It is now time to answer a question that must have already presented itself to your minds; and that is, "How can one and the same cord give rise to several sounds simultaneously?" In the case of a string, for instance, the segmental vibrations, which, alone, would yield certain partial tones, are superposed on that of the string vibrating as a whole; and those corresponding to its various segments are so combined as to yield a compound motion as a resultant. In Fig. 44 we have represented two of the simplest cases of this kind. The string *A M B*, *A C B*, when vibrating as a whole, emits only its fundamental, and while doing so does not undergo any subdivision. The string *A' M' B'* yields simultaneously its fundamental and its first partial. In this case it assumes the form *A' C' B'*, indicated

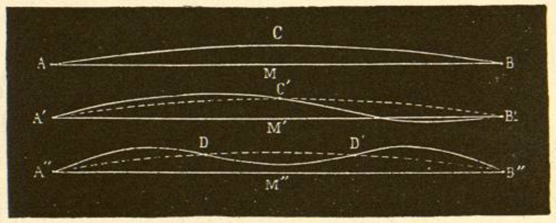

FIG. 44.

by a continuous line, — that is, while vibrating as a whole, it at the same time divides itself into two parts, *A' C'* and *C' B'*, each of which vibrates with twice the rapidity of the whole, as would strings having one half the length of the whole. The same string, represented in *A'' M'' B''*, gives simultaneously its fundamental and its third partial. It then assumes the form *A'' D M'' D' B''*; which means that while vibrating as a whole, it is at the same time subdivided into three segments, each of which has a rapidity of motion three times as great as that of the whole string, and therefore vibrating as rapidly as would a cord one third of the length of the whole. In the latter two cases, the fundamental is represented by dotted lines, while the resultant compound tone is represented by lines which are continuous.

If a larger number of partials were superposed on the fundamental, a more complex tone would result, and the form assumed by the vibrating string in yielding such compound tone would depend on the number and relative intensity of the partials present. And if in addition to the harmonic partials, inharmonic partials were added, as is sometimes the case, the movements of the string would be still further modified.

Thus far we have been employing the sonometer in elucidating the laws of vibrating strings. We can, however, investigate them with other apparatus and from other points of view. The experiments to which your attention is now invited, beautifully corroborate those already made. They also add materially to our knowledge of the laws of vibrating strings, inasmuch as they enable us to see clearly and in a different light what we have seen only imperfectly in our experiments with the sonometer.

Chief among the phenomena to which I wish to direct your attention is that which concerns the formation of nodes and ventral segments. The illustrations so far have been on only a small scale, and none of you, except those very near the sonometer, have been able to see the nodes and ventral segments referred to, unless indirectly by the device of the riders employed.

There are various methods of rendering visible at a distance the nodes and ventral segments of vibrating strings. The first one we shall have recourse to is merely mechanical, but it is none the less instructive or beautiful.

In my hand I hold one end of the brass spiral which we used in illustrating the propagation of sound through the air or other media. The other end of the spiral is fastened to a hook in the wall at the other side of the room. By properly timing the motion of my hand, I can cause the spiral to vibrate as a whole, giving, as you see, one long vibrating segment. Doubling the rapidity of motion of my hand, the spiral also is made to vibrate with twice the rapidity it did before. This time, however, it does not vibrate as a whole, but divides itself into two ventral segments, separated from each other by a stationary node. Trebling or quadrupling the rapidity of motion of the hand causes the spiral to divide itself into three or four segments, separated by a corresponding number of nodes. By moving the hand yet more rapidly, I can still further increase the number of subdivisions. There are ten of them now, each segment presenting the appearance of a gauzy spindle, and separated from its neighbor by a dark and apparently motionless node.

I say "apparently motionless," because, as a matter of fact, the node is never a point of no motion, otherwise the formation of vibrating segments would be impossible. But the amplitude of vibration of the node, in comparison with that of the ventral segment adjoining, is ordinarily so small that the node seems to be a point of absolute rest. By moving my hand through a very small distance, an inch or so, I can give to the ventral segment of the spiral an amplitude of motion equal to a foot or more. The same result might be accomplished if the part held in the hand were to have a transverse motion of only the fraction of an inch. The motion at the point clasped by the hand soon accumulates at the ventral segments to such an extent that their amplitude of vibration far exceeds that of the point held by the hand. And what holds true of the part grasped by the hand — which is in reality a node — holds true of the various nodes separating the ventral segments from each other.

