CHAPTER VII.

RESONANCE AND INTERFERENCE.

SO far we have been dealing with single, individual sounds. We have, it is true, had occasion to listen incidentally to two or more sounds simultaneously produced; but I have reserved a more detailed account of such concomitant sounds for the present lecture. To-day I shall speak of what is known as resonance, and its correlative, called interference, of sound. Some of the most practical and important consequences to musicians follow from the first of these phenomena, and some of the most interesting and paradoxical results arise from the second.

To understand the nature and effect of resonance, it is important at the outset to appreciate properly the cumulative effect of feeble impulses, when suitably timed, in moving comparatively large masses of matter. We have before had occasion to employ various contrivances to illustrate by slow mechanical motions the much more rapid movements of sonorous bodies; and a similar procedure now will enable us better than anything else to comprehend the full import of the various and striking phenomena embraced under the general head of resonance.

On a strong wooden frame is suspended by a cord a good-sized cannon-ball. Attached to the ball is a fine cambric thread, which is capable of supporting only a small fraction of the weight of the ball. I give the string a very gentle pull, and by this means there is imparted a slight, almost an imperceptible, motion to the ball. By properly timing these slight pulls, always pulling when the ball is coming towards me, and never when it is moving in the opposite direction, I can cause the ball to swing

through quite a large arc. The pulls, however, must be isochronous; that is, they must be of the same period as the ball which oscillates as a pendulum. Should I attempt to pull the string when the ball is moving away from me, it would at once snap in twain. The force now stored up in the moving ball is so great that it can only be overcome by using a much stronger cord, or by gradually counteracting it by slight periodic pulls with the cambric thread when the ball is receding. This experiment shows us that quite large masses of matter can be put in motion by very slight impulses, and that these same slight impulses, when periodically applied, are sufficient to bring again the moving mass to a standstill.

We may vary the experiment by imparting gentle impulses in a different manner. Instead of using fine thread, we have recourse to slight periodic puffs of air from the mouth. "But," you will exclaim, "such an insignificant force is utterly inadequate to move such a heavy mass." So it seems. But let us try.

Having found out by the foregoing experiment the period of the ball, I know how to direct my breath against it. I blow against it once, and again, and still again, and there is scarcely any perceptible movement. I continue to direct little puffs of air against it, and in a few moments the motion becomes very considerable. Should the impulses directed against the ball be improperly timed, the effect produced would be little, if anything at all. And, as in the first experiment, I can bring the ball to rest by little puffs of air impinging against it every time it comes towards me.

Allow me to modify the experiment still further. Instead of the cannon-ball we may now use a smaller ball, also of iron, as a pendulum. Close to it, and from the same support, is suspended by the same length of string another ball identical in size and material. But the size and material of the balls is not of so much importance as that the strings supporting them should be of exactly the same length. We have here what are in reality two pendulums whose periods of vibration are isochronous. When one of them is made to swing to and fro, observe what takes place. The other one remains at rest for a moment; but soon you perceive a slight oscillation, which eventually becomes as great as that of the first ball.

How do we explain this? Is there an invisible string or breath of air to cause the first to act on the second? No; but the vibratory movement of the one is communicated to the other in a no less effective manner. In this case the vibrations — they are very slight, it is true — are conveyed through the beam that acts as the common support. The vibrations are so slight as to be imperceptible to sight or to touch, but they are none the less real and operative.

Clock-makers have long known of these forced vibrations. They were first observed by the famous Huygens, the inventor of the pendulum clock, over two hundred years ago. It is well known, for instance, that two clocks, whose rates are slightly different, will, when brought near together on the same table or other support, keep the same time. The pendulum of the more rapid clock forces up the speed of the slower one, and compels it to move at the same rate. But while the speed of the latter is advanced, that of the former is retarded correspondingly. If, however, there is any material difference in the rates of vibration of the two clocks, this effect will not take place. This fact can be easily illustrated by means of the two pendulums with which we have been experimenting.

