and two segments respectively, one being the octave of the other, *C* will vibrate with a motion which is the resultant of the other two components. I, II, III (Fig. 48), exhibit some of the forms which the string *C* assumes when under the joint influence of the movements which actuate *A* and *B*.

If instead of having one and two segments, as in the previous case, *A* and *B* have respectively one and three segments, the superposition of these two motions, as seen in *C*, would have a new form. Such a form would distinguish the interval of the twelfth, as the preceding forms

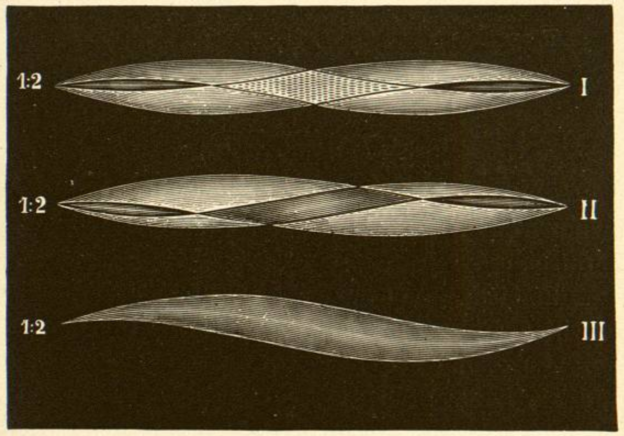

FIG. 48.

do that of the octave. In both cases the forms produced disclose the two component motions. With some experience, one could readily unravel forms of much greater complexity.

Before you is a most ingenious apparatus, contrived by M. Schwedoff, of Odessa, for illustrating the motions of cords such as we have just been investigating. It is far more convenient for the purpose than anything else with which I am acquainted, and besides it is universal in its action. As you will observe (Fig. 49), it is composed of a heavy metal stand supporting a board *P*, at one end of which is an electro-magnet, *E*. Above the board is a black

graduated bar of wood one metre in length. In front of the bar is stretched a white silk cord attached to *C* and to the little spring armature of the electro-magnet *E*. By means of a milled-headed screw, *T*, the tension of the cord can be modified with the greatest facility.

The current from a small Grenet cell near by is now allowed to pass through the magnet, and at once the little spring is set in vibration. In its present position the motion of this spring is parallel to the length of the string, and consequently the frequency of the spring is one half that of the vibrating armature. By loosening the screw that holds the magnet to the board *P*, and turning the magnet through an angle of ninety degrees, which can be done without changing the length of the cord, the vibra-

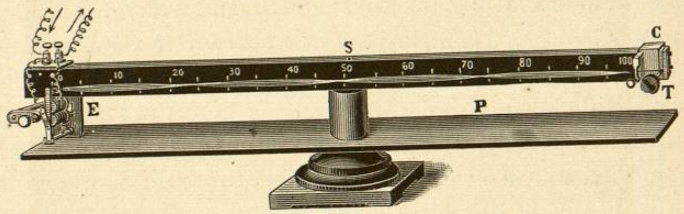

FIG. 49.

tions of the spring become perpendicular to the length of the string. This is at once revealed by the number of ventral segments, which is just twice what it was before.

Loosening or tightening the screw *P*, the number of segments is augmented or diminished at will. With the tension now applied to the string it vibrates as a whole. Gradually relaxing the tension, the number of segments increases, until there are now twelve or fifteen. Only with certain tensions, however, do we get perfectly defined segments. When the string has not the required tension, there is only an irregular flutter distinguishable, in place of the beautiful gossamer spindles and the stationary nodes otherwise observable.

By moving the magnet so as to give it a position intermediate between the positions which it occupied before, we get the compound motion afforded us by the large electric tuning-fork with which we were experimenting a few moments ago.

But the beauty and complexity of the forms now produced are much greater than any we have yet seen. By modifying the tension of the cord, or the position of the magnet, or both, we are able to produce an almost endless variety of gauzy forms of the most marvellous symmetry and delicacy.

Placing the magnet in such a position that it gives simple, well-defined ventral segments, and loading one section of the cord with a small white bead, we have at once a beautiful illustration of the effect of augmenting the density of the string. It vibrates in segments as before; but, as you will observe, the weighted segment is much shorter than the one that has no extraneous load to carry. Adding another bead, or replacing the one now on the string with a heavier one, would make the ventral segment which carries it still shorter. The relative lengths of the loaded and unloaded segments can be read off at a glance on the graduated metre scale before which the cord vibrates.

By means of our little white bead we are able also to make another interesting observation in connection with the manner in which strings vibrate, especially when under the influence of two or more vibratory movements.

