to be in unison with the one that is given by the wheel having 48 teeth. Sounding in succession the four notes of the siren, beginning with the lowest and going to the highest, you notice not only a rise in pitch, but also that the pitch of the notes emitted corresponds exactly with that given by the four serrated wheels.

The siren and the toothed wheels prove, therefore, conclusively that pitch depends on the rate of vibration of the sonorous body, although the sounds emitted are comparatively feeble, and are accompanied with so much noise that a great part of their musical nature is lost.

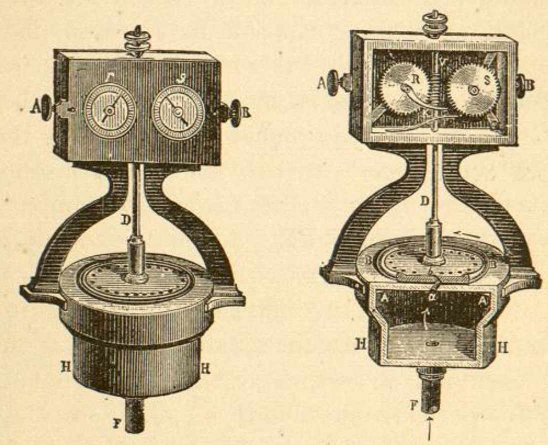

FIG. 24.

It is now time to make you acquainted with an instrument that is capable of yielding much louder and purer tones, and of giving much more satisfactory results. It is, in reality, only a modified form of Seebeck's siren, but is in every way a superior instrument. It is known, from its inventor, as the siren of Cagniard de la Tour. It was called a siren because it can be made to sing under water. The notes are not, however, such as we are wont to associate with the songs of the sirens of Homer.

As you will observe, the instrument (Fig. 24) is composed of a cylindrical wind-chest, *HH*, in the top of which are fifteen holes equidistant from each other, and equidis-

tant from the centre of the circle which they form. Above the wind-chest is a disk, *BB*, attached to an axis, *D*, to keep it in place. Like the wind-chest, the disk is pierced with fifteen holes, those of the latter being immediately above those of the former. In both, the orifices, *a* and *b*, are inclined to the perpendicular, those of the disk being inclined opposite to those of the wind-chest. When air is urged through *F* from the wind-chest of a bellows, it passes through the apertures in *AA*, and impinges against the sides of the holes in the disk, and with sufficient force to cause it to revolve, — the rapidity of the revolution depending on the pressure of the air. When the disk makes one revolution, fifteen puffs of air are given off, and fifteen vibrations are the result. Air is now admitted from the bellows into the siren, and immediately the disk begins to revolve. At first the movement is so slow that the puffs can be counted. Gradually they succeed each other more rapidly, and soon the puffs blend into a continuous sound. Augmenting the air pressure, the sound gradually rises in pitch until the notes becomes so loud and piercing as to be positively painful. By diminishing the pressure of air or placing the finger on the disk, the pitch is instantly lowered, showing, as in the preceding experiments, that pitch depends solely on rapidity of vibration.

By means of clockwork, *R S*, in *A B*, which can be connected with an endless screw, *VK*, on the axis which carries the revolving disk, we can determine, by merely looking at the dials, *r s*, the number of vibrations corresponding to any given sound. It is, indeed, just such an instrument as this that some of the most distinguished scientists have employed in their researches on the pitch corresponding to various notes, and as given by different sonorous bodies. The eminent French physicist, M. Lissajous, had recourse to it in his very difficult and delicate task of determining the pitch of the standard tuning-fork of France, — the "Diapason Normal" of the French Conservatory of Music.

Let me now give you an idea of how the work is done. One cannot make any pretensions to great accuracy in a lecture experiment, as exact results would require greater time and more attention to many details than can be given now. In an illustration, however, exactness is not necessary. It is only the method we wish to understand, and not the great delicacy of which it is susceptible.

In one of the orifices of the wind-chest of the acoustic bellows is placed an organ-pipe, near that occupied by the siren. We now cause air to enter both pipe and siren at the same time. The tone of the organ-pipe comes out at once, loud and clear. The siren starts with a succession of puffs, and gradually reaches the same note as is emitted by the pipe. When the siren gives exactly the same note as the pipe, it is said to be in unison with it, and when it is in unison it gives the same number of vibrations. And what is true in this particular case is true universally. When two or more instruments give the same note, they are in unison, and when they are in unison, their frequency — that is, the number of vibrations they execute in a given time — is the same.