We will lengthen the string of one of them, and then set it in vibration. As you perceive, it has no effect on the other. But if the string be still more elongated, and made twice or three or more times as long as the string of the other pendulum, the result will be different. By setting the longer pendulum in motion, it will after some time cause the shorter one to vibrate also. In this case the former imparts an impulse to the latter, not at every swing of the latter, but at every second or third swing, according to its length. The number of impulses communicated being then only one half or one third as numerous as when the pendulums were of equal length, the amount of motion set up in the shorter pendulum will be proportionately less.

In the preceding experiments a large ball was moved by a small string or by small puffs of air. A similar effect to that just produced by one pendulum acting on another of different length, would be obtained by pulling the ball or blowing against it every second or third vibration. But the result secured would obviously be correspondingly less than when the motion is accelerated at each vibration. In all these experiments, however, the important fact to bear in mind is that the impulses communicated, whatever their nature, and whatever their number, must be of the same period — or multiple or submultiple of the period — as that of the vibrating bodies themselves, and must take place in the same phase.

There are many familiar instances of synchronous motion produced by regularly recurring impulses. The aërial pulses generated by certain organ-pipes shake the windows and pews and columns of a church. A large bell set swinging by the properly directed efforts of a single boy will in turn convey a very marked vibratory movement to a massive tower or belfry. We have all observed how a six or seven story building may be caused to vibrate from cellar to garret by the passage of a carriage over the cobble-stones of the street. A company of soldiers in crossing a bridge is made to break step, in order to prevent the injurious results that might follow from forced vibrations. Hence also the reason of the prohibition to drive over a bridge "faster than a walk."

Lord Rayleigh, in his admirable *Theory of Sound*,[1] remarks that "illustrations of the powerful effects of isochronism must be within the experience of every one. They are often of importance in very different fields from any with which acoustics is concerned. For example, few things are more dangerous to a ship than to lie in the trough of the sea under the influence of waves whose period is nearly that of its own natural rolling." Indeed, so great

[1] Vol. i. p. 61.

may be the cumulative effects of periodic impulses, however feeble, that a distinguished English physicist has not hesitated to declare that he could, with a suitable appliance, break an iron girder by projecting against it ordinary pith-balls.

We are now prepared to pass from the visible mass-motions with which we have been dealing, to the invisible molecular motions, and the almost invisible segmental mass-motions which generate sound.

On the table are two tuning-forks, *A* and *B*, on a resonant case, each fork giving exactly the same number of vibrations per second, 512. The forks are placed a foot apart, with the openings of the resonant boxes facing each other, and one of the forks is then excited by a violin-bow. But no sooner is one, *A*, set in vibration than we hear the other, *B*. This is a most startling result; and yet only what should have been expected after our experiments with pendulums.

But how does one fork convey its tremors to the other? Not through the material of the table, as the vibrations of one pendulum were conveyed to the other through their common support, because, as you will notice, the resonant cases are so constructed that this is impossible. Attached to the bottom of each case are two caoutchouc tubes that effectually destroy any vibrations that might otherwise pass from one fork to the other through the material of the table. The only means of communication therefore is the air. But can the air transmit impulses with such force as to give rise to the loud sound you have just heard in the second tuning-fork, *B?* Yes; but only under the same conditions under which one pendulum can cause another to oscillate.

The first condition is that the two forks must be in unison. When *A*, then, is set in vibration it generates a series of air-pulses which are conveyed to *B*, and these, impinging against it, throw it into vibration. From the fact that the forks are isochronous, each impulse from *A* strikes *B* when it is in the same phase; that is, in the same position and moving in the same direction with reference to its point of departure. *A* then generates in the air waves of

condensation and rarefaction, and the air-pulses thus formed impinge against *B* at the rate of 512 per second. These aërial impulses taken separately are very feeble; they may be all but infinitesimal; but the number and absolute periodicity of the impulses are capable by their cumulative effect of producing results that would be deemed incredible, if not impossible.