When the string vibrates in a direction parallel to that of the cord, the latter moves almost in a vertical plane. When the spring's motion is at right angles to the length of the cord, the vibrations of the latter are in a plane that is nearly horizontal. Looking at the bead, brightly illuminated, when the cord is vibrating either in a vertical or a horizontal plane, its path is found to be a simple straight line. Turning the magnet around, however, so as to compound the cord's parallel and transverse motions, we get quite different results. Instead of moving in a straight line, the bead now describes curves of various forms and degrees of complexity. Sometimes we have circles, sometimes ellipses, sometimes the figure 8. These curves are

modified by the superposition of smaller vibrations on that answering to the vibration of the string as a whole, and then their outlines are broken by loops and sinuosities which give rise to constantly changing figures of indescribable beauty.

These figures were first observed by Dr. Thomas Young, who obtained them by allowing a ray of sunlight to strike a wire on the pianoforte. The point thus illuminated described, when the wire was caused to vibrate, figures which were in many cases identical with those obtained with the apparatus before you. Some of the curves given under such circumstances are shown in Fig. 50. We shall see in the sequel that the quality of tone depends on the form of the sonorous wave. It is manifest, then, that even when

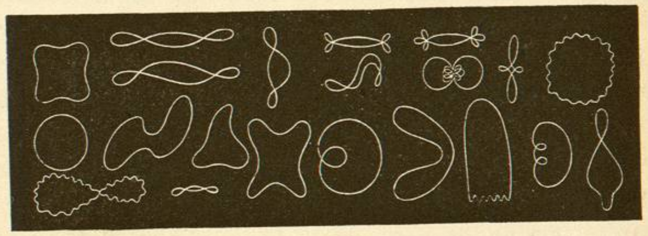

Fig. 50.

the tension, length, and material of a vibrating string remain the same, the tones elicited from it may vary in quality, just as its vibratory motions may vary. This is strikingly illustrated by the tones obtained from a violin by a beginner and by a virtuoso. Although the string emitting a given note may remain unchanged as to tension, length, and material, the sound produced is in the one case peculiarly rasping and scratching in character, while in the other case it is remarkable for great purity, steadiness, and volume. The bowing, and the motions of the string consequent on the bowing, are the sole causes of the great difference in the quality of the tones in question.

Thus far we have been considering the *transverse* vibrations of cords. We may now study their *longitu-*

dinal vibration, and learn in what respect one kind differs from the other.

The sonometer affords us a ready means of obtaining and examining these longitudinal vibrations. Taking a piece of chamois leather on which is strewn some finely powdered resin, and passing it to and fro along the wire, I cause it to yield a loud pure note. Placing the movable bridge in the centre of the wire, and rubbing one of the halves of the wire, I elicit a note that is an octave higher than that elicited when the string was excited as a whole. Rubbing in succession one third and one fourth the length of the wire, we obtain the twelfth and the fifteenth (or second octave) of the fundamental. We thus find that the law for longitudinal vibrations is the same as that for transverse vibrations; namely, that *their number is inversely as the length of the vibrating string.*

Let us change the tension of the string first by augmenting, and then by diminishing, the stretching weight. This, as you observe, has no appreciable effect on the pitch of the note emitted. The reason is that longitudinal vibrations do not depend on the tension applied to the wire, unless the tension be very great, but on the elasticity of the wire itself. The tone, moreover, within certain limits, at least, is independent of the diameter of the wire or string. These facts can be well illustrated with the three catgut strings of a violin. Passing the bow successively along the direction of these strings, we observe no appreciable difference in the pitch of the tones produced. And unless the tension is very greatly modified, it is impossible to detect any difference of pitch due to tension. Thus the E_4 string of the violin gives, when set in longitudinal vibration, a note approximating F_6. If now the tension of the string be so diminished that the note due to its transverse vibration becomes E_3, — a fall of an octave, — we shall find that the pitch of the note due to the longitudinal vibration of the string is almost the same as it was before. As a matter of fact, the fall is hardly equal to a comma, — the smallest interval used in music.

From the fact that a cord cannot execute transverse vibrations without undergoing a change in length, it is obvious that such transverse vibrations must in all cases be accompanied by longitudinal vibrations. These longitudinal vibrations may sometimes be recognized in the A string of the violoncello.

More than this. It is found that in addition to the transverse and longitudinal vibrations executed by all strings, whether bowed or plucked, they likewise have a third motion, which Chladni called *turning* or *rotary*. The vibrations peculiar to this motion are executed through a small arc of a circle around the axis of the string, and are alternately in opposite directions. They are ordinarily known as *torsional* vibrations, because they are due to a greater or less twisting of the string. But such vibrations have a mathematical rather than a musical interest.

As will be remarked, the notes due to longitudinal are much more acute than those due to transverse vibrations. Hence the importance on the part of the violinist of using the bow in such a manner as to produce only transverse vibrations; as in the event of his exciting longitudinal vibrations simultaneously with the former, the result would in most cases be in the highest degree discordant.

From what has been said regarding the vibration of strings it is manifest that there may be an infinite variety of tones evoked from the same string. But as these tones differ from each other so slightly, the majority of them appeal even to the most sensitive and highly cultivated musical ears as one and the same sound. It is as impossible for the musician to distinguish the various tones produced as it is for the geometer to analyze the amazingly complex curves to which this infinitude of tones corresponds.