As soon as the siren is in unison with the organ-pipe, the clockwork is set in motion and kept going for some time, — say ten seconds. If the siren can be kept steady, — and this is not an easy matter, — we have only to read off from the dials of the clockwork the number of revolutions made by the rotating disk of the siren. Multiplying the number of revolutions by the number of apertures in the disk, we have the number of vibrations made by the siren in ten seconds. Dividing this product by ten, we have the number of vibrations made by the siren in one second.

But as the two sounds were kept in unison during these ten seconds, it follows that the number of vibrations we have found for the siren answers also for the number of vibrations of the pipe. In a similar manner, we could find the pitch of the human voice, or of a musical note emanating from any sonorous body whatever.

This method of determining, by means of the siren, the number of vibrations corresponding to any given sound, is, you will say, quite satisfactory. So it is. It is simple

and ready, and, with proper precautions, capable of giving results that are correct to a fraction of a vibration. Surely, one might think, this ought to be sufficiently near the truth to satisfy any one. Scientific men, however, are very exacting, and demand a more certain and more delicate instrument than even the most perfect form of siren.

Such an instrument is before you. It is ordinarily called the vibroscope of Duhamel. It can be used for several most delicate and most interesting experiments. The

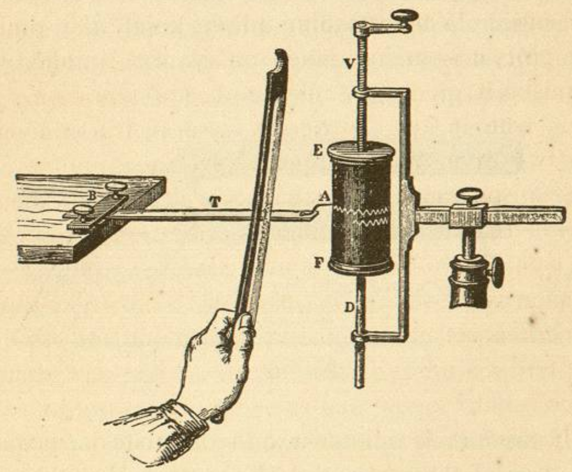

FIG. 25.

apparatus we shall now employ is, as you may observe, composed of a cylinder, EF (Fig. 25), mounted on an axis, VD, on which a screw is cut in such a manner as to permit axis and cylinder to move endwise when the crank attached to the axis is turned. Around the cylinder is gummed a sheet of smoked paper, and in front of it is fastened an elastic strip of metal, BT, to the end of which is attached a light style, A. The end of the style is made just to touch the smoked paper. By moving the style along a line parallel to the axis of the cylinder, a straight line is traced. On turning the cylinder when the style is at rest, the latter will again inscribe a simple straight line on the smoked paper, but at right angles to the axis of the cylinder. By bowing the elastic strip it is set in vibratory motion; and if at the same time the cylinder is turned, we get as a resultant of the double motion, a beautiful wavy line instead of the straight one we obtained before. By this means the elastic strip writes out its own motion, and tells, in a manner that cannot mislead, the exact number of vibrations it executes in a given time.

Instead of the thin elastic bar just used, let us make the same experiment with a tuning-fork. This can be done very simply, by attaching a light point, *b*, to the fork, *A* (Fig. 26), and passing under it a plate of smoked glass,

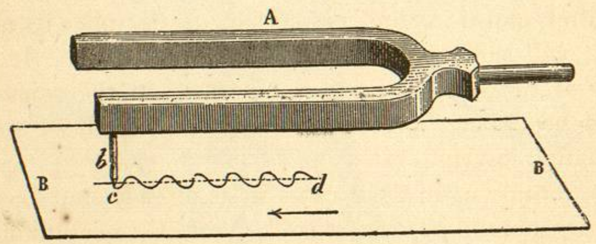

Fig 26.

B B. If the fork is quiescent, and the plate is moved in the direction of the arrow, the point attached to the prong will inscribe a simple straight line, *c d*. But if the fork is set in vibration, and the plate is moved as before, a sinuous curve will be formed, similar to the one traced by the vibrating elastic bar. The movement of the plate being uniform, divisions of equal lengths on the straight line, *c d*, would correspond to equal periods of the vibrating fork. We might, in a similar manner, cause a string vibrating under the influence of molecular forces only to write out the story of its motion, and the curve obtained would be identical with those just examined. Vibrating plates and membranes will also, under proper conditions, give the same curve. The air particles in an organ-pipe, vibrating between fixed nodal surfaces, likewise yield just such

curves. Mach has devised an instrument — which, however, cannot be used here — whereby they can be made to give a record of their motion.