The forks are separated still more, one of them now being full twenty feet away from the other. The bow is again drawn across *A*, and its distant companion at once responds. Indeed, so quick is the answer that *B* is heard almost as soon as *A*. We might separate them a hundred feet or more, and the result would still be the same.

With two similar tuning-forks executing 128 vibrations per second, and placed with the open ends of their resonant cases facing the opposite ends of the conduit of St. Michel, in Paris, Dr. Koenig was able, by exciting one, to cause the other to resound very distinctly, although more than a mile distant. When we reflect that the density of steel is more than six thousand times that of air, the fact that it can be thrown into sonorous vibration, and at such a distance, by such insignificant impulses as are brought to bear on it, is truly marvellous.

But one fork will not only set another into vibration, it will also communicate its vibratory motion so completely that the latter can be made to resound as loud as the former, and in some cases even louder. This, however, will take place only when the two forks are perfectly isochronous.

Retaining the two forks, *A* and *B*, which we have been using, it is easy so to vary the experiment we have just made as to secure a more surprising result than any we have yet witnessed. I cause *A* to vibrate as before, and then immediately damp it by placing my fingers on the prongs. You now hear *B* vibrating alone. I take my fingers off *A*, and it is again excited by the vibrations of *B*. I damp *B*, and *A* is now heard vibrating as before, but with diminished intensity. I again damp *A*, and once more *B* is heard. I can thus cause *A* and *B* to communicate to each other their vibratory motion several times in succession, the sounds continuing quite audible, though the two forks may be at different ends of the room, or at even more considerable distances from each other.

This remarkable property that one sonorous body has of impressing its vibratory motion on another sonorous body is called *resonance*, or *consonance*. Resonance is the term more generally employed, as consonance is also used to designate the harmonious effect produced by the simultaneous sounding of two or more musical notes. When the notes produced are in perfect unison, as is the case in those generated by the tuning-forks *A* and *B*, the sound excited in *B* by *A* is sometimes spoken of as a *sympathetic sound*, being caused by what are called *sympathetic vibrations*. The German word *Mitschwingung*, co-vibration, expresses admirably the character of the vibratory motion that gives rise to resonance, or sympathetic sounds.

I would not, however, have you conclude from what has been said that resonance requires absolute periodicity in the source of sound and in the body in which the sound is originated by influence or co-vibration. To obtain such marked responsive effects as you have just witnessed in the forks *A* and *B* perfect periodicity is of course essential. But if these forks differed from each other by a very few vibrations, resonance could still be excited in *B* by sounding *A*. The response, however, would be much slower and much feebler. Any great difference in the frequency of the forks, barring an exception I shall presently speak of, would destroy resonance entirely.

Let me illustrate. Before you is a glass jar (Fig. 117) twenty inches in depth. I hold over it a tuning-fork, C_3, making 256 vibrations per second, but as yet no sound is audible. Water is slowly poured into the jar, and soon you perceive a gradual augmentation of sound. When, however, the water reaches a certain height the note of the fork attains its maximum intensity. If now more water is poured into the jar the sound rapidly dies away, until it

becomes quite inaudible. Pouring out some of the water, and thereby lengthening the air-column, the sound is again reinforced. It is found, however, that for this particular fork the water must always be at the same height in the jar in order that the reinforcement of sound may be at its maximum, or, what amounts to the same thing, in order that we may have the most perfect resonance. If we diminish or increase the amount of water, we do not at once destroy resonance completely, as is so often asserted, but we lessen it in a very marked manner. Beyond certain limits it entirely disappears.

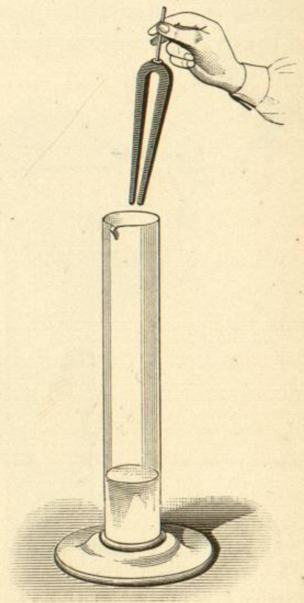

Fig. 117.

