said, to pulses of condensation, while those below represent pulses of rarefaction. The letters *n*, *c*, and *r*, in (1), and *n*, *e*, *d*, in (2), indicate respectively the nodal points where there is no motion, and the points of greatest condensation and rarefaction, or elevation and depression.

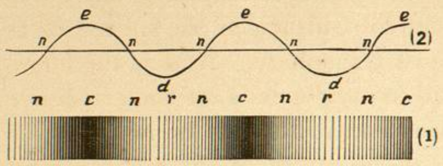

FIG. 19.

So far we have been considering sonorous waves that move in one direction only. Ordinarily, however, sound is propagated in many, or in all directions, simultaneously. When a skylark, for instance, is singing in the air, the sonorous pulses which it originates are propagated in all directions. Spherical waves or shells are thus formed, which recede from the centre of disturbance with the velocity of sound, alternate condensations and rarefactions being generated precisely in the same manner as when the sound-pulse travels only in one direction.

This is well illustrated by the accompanying diagram (Fig. 20). *A* is the source of sound. During the first half-vibration, motion is communicated to the entire sphere, *P Q*, whose centre is *A* and radius *A R*. During the time of the next half-vibration, all the space between *P Q* and *P′ Q′* is set in movement. Thus in the second interval of time a sphere of twice the radius of the first is made to vibrate. In the third interval of time the space between *P′ Q′* and *P″ Q″* has been set in vibratory motion. The volume of

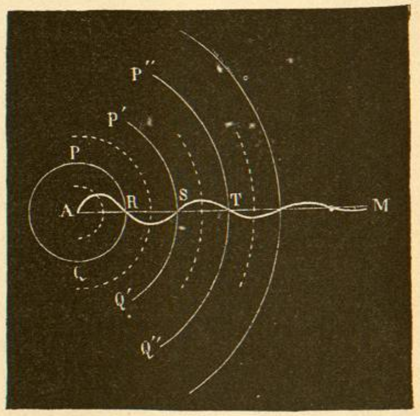

FIG. 20.

air, therefore, which is agitated augments in proportion as the spherical sound-wave recedes from the centre of disturbance. The amount of air set in vibration at any given instant varies directly as the surface of the sphere, or as the square of the radius of the sphere. And as the intensity of sound, as we shall learn, depends on the amplitude of motion of the sonorous body, its intensity, in any given case, will vary inversely as the square of the distance from the centre of agitation. This is illustrated by the curve *ARST*, which represents the condition of the air at a determinate instant in the direction *AM*. The amplitude of movement at any given point of the curve would, as you know, be represented by a perpendicular drawn from that point to the horizontal line *AM*. The wave-lengths are all equal, being independent of the amplitude of movement and of their distance from the origin of motion. The intervals of time are also equal, because the vibrations considered are of the class called isochronous.

It is now apparent, I think, that our modern notions regarding the propagation of sound are only a natural development of theories held by Aristotle, Vitruvius, and others of their time. We have simply cleared up their conceptions, but have not, I venture to say, introduced any essential modifications. We can state their theory more accurately than it was possible for them to do, and, thanks to our modern delicate instruments of research, we are able to demonstrate experimentally what they were able only to infer.

We must, then, view sound as conveyed by waves or pulses. Newton tells us in his "Principia" that "Sounds, since they arise in tremulous bodies, are no other than waves — *pulsus* — propagated in the air." It is a *motion* that is transmitted, not a *substance*. There is a transference of a *condition*, or a *system of conditions*, of matter, but no transfer of *matter itself*. The waves that strike on the drum of the ear are similar to those that are excited in the sonorous body, but they are not the same. The sonorous body communicates its vibratory motion to the air-particles nearest to it, and these in turn deliver their motion to the particles adjoining. Motion is thus conveyed from particle to particle, until it finally reaches the organ of hearing, where it is taken up by the auditory nerve and transmitted by it to the brain, which converts or translates it into the sensation which we call sound.

A simple illustration will show you how a transfer of motion, like that which obtains in the case of sound, is possible.

Before you is an apparatus devised over two hundred years ago by the distinguished French physicist, Abbé Mariotte, one of the ablest and most successful investigators of his time. On a stand (Fig. 21) are suspended seven elastic balls of lignum vitæ, each of which almost touches its neighbor. Drawing the ball *A* aside from its position of rest and allowing it to impinge against the one nearest to it, you observe that directly the first ball touches the second, it is stopped in its course, and its motion imparted to the second. This, in turn, transfers its motion to the third, which gives it up to the fourth; and so on until the motion reaches the seventh ball, *C*, which at once flies off to the right, while the other six remain motionless. What then has taken place? The motion which was primarily imparted to the first ball was communicated to the succeeding six, but only the last of these showed the visible effects of this motion.

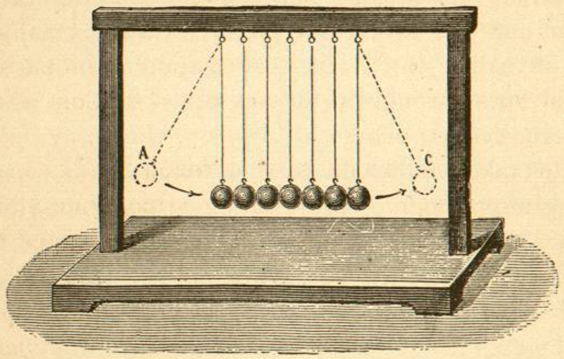

FIG. 21.