If, again, we were to cause a plate of smoked glass, like the one used in Fig. 25, to pass, with uniform motion, under an oscillating pendulum in such a manner that the line *c d* should move in a direction at right angles to the plane in which the pendulum swings, we should obtain a sinuous curve in all respects similar to those afforded by the tuning-fork and the vibrating bar.

Let us now examine the record that has been made in the cases considered, because it is important, before going farther, that we should become acquainted with this form of writing. We shall frequently have occasion to study it hereafter, and if we understand how to decipher its meaning, it will tell us many and wonderful things. Indeed, some of the most striking conclusions in the science of sound have been deduced from a close study of similar undulating inscriptions.

The motion in all these cases is, as already stated, called *pendular* motion, because it is like that of a pendulum. It is also, as you will remember, called simple *harmonic* motion. The curve traced by the pendulum, and by the other vibrating bodies referred to, is called the *curve of sines*, a *sinusoidal curve*, a *sinusoid*, or, better still, a *harmonic curve*. In Fig. 25 there is a series of such sinusoids, or harmonic curves. As one complete vibration traces out a complete curve of the sort we are now studying, we have in Fig. 25 six harmonic curves connected with one another so as to exhibit a continuous undulating line. When considered as a symbol of wave-motion, the indentations, or portions of the curve above the straight line *c d*, are called *crests*, while those below are called *troughs*. A trough and a crest form a complete wave. A succession of waves, as in Fig. 25, constitutes an *undulation*. The distance the wave travels in one period is one wave-length.

Water-waves and sound-waves are alike in this, that there is no transference of matter by the waves in either case.

In the case of water-waves, the progressive motion of the masses of water that constitute the wave is only apparent. The individual particles of water in each wave have nothing more than an up-and-down motion at right angles to the line of progression. It is ordinarily said that these particles move in straight lines perpendicular to the direction of the wave's motion; but this is not strictly true. Each particle in reality describes a curve — a circle or an ellipse — in a plane in the line of progression. In the case of sonorous waves, however, the particles composing the waves have, as we now know, a motion parallel to the direction of propagation of the wave. The motion of the particles, then, is simply a *to-and-fro* motion, one of advance and retreat; and the results, as already explained, are conditions of compression and dilation known as waves, or pulses, of condensation and rarefaction.

Like the motions of the pendulum, the periods of sonorous vibrations are independent of their amplitude. Whether the width of swing of a sonorous body, or of the air particles excited by a sounding body, be great or small, the pitch of the sound remains the same. The amplitude of vibrations may change, as they do when this tuning-fork is excited with the bow and then left to itself, but the pitch of the sound remains unchanged. Whether the pitch of the sound be strong or weak, you recognize it as the same note. A change in amplitude of vibration, then, means simply a change in loudness or intensity, and nothing more. The period, therefore, of sound-vibrations, as well as of pendulum-vibrations,[1] is independent of amplitude.

The knowledge of these facts will enable us still better to understand the sinuous line our tuning-fork has described for us. In the particular figure we have been studying, we observe that the lengths of the waves remain the same. This depends, if you will, on the uniform motion of the glass plate during the production of the figure; but were there any change in the pitch of the note emitted, the

[1] The period of pendulum-vibrations is independent of their amplitude only when the arc through which the pendulum oscillates is small.

wave-length would vary, notwithstanding this uniform motion. The pitch remains the same because the wave-lengths remain the same. This, however, is only another way of stating what has already been said; namely, that the vibrations of any given continuous sound are periodic, and they are periodic because the wave-lengths remain unchanged.

By counting the number of indentations, or sinusoids, made by the fork in one second, — and this is a very simple matter, — we at once obtain the *vibration-number*, or what is more appropriately called the *frequency*,[1] of the fork. By this method we can determine with great accuracy, not only the number of the vibrations of the fork we are now using, but also that of any other sonorous body whatever.

