cause of the small amount of surface it exposes to the air. But I shall not forestall what properly belongs to the subject of resonance, which will be considered in another lecture.

The toy called the string telephone, with which every one is familiar, is another pretty illustration of the facility with which solids transmit sounds. The telephones before you are composed of two brass tubes, the smaller ends of which are covered with a thin membrane. The centres of these membranes are connected with each other by a light cord, and by this simple means sounds, otherwise inaudible, can be heard at a distance of a thousand feet or more.

A simple experiment will show the capacity that liquids have for transmitting sounds. On this resonant case is placed a long, narrow jar filled with water, and into the water at the top of the jar is placed the foot of a tuning-fork. As soon as the fork touches the water a loud, clear note is heard, where before all was silence. Any other liquid would answer the purpose as well as water.

Here I must call your attention to an interesting property of sound which was first pointed out by Doppler in 1842, in a remarkable memoir on the colors of double stars. If an observer approach a source of sound it is obvious that the number of sonorous pulses which will reach his ear will be increased in proportion to his rate of motion. The pitch of the sound, therefore, will be heightened. If he recede from the sonorous body, the number of sound-waves that will reach him will be diminished in proportion, and the sound, consequently, will appear more grave. The same results will be observable if the hearer remain stationary and the sounding body be put in motion. Thus, if one could move with nearly the velocity of sound towards a brass band playing a piece of music, its pitch would be so greatly augmented that, although the performance would still be in time, its character would be entirely altered, and it would be nearly, if not quite, inaudible except to ears specially sensitive to very acute sounds. If, on the contrary, one were to move

away from such a musical source with a velocity approaching to that of sound, the sounds heard, if at all audible, would be proportionally flattened. If, further, the observer were to recede from the band with a velocity greater than that of sound, a piece of music commenced after he had started would never reach him, but "sounds previously executed," as Lord Rayleigh observes, "would be gradually overtaken, and heard in the reverse of the natural order."[1] And, finally, if the observer's velocity were to be twice that of sound, he would "hear a musical piece in correct time and tune, but backwards."

An illustration of the effect of motion on the pitch of sound is afforded by the whistle of the locomotive as it approaches or recedes from the observer. In the former case the pitch is augmented, in the latter it is diminished. Thus, for a train moving at the rate of thirty-eight miles an hour, the velocity is about fifty-five feet per second. This, calculation shows, is sufficient to raise the pitch of the whistle a semitone as it approaches the observer, and to lower it by the same amount as the locomotive retreats. Thus, if, when both locomotive and observer were stationary, the whistle were to give the note A_1, it would, with the velocity above mentioned, give the note $A\sharp_1$ as it approaches, and $A\flat_1$ as it leaves him. Just at the moment of passing by the observer there would be a change of a whole note, that is, from $A\sharp_1$ to $A\flat_1$. By doubling the velocity of the train the whistle would be augmented by a whole tone when approaching, and diminished by a whole tone on leaving. If two express trains, each going at the rate of thirty-eight miles an hour, were to pass each other, the whistle of the engine of one train would appear, when approaching an observer in the other train moving in an opposite direction, to be a whole tone higher than when whistle and observer were both stationary. After the two trains had passed each other the note of the whistle would appear a whole tone lower than it would if both observer and whistle were stationary. At the instant of passing

[1] Theory of Sound, vol. ii. p. 240.

there would be a change of a major third, or of two whole tones. If instead of thirty-eight miles the velocity of the two trains were to be equal to that which is now frequently attained by some of our limited express trains, there would be, at the instant of passing, a transition equivalent to an interval greater than a fourth, and approximating to a fifth.[1]

Doppler's principle, as it is called, at first only a theory, has, in its application to sound, been experimentally verified by Buys-Ballot and Scott Russell, by means of musical instruments carried on locomotives, whose pitch was determined by musicians stationed along the road over which the engines passed.

By applying the same principle to luminous vibrations, astronomers have been able to determine, not only the direction of motion, but also the velocity of many of the stars as they approach or recede from the earth.

A simple laboratory instrument for showing the influence of motion on the pitch of sonorous bodies has been devised by Mach. It is composed of a tube six feet in length, mounted on a stand, and turning about an axis at its centre (Fig. 34). At one end of the tube is fixed a reed, which is sounded by forcing air into the tube through an aperture at its axis of rotation. If, while the tube is rotating, an observer stand in the prolongation of its axis of rotation, he will hear a note of constant pitch. If, on the other hand, he be stationed in the plane of rotation, he will hear a note which alternately rises and falls in pitch according as the sonorous body approaches or retreats from him.

