of the sonorous body from the ear. A little consideration will enable us to determine the law that governs the rate of variation. Exciting the tuning-fork before me, it gives off sonorous waves in all directions. But the amount of matter put in motion at a distance of one foot from the centre of disturbance is, as geometry tel[illegible]s, only one fourth of that which is agitated at a dista[illegible] of two feet, and only one ninth of the amount cause[illegible]ibrate at a distance of three feet. In other words, [illegible] learned in our last lecture, the amount of matter [illegible]n vibration increases directly as the square of the ra[illegible] of the shell affected. But as the volume of air put in [illegible]n increases, the loudness of the sound decreases, and [illegible]e same proportion. The rate of diminution is put in the form of a law by stating that *the loudness of sound varies inversely as the square of the distance of the sonorous body from the ear.*[1] At this rate, to one standing twenty feet away from the fork just used, the sound would be only one fourth as loud as to one but ten feet away. It would, however, be difficult to compare accurately the relative degree of loudness in this way. The experiment could be made more satisfactorily in another way. If one tuning-fork were to be placed ten feet away, and four others, giving exactly the same pitch and intensity as the first, were to be placed twenty feet off, we should find that the sound emitted by the fork ten feet distant equalled in loudness the aggregate sound of the four other forks twice the distance away. We thus see that doubling the distance reduces the loudness of the sound to one fourth. Trebling the distance would

[1] Mersenne gives this law in Prop. 14, lib. i., Harm.

reduce it to one ninth, and quadrupling it would, for the same reason, bring down the intensity to one sixteenth.

Loudness of sound is also modified by the density of the air in which it is excited. We saw in our last lecture the effect of rarefied air in diminishing the intensity of vibrations set up by a sonorous body. Using hydrogen gas, which is about fifteen times lighter than air, we obtained a similar result. In a heavier gas, like carbonic acid, the loudness of sound is augumented. The effect of air of slight density in diminishing the loudness of sonorous vibrations is illustrated in a very marked manner on the summits of very high mountains. Here the report of a pistol, as has frequently been remarked, sounds much like the discharge of a small fire-cracker.

Again, the loudness of sound produced by a sonorous body is strengthened by the proximity of other bodies capable of vibrating with it. I hold in my hand a small tuning-fork. It is unlike those hitherto used in that it is not mounted on a resounding box. When it is struck against the table and set in vibration, the sound is so feeble that it is scarcely audible; but when its base is placed upon the table, it immediately breaks forth into a clear, powerful note. The board on which the fork rests is also thrown into a state of vibration, and hence the increased loudness of sound as a result. Later on, we shall study more in detail this phenomenon of co-vibration, — resonance, as it is called, — and we shall see what an important part it plays in reinforcing sound in many of the more important instruments of music. It is sufficient here to allude to it as one of the important factors that materially augment the intensity of sonorous vibrations.

We have said that there is no measure for the loudness of sound as far as its sensation is concerned. Prof. A. M. Mayer has, however, attempted to determine the mechanical equivalent of a given sonorous aërial vibration, though much yet remains to be done in this direction. He found that the sonorous air vibrations produced by a C_8 fork, placed before a suitable resonator during ten seconds, was

equivalent to the mechanical energy necessary to lift 54 grains one foot high. Joule's mechanical equivalent of heat, or thermal unit, being 772 foot-pounds, the intensity of the sonorous vibrations of the fork used was, therefore, only about the $\frac{1}{100000}$ part of a Joule unit. Professor Mayer's investigations are interesting, because, among other reasons, they indicate a universal method for the exact determination of the relative intensities of sounds of different pitch. Some method, like the one referred to, is quite a desideratum, and, when discovered, will enable the acoustician to solve many problems that constantly present themselves to him in the course of his researches.[1]

We come now to consider the second characteristic of sound, — its pitch. In some of the experiments made in the last lecture with Savart's wheel and Seebeck's siren, we were given a hint as to what constitutes pitch.

Galileo seems to have been the first to suspect the true cause of pitch. He noticed that in passing a knife over the milled edge of a coin, a musical sound was produced, and that the pitch of the sound was higher as the number of serrations passed over in a given time was greater.

But the first one to investigate thoroughly the cause of pitch, and the first to determine the pitch of a known musical note, was the illustrious French ecclesiastic, Father Mersenne, of the order of Minims. Père Mersenne, as he is usually known, is justly called the Father of Acoustics. He did for the science of musical sounds what Galileo did for mechanics, and what Copernicus and Kepler achieved for astronomy. He put it on a solid scientific basis, and by the number and variety of his experiments, in almost every department of acoustics, he made the way easy for subsequent investigators. Besides being an excellent musician, he was one of the most eminent mathematicians of an age of great mathematicians. He was the intimate friend and correspondent of Descartes, and was the real founder of the French

[1] See the American Journal of Science and Arts, No. 47, vol. viii. p. 365.

Academy of Sciences. He translated and made known in France the works of Galileo, and made many discoveries in mathematics and physics. But the greatest monument of his genius is his work on sound and music, the first edition of which appeared in French in 1636, and is called "Harmonie Universelle." A later edition, in Latin, revised and corrected, is entitled "Harmonicorum Libri XII."[1] It is to this edition that I shall always refer. In this admirable but little known work, the learned author gives evidence, on nearly every page, of his skill as a clever and industrious experimenter and profound thinker. Indeed, many of the laws governing sonorous vibrations are to-day given in almost the same language in which he first formulated them. Mersenne, Chladni, — of whom more anon, — Helmholtz, and Koenig may be considered as the four great pillars of the science of acoustics, as they, by the number and originality of their experiments, have contributed more to its advancement than any other four that could be mentioned.