By means of a series of carefully made experiments Koenig has shown that the limit of departure from unison at which the reciprocal action of two tuning-forks ceases to be perceptible is proportional to the frequencies of the forks. Thus the intensity of resonance for the forks C_3, C_4, C_5, C_6, C_7, was about the same when they differed from unison by 2, 4, 8, 16, 32 vibrations per second, — that is, when they differed from unison by 1 vibration to every 128 vibrations per second.

Let us now try another fork, C_4, making 512 vibrations per second. Bringing it over the mouth of the jar, we find that the greatest resonance is obtained when the air-column is just one half the length of that which responded with greatest intensity to C_3. Trying C_5, whose frequency is 1024, the vibrating air-column must again be divided by 2 in order to secure the greatest augmentation of sound. We might try any number of forks with different rates of vibration, and we should find that in each case only one certain length of air-column in the jar would be capable of exciting the maximum of sympathetic resonance.

Measuring the lengths of the air-columns resounding the loudest to the forks C_2, C_3, C_4, we find them to be 13, 6½, and 3¼ inches, respectively. These measurements agree very closely with what calculations, based on the known rates of vibrations of the forks, and the velocity of sound in air at the temperature of this room, should lead us to expect. They show also that the lengths of the most effective resonating air-columns are inversely proportional to the frequencies of the tuning-forks used in our experiments.

If we examine the matter with a little attention, we shall find that we have here exactly the same condition of things as obtained with the two unisonant tuning-forks. The air-columns in the glass jar resound most perfectly to the different tuning-forks only when their periodic vibrations are the same as those of the forks.

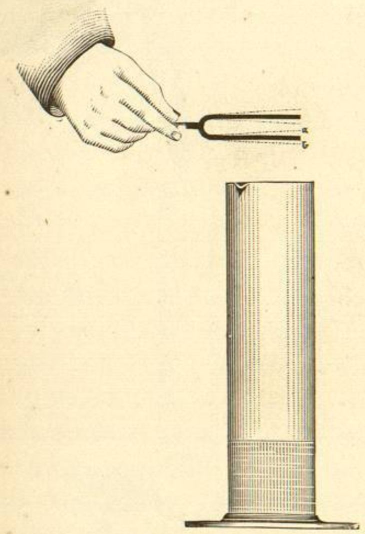

FIG. 118.

While the prong of the fork is moving from *a* to *b* (Fig. 118), the condensation produced runs down to the surface of the water, and is reflected back to *a* just as the fork is ready to return to *b*. The accompanying rarefaction follows the condensation in the same manner, but in a reverse order; viz., going downwards while the condensation is coming upwards. The waves both of condensation and rarefaction are so timed that their upward and downward motion are in perfect unison with those of the fork. If there should be a slight difference in the periods of the air-

column and the fork, a consequent diminution of resonance would be the result, just as we saw is the case when two tuning-forks differ from each other by a few vibrations.

The foregoing experiment affords an explanation of the office of the resonant boxes attached to many of the tuning-forks before you. It is to heighten resonance, and it does so the more effectually the more nearly the periodic times of fork and box are in unison. As a matter of fact, the resonant chamber is not, as a rule, constructed so as to be perfectly in unison with its accompanying fork, for the