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[1] Designating by n the number of vibrations of the sonorous body when at rest, by V the velocity of sound, by V' the velocity of the sonorous body when approaching or receding from the observer, and by n' the number of vibrations corresponding to the sound perceived by the observer, we have the two following formulæ: —

$$n' = \frac{n(V+V')}{V} \text{ as the sonorous body approaches observer.}$$

$$n' = \frac{n(V-V')}{V} \text{ as the sonorous body recedes from observer.}$$

Koenig illustrates this phenomenon in another way equally striking. For this purpose he employs a pair of tuning-forks mounted on resonant cases, like those now before you. The frequency of one of them is C of 512 vibrations, and that of the other is exactly four vibrations higher. They thus, when stationary and sounding together, give four beats per second. If now I excite the two forks, and leaving the more acute one on the table, move the graver one towards it, in a line joining my ear and the stationary fork, over a distance of about two feet, — approximately the wave-length of the fork, — in a second I thereby lower the pitch of the graver fork by one vibration. This increases the difference between the forks to five vibrations, and gives rise to five beats per second. A movement in the opposite direction would, for a like reason, produce three beats a second. Thus by properly timing the movement of the graver fork between the ear and the fork on the table, we have alternately three and five beats per second, — three beats as the fork is brought towards the ear, and five beats as it moves away. By this means, also, it is evident one can determine approximately both the wave-length and the pitch of a sound.

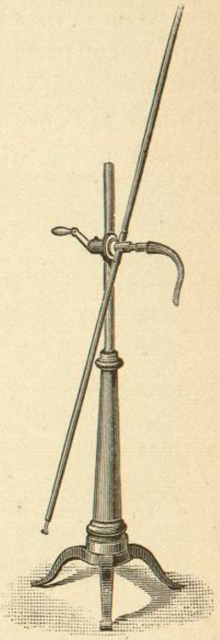

FIG. 34.

A modification of this experiment will enable you all to see at a glance the effect of motion on the frequency of sonorous vibrations. For this we shall use two forks on cases that are exactly in unison with each other. And in this experiment I shall anticipate, to some extent, what I shall have to say on the subject of resonance and sympathetic vibration. When one fork is agitated, the other, although at some distance, immediately begins to vibrate, as you see by the small pith ball that is projected away from the prong against which it was suspended. This happens, however, only when both forks are stationary. If now one of them is moved rapidly backwards and forwards in a line connecting the two forks, the perfect unison that previously existed between them is destroyed. For from what has been said, when one of the forks approaches the other, the pitch of the fork in motion is heightened, and when it recedes the pitch is lessened. And as in this experiment perfect unison is necessary in order that one fork may excite sufficient vibratory motion in another to produce the effects noted, we see at once in the absence of such motion what influence the movement of one fork towards or away from the other has on the pitch of the sonorous vibrations in question.

In a homogeneous medium sonorous waves are propagated in the form of concentric spheres. When, however, the homogeneity of the medium is disturbed, or an obstacle is encountered, sound-waves suffer partial or total reflection. In this respect they obey the same laws as those which govern rays of light and radiant heat. If, in Fig. 35, MN represent a fixed elastic surface, a sound produced at C will be heard by an observer at O both directly in a straight line, and by reflection from the point I. The sound in the latter instance appears to come from I or from C', a point in the line OI produced. Making PI perpendicular to the reflecting surface MN, and calling CI the incident, and IO the reflected, ray[1] of sound, it is found that in all cases the angle of incidence, CIP, is equal to the angle of reflection, PIO.

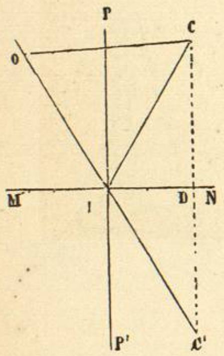

FIG. 35.

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[1] A *ray* of sound, as is obvious from what has been said concerning the nature of sonorous vibrations, must be considered as a simple abstraction, and nothing more. In explaining the laws of reflection and refraction of sound it is a convenient term to use, and for this reason only is it introduced.

It is found also that the incident and reflected rays are always in the same plane, and that this plane is perpendicular to the reflecting surface.

When concentric sound-waves encounter a fixed obstacle they return upon themselves, as if emanating from a second centre on the opposite side of the obstacle. Thus, in Fig. 36, the sonorous waves whose source is O, on arriving at the fixed surface AB, are reflected in such a manner that they seem to proceed from the point O' on the other side. A single ray of sound from O, impinging against the point I, would be reflected to the point M, along the line IM. This line may be regarded as a continuation of that drawn from O', the virtual centre of the waves reflected from the surface AB.