To establish the fundamental law regarding the pitch of sound, Mersenne stretched a hempen rope over ninety feet in length, so that the eye could easily follow its displacements. It did not then emit any sound, but one could easily count the vibrations it made in any given time. He then shortened the cord by one half, and found it then made twice the number of vibrations in the same length of time. In reducing it to a third or a fourth of the original length, he observed that the oscillations became three and four times as rapid. He also made similar experiments, with like results, with a brass wire. He thus established the law that, all other things being equal, the number of vibrations of a cord is inversely as its length. When the cord was sufficiently shortened it gave forth

[1] The full title of the "Editio Aucta," published in 1648, of this extraordinary, but almost forgotten, work is, "Harmonicorum Libri XII, in quibus agitur de Sonorum Natura, Causis, et Effectibus: de Consonantiis, Dissonantiis, Rationibus, Generibus, Modis, Cantibus, Compositione, Orbisque totius Harmonicis Instrumentis."

a sound, and this sound became higher in pitch in proportion as the cord was further shortened. In this manner he proved that the pitch of sound depends upon the number of vibrations made, and is heightened exactly in proportion as the number of vibrations is augmented.[1]

This law being once established, it is obvious that knowing the length of a string and the note emitted by it when in vibration, it is an easy matter to calculate the note that would be given by another string of the same size and material, and under the same tension, but of different length. Thus Mersenne "took a musical string of brass three quarters of a foot long, stretched it with a weight of six and five eighth pounds, which he found gave him by its vibrations a certain standard note in his organ; he found that a string of the same material and tension, fifteen feet, that is, twenty times as long, made ten recurrences in a second; and he inferred that the number of vibrations of the shorter string must also be twenty times as great; and thus such a string must make in one second of time two hundred vibrations."[2]

The next one, after Mersenne, to attempt to determine the pitch corresponding to a given sound was Sauveur, about the year 1700. He endeavored to solve the problem in two ways: first, by the method known as that of beats, and secondly, by the application of mechanical principles to the vibrations of strings. Both of these methods, although indirect, gave quite accurate results; but they are rather too recondite for discussion here. It will therefore be sufficient simply to refer to them, without entering into details.

In 1681, Robert Hooke improved on the experiment of Galileo by using a serrated wheel of brass instead of a coin. He found that on striking the teeth of such a wheel a distinct musical sound was emitted. Stancari repeated a similar experiment before the Academy of Bologna in 1706, and showed that the pitch of the sound produced increased with the velocity of rotation of the wheel; and

[1] Harm., lib. ii. Prop. 18.

[2] Op. cit., lib. ii. Prop. 21.

the number of teeth being known, it was easy to compute the number of vibrations per second corresponding to a determinate note.

About the beginning of the present century, Chladni endeavored to determine the pitch of sounds by means of vibrating bars similar to the one shown in Fig. 1 of our last lecture. The vibrating portion of the bar was at first sufficiently long to enable him to count the number of vibrations in a given time. By a series of carefully conducted experiments, Chladni found that the number of vibrations per second varied inversely as the square of the length of the bar. When the bar was made sufficiently short, it emitted a musical note, the pitch of which became higher as the bar was made shorter.

It is obvious that Chladni proceeded in essentially the same way with vibrating bars as did Father Mersenne with vibrating strings. In practice, however, it has been found that the results yielded by bars were not so exact as those afforded by strings; and for this reason the determinations made by Chladni have not the same accuracy as those made by his distinguished predecessor.

Let us take Savart's wheel again, which was used in our last lecture, and push our experiments a little farther. By pressing a card against the wheel, sound is at once produced, as before. Turning the wheel more rapidly, a more acute sound is the result; and the more rapidly the wheel is rotated, the shriller, as you observe, the sound becomes. Evidently, then, pitch depends upon the number of vibrations produced in a given time. The time spoken of in experiments of this kind is always one second. When we wish to determine the pitch of any sound, we find out how many vibrations it makes per second. With the wheel before us this is an easy matter. It is only necessary to count the number of teeth, and the number of revolutions the wheel makes per second, to know the number of vibrations produced. As one vibration is made by each tooth, the entire number of vibrations will obviously be equal to the product obtained by multiplying the number of teeth in the wheel by the number of revolutions it makes in one second.

We have here the means of showing in another beautiful way that pitch depends on the number of vibrations. On the rotator before you are four of Savart's wheels, with 48, 60, 72, and 96 teeth respectively. Placing a card against the wheel having 48 teeth, and then against the one with 60, you observe that the latter gives the higher note, although the rate of revolution of the wheel has remained unchanged. The musicians present will notice something more. They will remark that the two notes emitted, whether sounded in succession or simultaneously, constitute what is called a major third. The third wheel has 72 teeth, and the fourth 96. By turning the rotator at the same speed as before, and touching the wheels with the card, you hear notes that are more acute than either of the two sounded previously. The fourth wheel, with 96 teeth, gives just twice the number of vibrations that the first with 48 teeth makes. Sounding the two notes together, we have the interval called in music the octave. Sounding all four wheels together, we have the perfect major chord.

FIG. 23.

But let us compare the results given by Savart's wheels with those obtained from Seebeck's siren. In the siren we shall now use (Fig. 23) there are four concentric series of holes. The first circle has 48 holes, and the next three 60, 72, and 96, respectively. The number of holes in the four circles of the siren corresponds exactly with the number of teeth in the four toothed wheels. At the same rate of revolution, therefore, the siren should give the same number of vibrations as the wheels. Let us try. Taking a small bent tube, bringing it over a point in the circle having 48 holes, blowing through the tube, and turning the rotator, you hear a note which you recognize