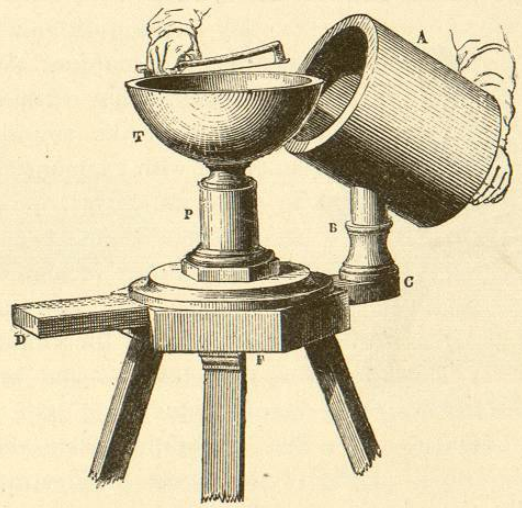

FIG. 119.

reason that when perfect resonance exists, the sound of the fork dies away much more rapidly than when there is a slight difference in the periods of vibration.

The cause of this is obvious. When the resonant case and the air contained within it vibrate in perfect unison with the fork, the amplitude of the vibratory motion both of air-particles and box is at its maximum. But this intensity of vibration is kept up only in virtue of the energy imparted to it by the vibrating fork. The greater the resonance, therefore, and the closer the approximation of the periods of fork and resonant case, the greater the amount of energy required, and the shorter the duration of the sound produced.

Savart has devised a very beautiful apparatus for exhibiting the phenomena of resonance. It consists of a bell, *T, P,* mounted on a stand, *D, F, C* (Fig. 119), accompanied by a resonant tube, *A, B,* in which there is a movable piston. Agitating the bell by means of a resined bow, it at once bursts forth into sound. When the opening of the resonator is brought close to the rim of the bell, the sound is considerably intensified. By moving the piston in the tube, the sound is made to vary in loudness according to the position which the piston occupies. When it reaches one certain point, however, the sound comes forth with extraordinary volume and power, and then resonance is most complete. This climax of sonorousness indicates, as you are now aware, that the vibration periods of bell and resonator are equal.

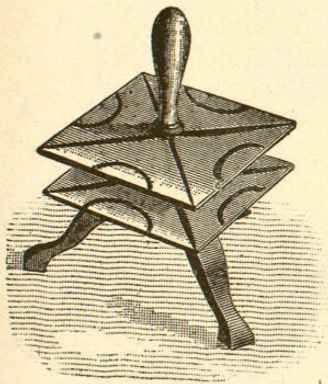

FIG. 120.

Vibrating plates can also be made to illustrate very beautifully the phenomena of sympathetic vibration.

Before you are two square brass plates (Fig. 120), one of which is mounted on a cast-iron support, while the other is attached to a simple handle. They are so constructed that when they give the same figure the notes emitted are as nearly as possible in unison. Fine sand is strewn over both plates, and grasping the one with the handle, I excite it with the bow. At once a characteristic Chladni figure is formed. Holding this plate, while yet in vibration, above the other, a figure is designed on the lower plate that is an exact duplicate of the one on the plate in my hand. The periods of the two plates being the same, one takes up the vibrations of the other even when some distance apart.

Membranes are particularly susceptible of co-vibration, on account of their lightness, extent of surface, and facility of subdivision. They are especially sensitive to shrill sounds. The note of a whistle or of a small bell will throw a membrane into violent agitation even when several yards distant. Sand strewn on the membrane at once shows the existence of vibrating segments similar to those exhibited by vibrating plates.

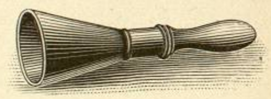

FIG. 121.

An elliptical bell, like Fig. 121, emitting a very strident note, is a most convenient instrument for the production of figures on membranes. Thus a circular India-rubber membrane (Fig. 122), which can be readily adjusted to various degrees of tension, is now tuned to the note given by the bell. On strewing the membrane with sand, and drawing the bow across the edge of the bell, a harsh, creaking sound is heard, which causes the sand immediately to arrange itself in the most complicated patterns.

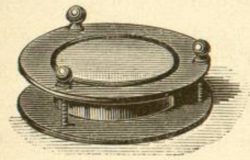

FIG. 122.