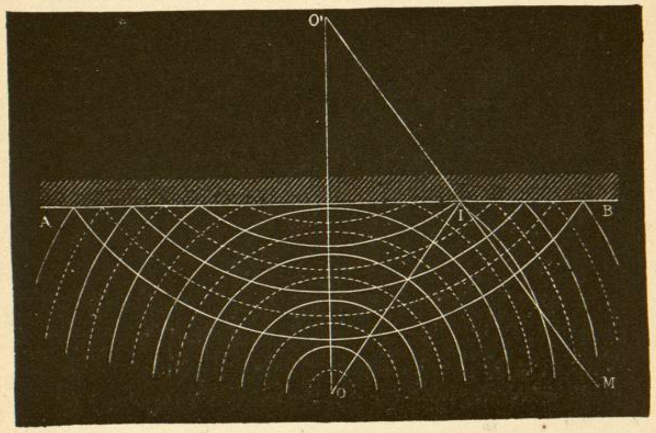

FIG. 36.

It is an easy matter to show experimentally the reflection of sound. Before you are two curved mirrors on metallic supports, A and A', about six yards apart. These mirrors — which are shown in section in Fig. 37 — have the property of converging parallel rays of light, heat, or sound, to a point called the focus. When, however, the rays start from the focus and are reflected from either mirror, they are given off in lines that are parallel. In the focus, F of one of the mirrors, M, is suspended a watch, and at the focus, *F′*, of the other mirror, *M′*, is a small funnel, which is connected with my ear by means of a rubber tube. By a special effort I am able to hear the ticking of the watch with the unaided ear; but by means of these two mirrors I can hear its ticking with remarkable distinctness. The sound-rays from the watch strike against the mirror adjacent, and by it are reflected to the one more distant; and by this last the rays are concentrated at a single point, which, by means of the tube, is now in direct communication with my ear. By this means the ticking of a watch can be distinctly heard at a distance of two or three hundred feet, whereas the unaided ear would be unable to detect the slightest sound at a very small fraction of this distance. Good results may likewise be obtained from one mirror, as can be easily demonstrated. Leaving the watch suspended as it is, I turn the adjacent reflector so as to direct the sound-rays towards the audience. With a little attention I think that even those in the most distant part of the room can hear the ticking of the watch, when the reflector is so adjusted that the reflected sonorous waves shall strike directly the tympanic membrane of the ear.

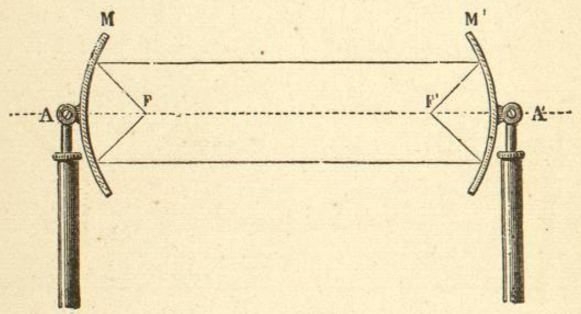

FIG. 37.

Mr. Cottrell has devised a very ingenious instrument for exhibiting the reflection of sound and showing that the angles of incidence and reflection are equal and in the same plane. It consists (Fig. 38) of a tube, *R B*, by means of which the acute sound of a small reed is directed against a mirror, *M*, by which it is reflected into another tube, *AF*, carrying at its extremity a sensitive flame. The axes of the two tubes can be turned towards the mirror at any angle, and the support is so graduated that the angles of inclination of the tubes to the normal of the mirror can be read off at a glance.

When the angles are equal and the reed is sounded, the sonorous pulses are reflected from the mirror into the tube bearing the sensitive flame. The flame, as you observe, is now violently agitated, and this disturbance persists as long as the sound continues. If, however, the angles are unequal, the sensitive flame will remain quiescent. I now make the angle of reflection greater than the angle of incidence, and sound the reed as before; the flame remains perfectly quiet. Nothing could be more sensitive than the flame, when properly adjusted, or illustrate more clearly the laws governing the reflection of sonorous rays.

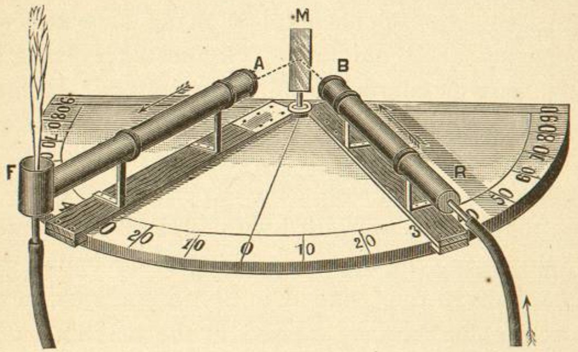

FIG. 38.

But it is not by any means necessary to have a solid surface, such as this mirror, for a reflector. Liquids and gases have also the power of reflecting sound. Every one may recall instances of the reflecting power of liquids, especially the water at the bottom of wells or under the arches of bridges. But the power which gases have of reflecting sounds is not so well known. It can neverthe-