Were it not for the elasticity of the balls, this transfer of motion, as just shown, would be impossible. If the balls were perfectly elastic — they are far from it — the motion of the seventh ball would be equal to that given to the first. By using ivory balls, or, better still, glass balls, the loss of motion would be less, as ivory and glass are more elastic than is lignum vitæ.

Imagine, now, these wooden balls replaced by particles of air. Imagine also the particle of air nearest a sounding body taking up the motion of that body and imparting it to the adjoining particles in the direction of the ear, and imagine further this motion transferred in succession to all the particles intervening between the sonorous body and the ear, and you have a true picture of what actually takes place in nature when vibratory motion is propagated in straight lines through air or any other medium whatever, and perceived as sound.

Let us take another illustration, which shows even more strikingly the mode of propagation of sonorous vibration. I hold in my left hand one end of a brass wire-spiral, twenty feet long, made of the best spring brass. The other end of the spiral is attached to a small box. With my right hand I grasp the spiral about six inches from my left, and pulling the turns of the spiral some distance apart, I suddenly relax my hold with the right hand. In virtue of the elasticity of the wire the turns that were separated from each other tend to return to their orignal position. At the same time, however, a vibratory motion, or pulse, is sent through the whole length of the spiral, and announces its arrival at the other end by a loud rap on the box. This pulse on reaching the box is reflected immediately, and quickly returns to its starting-point at my hand. Thence it again returns to the box, repeating the tap you heard before, and is again reflected to my hand. This oscillatory motion is repeated several times, each time becoming weaker, until it entirely disappears.

When the pulses are first produced they can not only be heard, but seen as well. To and fro you see them move, each pulse making the excursion from one end to the other of the spiral in the same period of time.

If we examine closely the condition of the spiral as the pulses pass along its length we shall find that, at a given instant, some of the coils are farther apart than others. As the pulse first starts forward towards the box we observe that at the end I hold in my right hand, several coils are closely pressed together, followed by others more widely separated from each other. As the pulse is carried onward, the condition of compression and separation is seen to be propagated from one end of the spiral to the other. On reaching the box these same compressions and separations are reflected back to their starting-point, and this motion is repeated as long as the pulse continues its forward and backward motion.

This, as has been stated, is exactly what takes place when sound is transmitted through the air. When a tuning-fork, for instance, is excited, its prongs, in moving away from each other, crowd together the air particles in contact with their outside surfaces. These air-particles compress those in front of them, whilst those first compressed by the tuning-fork tend, by reason of their elasticity, to return to their normal condition. But the return of the prongs of the fork to their original position pulls the particles that were at first crowded together farther apart from each other, and farther apart even than they were before the fork was set in vibration.

As in the wire spiral some of the coils were closer together than others, so when sound is transmitted through the air we have the air-particles alternately compressed and separated. This condition of compression and dilation, as in the spiral, is carried forward from the source of sound until the motion gradually dies away, or until it encounters some obstacle, when it is reflected back in its path, as in the spiral, or off in some other direction.

Mariotte's apparatus illustrates how one particle of matter can communicate its motion to a contiguous particle. The wire spiral exhibits the transfer of motion by the formation of pulses of compression and dilation. Mach, however, has provided us with an apparatus which beautifully exhibits both of these phenomena simultaneously. Such an instrument is before you (Fig. 22). It is about ten feet long and four feet high, and, taken altogether, is by far the best means yet contrived for showing the nature of all kinds of vibratory motion, both transversal and longitudinal. As you observe, twenty-one white metal balls are suspended from the cross piece *c d* of a frame *p a g b*. On a long bar, *st*, are fixed a number of pegs, at different distances from each other. These pegs are so placed as to represent one complete sonorous wave, composed of one condensed and one rarefied pulse. When the balls are held in position by these pegs, the former as well as the latter exhibit a complete sound-wave. If, now, when the balls are in this position, the bar is suddenly withdrawn, they will commence to swing in the same plane, and while swinging they will retain the same relative positions with reference to each other which they had before they were put in motion. They are now oscillating all in the same plane and in the same period. But in addition to the excursions made by each individual ball, you see, in a most striking manner, a transfer of pulses of conden-

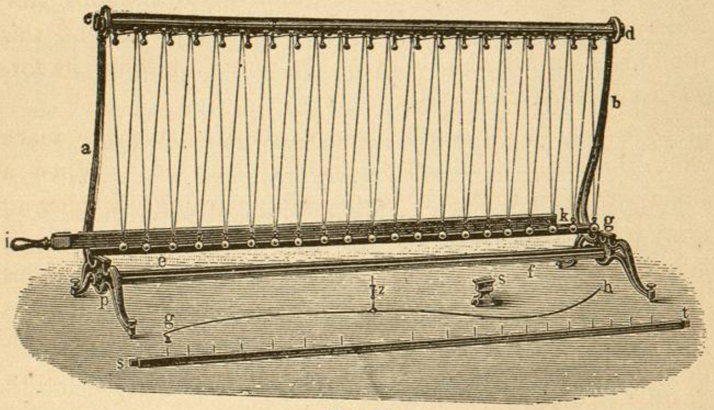

FIG. 22.

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.