Mr. Sedley Taylor has devised a clever method of showing the manner in which sound affects liquid films. The apparatus used consists of an air-chamber (Fig. 123) that may be covered with metal plates, in which are circular, square, or triangular openings. A tube through which sound-pulses may enter is attached to the side of the air-chamber. If now a soap-film be stretched over the openings in either of the plates, and projected on a screen, we obtain, by speaking or singing into the resonant cavity of the apparatus, the most gorgeous kaleidoscopic effects conceivable. Every note, and

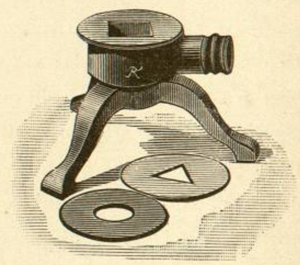

FIG. 123.

every vowel sounded on the same note, instantly evokes the most marvellous figures, tinted with all the delicate hues of the rainbow. There is nothing in the whole range of physics more beautiful than the phenomena here exhibited, — nothing that discloses more strikingly the complicated nature of sonorous vibrations, and portrays more clearly those infinitesimal differences of quality of sound that entirely elude even the most sensitive ear. The forms and patterns that rapidly succeed one another, with all the varying changes of tone, are as exquisite in design as they are magnificent in chromatic display; and the agent employed in the experiment, an ordinary soap film is as simple as the exhibition is superb.

It is resonance that gives to musical instruments all the value they possess. Without a resounding body in connection with the origin of sound, the note produced would be scarcely audible. In violins, harps, and pianos, for instance, the sounds are excited by vibrating strings; but as they come forth from the strings alone, they are almost, if not entirely, imperceptible. It is only when they are reinforced by suitable sounding-boards that they acquire sufficient volume for the purposes of music.

You will observe, however, that the resonance of the sounding-boards of musical instruments has a much wider range than that of the resounding bodies of which we have been speaking. Unlike the glass jar, and the resonant case of the tuning-fork, which respond to only one note, the sounding-boards of musical instruments reinforce all the notes within their compass. But besides this general resonance for all notes there is a particular resonance corresponding to some one special note. And, strange as it may seem, this special resonance in musical instruments is something that is, as a rule, passed unnoticed even by the most accomplished musicians.

Thus the proper tone of the violin is C_3, as can be shown by blowing across the "*f* holes," or by sounding in their widest part a properly tuned fork. The viola and the violoncello have likewise proper tones, which can be

evoked in the same manner. Fortunately, however, these proper notes, on account of the peculiar construction of these various instruments, are not so prominent as one would expect them to be. If they were, they would very seriously affect the quality of the scale, as played on stringed instruments. As it is, special attention must be directed to them in order that they may be heard at all.

Sounding-boards enhance the volume of sound emitted by musical instruments by exposing a larger vibrating surface to the air, and, in many instruments, by simultaneously throwing into vibration a large mass of air contained within the resonant body. The process in all cases is somewhat complex. In the violin, for instance, the string is first excited by bowing. Its vibrations are then communicated by the bridge and post to the belly and back of the instrument, and to the mass of air intervening between these two highly sonorous pieces of wood. The body of the violin and the contained air being thus agitated as a whole, the vibratory motion superinduced is finally communicated to the circumambient air.

There are still other instances of resonance as illustrated by musical instruments to which I must advert. They are as interesting as they are instructive, and so simple that they can be studied by any one.

Press down gently one of the keys of a pianoforte so as to raise the damper, without, however, causing the hammer to strike the wires, and sing loudly the corresponding note. At once the note is echoed back with surprising distinctness. That it has been generated by the sympathetic vibration of the uncovered string is proved by allowing the damper to fall back, when the sound is immediately extinguished. Raise the damper again, and pluck sharply one of the three strings that combine to produce the note before sounded. After a few seconds damp this wire with the finger, and you will hear the other two continuing the same sound. They have been thrown into sympathetic vibration by the first, which has been tuned in unison with them. We can easily assure ourselves of this fact by