At the end of the wire attached to the hook in the wall is also a node, for it is customary to regard both ends of a vibrating string as nodes. At the fixed end of the wire, however, no motion is necessary, for the pulse sent along the spiral from the hand is, on reaching this point, reversed in position and direction, and returned to its starting-point in accordance with the laws of reflection.

But in all cases, be it observed, the period of my hand must be the same as that of the vibrating spiral. If it is not so, if the impulses given are not properly timed, if the

period of the hand does not synchronize with that of the spiral, it will be impossible to produce the subdivisions alluded to, or to secure the perfectly uniform motion and beautiful results you have just witnessed. With a little practice, however, one can so time the motion of the hand as to bring out with comparative ease and readiness the various segmental motions that we have been illustrating.

Instead of imparting motion by the hand we might impart it by any mechanical contrivance whatever. But by far the most interesting and instructive method is that due to M. Melde, of Marburg. Tuning-forks were employed

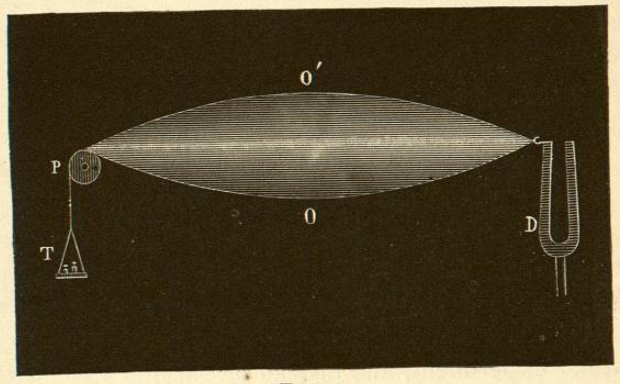

FIG. 45.

by him to generate the initial impulses necessary for the production of the vibrating motions which we have just been studying. And as his method at the same time illustrates in a most striking manner the formation of nodes and ventral segments, it affords us a new means of verifying the different laws of vibrating strings as determined by the sonometer.

Before you are four tuning-forks, C_2, C_3, G_3, C_4, whose frequencies are 128, 256, 384, and 512 vibrations per second. Their relative rates of vibration are therefore as the numbers 1, 2, 3, 4. To the prong *D* of C_2 (Fig. 45) is fastened, by means of a small hook, one of the extremities of a small silk cord, *O O′*. The other extremity passes over a pulley, *P*, and has attached to it a scale-pan,

T, for carrying weights, which can be increased or decreased at pleasure. Setting the fork in vibration, its motion is communicated to the string, and it is found that with a certain tension and a determinate length of string, the string vibrates as a whole.

Substituting the fork C_3, for C_2, and keeping the stretching weights the same, we find that the length of the string that will now vibrate as a whole is only one half of what it was for C_2. Employing in turn the forks G_3 and C_4, and retaining the same tension as before, we discover that the length of the strings required are respectively one third and one fourth of what was necessary for C_2. The relative frequencies of the forks, as stated, are as the numbers 1, 2, 3, 4. The relative lengths of the strings set in vibration by these forks are, as we have just seen, the reciprocals of these numbers, namely, 1, $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$. Hence, by this novel method we have corroborated experimentally the truth of the law already established, which is that *the number of vibrations is inversely proportional to the length of the string.*

We may now repeat the experiment in another way. This time we shall keep the tension constant, as in our previous experiment, and instead of varying the length of string for the various forks as before, we shall retain the same length of string for the four forks. With the fork C_2, the string vibrates as a whole, and gives, as you see, but one segment (Fig. 44). With the fork C_3, however, the case is different. The vibrations of this fork being twice as rapid as those of C_2, the cord must divide into two segments, as in Fig. 46, I, in order that it may synchronize with the increased number of vibrations by which it is actuated. Substituting G_3 for C_2, the string, in order to accommodate itself to the period of the fork, breaks into three segments, separated by two nodes, as in Fig. 46, II. In like manner, and for a similar reason, the fork C_4 would cause the string to vibrate in four segments, separated by three nodes. The number of ventral segments of the string is therefore in proportion to

the number of vibrations of the fork with which it is connected.

The number of ventral segments may also be varied by retaining the same fork and length of string, and changing the weights. If with any given weight the string vibrate as a whole, it will, with one fourth of this weight, divide itself into two segments, and with one ninth the weight it will form three segments. And in general, whatever the diminution of the weight, it will always be found that the number of ventral segments will be inversely proportional to the square root of the tension.