In a small vice is fastened an elastic steel rod whose point just touches the smoked paper around the vibroscope. Near by a tuning-fork is so placed as to register its vibrations alongside those of the steel rod. Exciting the rod and the fork by means of a bow, we cause them both simultaneously to trace their sinuous curves on the revolving cylinder. The number of vibrations made by the tuning-fork has been determined by the maker, and knowing the frequency of the fork, it is an easy matter to calculate that of the rod. The fork we are now using makes one hundred vibrations per second. Counting the number of vibrations registered by the fork and the rod on the paper during the same time, we find that while the fork writes out indentations corresponding to 75 vibrations, the rod inscribes 125. Now, as the tuning-fork makes one vibration in the $\frac{1}{100}$ part of a second, it will make 75 vibrations in $\frac{75}{100}$ of a second. But during this time the rod makes 125 vibrations, or one vibration in the $\frac{75}{100 \times 125}$ of a second. In one second, therefore, it makes $\frac{100 \times 125}{75}$, or $166\frac{2}{3}$ vibrations. This method of determining pitch, known as the graphical method, is due to Dr. Thomas Young, and is competent to give very accurate results.

Let us now replace the fork we have been using by

[1] This is the term — in Latin *frequentia* — employed by Mersenne.

another which is kept in vibration by a current of electricity. The advantage of such a fork is that it can keep in motion indefinitely, and thus we can secure records extending over periods of time longer than would be possible with a fork actuated by a violin-bow. By allowing the fork to vibrate for one hundred seconds, for instance, and counting the sinuosities produced, we can get the average rate of vibrations per second, by dividing the total number of sinuosities by 100. This is known as the electrographic method, and is even more accurate than the graphical method just described.

Prof. A. M. Mayer has, by ingenious additions, so modified the electrographic method and improved its efficiency that it is now almost all that could be desired.

Let us now see if we can determine the number of vibrations produced by a given note of the human voice. To do this it will be necessary to make use of some appliance that will take up the vibrations of the voice in such a manner that they can be recorded.

Such an instrument (Fig. 27) is before you. It is the Phonautograph, as devised by Scott and improved by Koenig. As its name indicates, it is a self-registering sound apparatus. It is a modification of the cylinder and tuning-fork we have been using, with an attachment for collecting sound-waves of whatever character, or however delicate. As you will notice, this attachment, *A*, is in the form of a concave paraboloid. This particular form is chosen because it possesses the property of reflecting all parallel waves to a point called the focus, near the smaller end. Just at this point is stretched a delicate membrane on a frame, *D*. All the waves that enter the paraboloid impinge on this membrane and throw it into vibration. On the side of the membrane next to the cylinder is attached a very fine and light style, which faithfully inscribes on the smoked paper around the cylinder the slightest motion given to the membrane. By means of a small adjustable clamp, *G*, held in position by a screw, *V*, it is possible, with a second screw, *V′*, to regulate at will the

tension of any given point of the membrane. In this way we can obtain a record of any sonorous wave that enters the paraboloid. By this instrument we find that each sound traces out its own characteristic curve, — writes out its own distinguishing autograph. Some sounds give indentations much like those of the tuning-fork, while others, like those of the human voice, give rise to sinuosities of much greater complexity.

By means of a tuning-fork, which is kept in vibration simultaneously with the style, the frequency of any sound

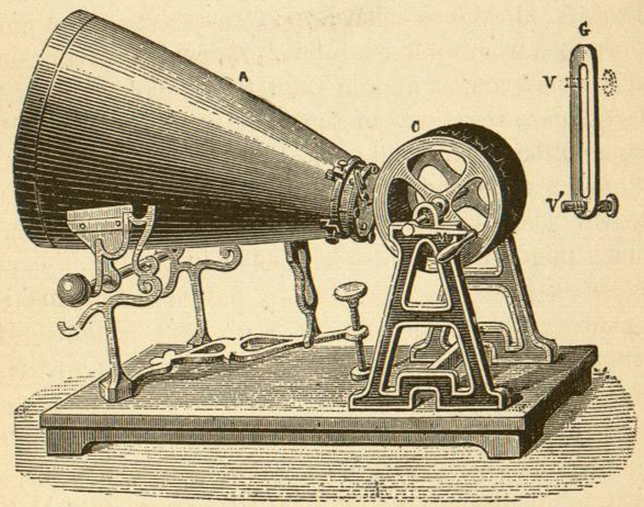

FIG. 27.

can be determined with the greatest ease and precision. The process is identical with that used a few moments ago in estimating the rate of vibration of an elastic rod. We have traces of both the sounds made on the smoked paper; and knowing the frequency of the fork, we have only to count the number of sinuosities of each sound corresponding to any given distance on the paper, when a simple proportion will give us the number of vibrations made per second by the sound collected by the paraboloid and recorded by the style attached to the membrane.

Let some one now sing a prolonged note into the open