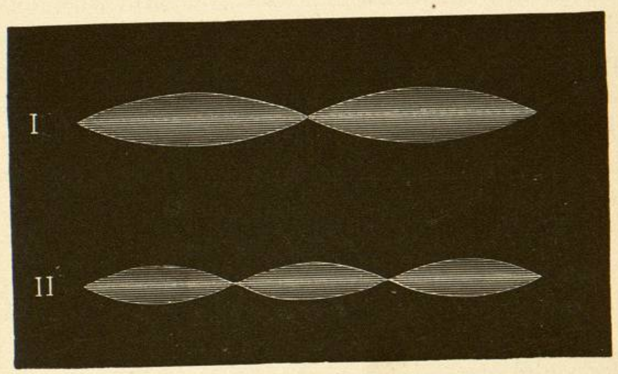

FIG. 46.

Taking again the forks C_2 and C_3, let us attach to them two strings of the same length and diameter. Stretching the string fastened to C_2 with a weight of one gram, it vibrates as a whole. Making the tension of C_3 equal to four grams, it also vibrates as a whole. The number of vibrations of C_3 is, as you know, just twice that of C_2, and yet in both cases we have but one ventral segment. But to obtain this result the tension of C_3 must be four times that of C_2. Hence the law established by the monochord: *the number of vibrations of a string is proportional to the square root of its tension.*

So far we have been considering the case of vibrations given to the cord by motions of the fork which are parallel with the length of the cord. Here we have the *longitudinal* vibrations of the fork changed into *transverse* vibrations in the cord. A brief examination of the manner in which the fork communicates its motion to the cord will reveal how this change of longitudinal into transverse vibration is effected. By referring to Fig. 45 one will see that when the prong *D* of the fork moves towards the pulley *P*, the cord will relax and reach the position *O*. When, however, the prong of the fork returns to its original position, the cord will do the same. A second excursion of the prong of the fork towards the pulley will cause the cord to move to *O′*, and when the prong returns to the point from which it started, the cord will again go back to its position midway between *O* and *O′*. The fork, therefore, executes two complete vibrations while the cord

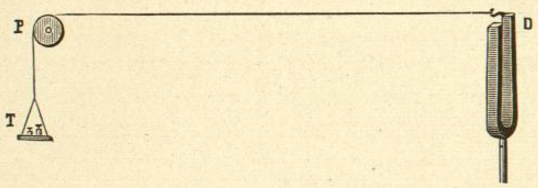

FIG. 47.

makes only one. If, then, the cord could emit a tone, such tone would be an octave below that produced by the fork.

If now we turn the fork through a right angle, as in Fig. 47, the vibrations will be executed in a direction transverse to that of the cord. Each time the fork moves backward or forward, it is followed by the cord. The number of vibrations of the latter are, in consequence, the same as those of the former. And if the frequency of the vibrations were high enough to render them audible, the notes given by the fork and the cord would be in unison.

To exhibit these phenomena we shall use a large electrically mounted fork devised by Mercadier. The advantage of using such a fork is that we can have vibrations of uniform amplitude continued for any length of time desired; and then, by regulating the strength of the current, we can obtain ventral segments of great or small width of swing, as may best suit our purpose.

Such a fork is before you. Attached to one of the prongs are two silk cords, one of which, *A*, is in the direction of the vibrations of the fork, and the other, *B*, is perpendicular to this direction. Both cords pass over pulleys, and are stretched by weights of equal mass. I now determine by trial what length the string *A*, with the tension to which it is subjected, must have, in order to vibrate as a whole. After some adjusting, I find the length is five feet. The vibrating portion of the string *B* is also made five feet in length. The forks are now set in vibration by causing the current from a good-sized Grenet cell to pass through the electro-magnet that is held in place between the two prongs of the fork. Immediately both cords take up the motion imparted by the fork. But behold! while *A* vibrates as a whole, and forms only one ventral segment, *B* undergoes instantaneous subdivision, and forms two segments, each of which is just one half the length of that furnished by *A*.

If we diminish the tension of *A* until a certain point, the string will form two segments in place of the one it had before. Lessening the tension of the string *B* in the same proportion, we have four segments in place of two. When we relax both strings still further, keeping the weights the same in both cases, *A* is thrown into three, and *B* into six, segments. Continuing to decrease the stretching weight of the two cords, we get in succession four, five, six, and more, ventral segments for *A*, and always, simultaneously, just twice the number of segments for *B*.

If now we attach a third cord, *C*, to the same prong to which the other two are fastened, and give it the same length and tension which *A* and *B* have, and place it midway between the two latter,—having it thus make an angle of forty-five degrees with its fellows, — it will, on being made to vibrate, have a compound motion made up of vibratory movements which characterize *A* and *B*. If the cords *A* and *B* vibrate in such a manner as to form one