times escape our mind, unless our attention be particularly drawn in their direction.

I hold a tuning-fork in my hand, and on turning it round near my ear I find that there are four positions of maximum loudness, and four positions in which no sound whatever is audible. Sounds are heard when the faces of the fork or the sides are turned towards the ear, and silence — interference — ensues when the intermediate points or edges of the fork are directed towards the auditory passage. At the points between those where sound attains the maximum of intensity and those where it entirely ceases, there is partial interference, and consequently a variation of sound from its maximum to zero.

These phenomena, first remarked by the celebrated Dr. Thomas Young, can be shown more strikingly, and in such a manner as to be audible throughout the room, by reinforcing the sound by means of a resonator accurately tuned to the period of the fork. As the fork I hold in my hand is revolved before the large aperture of this resonator, you notice the varying changes in the intensity of the sound, now loud, now medium, now quite imperceptible. During each revolution, as you observe, there are four periods of maximum intensity of resonance, and similarly four periods of absolute silence.

It is easy to show that this variation of intensity is produced by interference of sonorous vibrations. All that is necessary to do this is to cover one of the prongs of the fork with a small paper tube, which partially destroys the undulations from that prong, and consequently prevents their interference with the vibrations of the other prong. At once the sound bursts forth loudly, where before there was no sound at all. Uncovering the prong, the sound immediately dies away, and all is silence. Experimenting in a like manner with the other prong, we should obtain a similar result. Thus we demonstrate the existence of a most paradoxical fact, — the fact that under certain conditions sound added to sound gives silence. The demonstration in this case is complete. Sonorous vibra-

tions in different phases are mutually destructive, and when of equal period and intensity have no effect on the tympanum of the ear, and consequently excite no sensation in the brain.

In the experiments hitherto made you have observed that the sound is very feeble when the fork is made to vibrate alone. This is, in part, due to interference, as an examination of Fig. 132 will make evident. This pictures the tuning-fork as seen from above, the extremities of the prongs being represented by *a* and *b*. During their outward swings towards *c* and *e*, waves of condensation are formed by the prongs at *a* and *b*, which move in opposite directions. At *d* and *f* the sonorous impulses are always in the same phases, and sound here is at a maximum. The arrows indicate the alternate and the opposite movements of the prongs of the fork. Waves of rarefaction are generated in the space between the prongs of the fork; and as both the condensed and the rarified waves have the same velocity, they will meet along the dotted lines *g*, *h*, *i*, *k*; and since they are of equal period and intensity, one will exactly annul the effect of the other. Hence along these lines, which Weber has shown to constitute equilateral hyperbolas, there is total interference, and no effect whatever is produced in the organ of hearing.

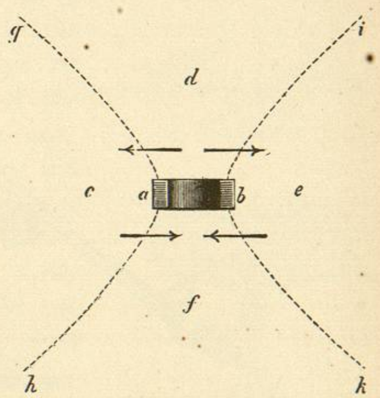

Fig. 132.

That the air under such circumstances remains in a state of rest can be most conclusively proved by several cleverly devised experiments.

As one of the proofs, I shall first show you a very striking experiment devised by Hopkins. For this purpose we may employ one of the round brass disks used in exhibiting Chladni's figures, and a forked metal tube, Fig. 133, which is supported above the disk. The tube *C* is adjusted to a given note produced by the disk, and as soon as the disk is set in vibration we obtain, on strewing it with sand, a characteristic figure. When the prongs, *D E*, of the fork are above two alternate sections, like *A* and *A′*, or *B* and *B′*, the air in the tube is violently agitated, as is shown by the action of the sand strewn on the membrane on the top of the tube. When, however, the two branches of the tube are over adjacent sectors, as

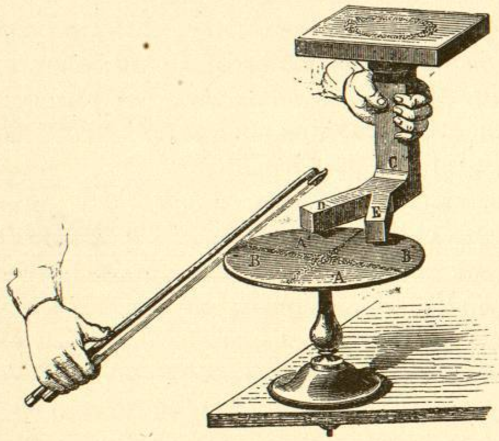

FIG. 133.

A and *B*, or *A′* and *B′*, the air in the tube is at rest, for in this case there is not the slightest vibration imparted to the membrane, as the sand remains undisturbed.

The reason for these opposite effects is obvious. When the branches of the fork are over alternate sectors the vibrations excited in them are in the same phase, and the vibrations of the air-column in the tube are equal to the aggregate vibrations of the two branches. But when the fork is so placed that its branches are over adjacent sectors, the vibrations excited are in opposite phases. One sector of the plate moves upward, while the other moves downward; hence a condensed and a rarefied pulse enter the tube simultaneously, — one neutralizing the effect of the

other. Thus the result, as might have been expected, is total interference.

Lissajous, to whose ingenuity we are indebted for so many beautiful experiments in acoustics, illustrates the same phenomenon in an equally interesting manner. Instead of a forked tube, he employs a disk (Fig. 134 *B*), cut into sectors, the number of sectors being one-half as great as those formed by the vibrating plate, *A*, used in connection with it. If the upper disk, for instance, has three sectors, and the one underneath, as indicated by the sand figures, is divided into six, then the pulses emanating from three of the alternate sectors of the lower disk will be quenched by the corresponding sectors of the upper disk. In this wise, condensations and rarefactions are prevented from neutralizing one another, and a strongly reinforced sound is the consequence. Only vibrations in the same phase are permitted to enter the ear, those of the opposite phase being suppressed. By rotating the upper disk, we at once hear risings and fallings of sound, according as the proper ventral segments of the vibrating plate are covered or exposed.

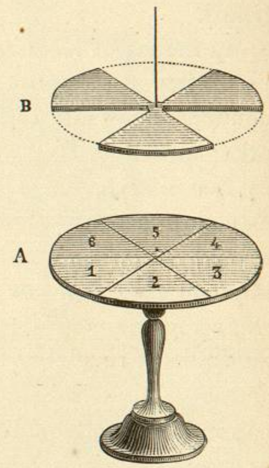

FIG. 134.

Interference can also be shown by means of organ-pipes. On a small wind-chest are mounted two unisonant pipes (Fig. 135), giving the note C_3. When the wind-chest is connected with the bellows, and air is admitted into one of the pipes, you hear a full mellow note. I next allow air to pass into the second pipe also. Now, it would seem that when both pipes are connected with the wind-chest, we should have a sound of double the intensity of that emitted by either pipe alone. Such, however, is not the case. The fundamental note of each pipe has been so weakened that at a short distance they are inaudible. All that you now hear is a rustling noise due to the escape of air from the embouchures of the pipes, and the octave of the fundamental, which still remains unaffected. The cause of this is that the wind in the wind-chest, by reason of the varying pressure in the pipes, passes into the two pipes alternately, and thus produces condensation in the one, and rarefaction in the other. These condensations and rarefactions being equal in intensity and opposite in phase, neutralize each other as respects their action on the surrounding air, and the result is that it remains at rest, and no sound is heard.

By means of Koenig's manometric flames we are able to prove beyond a doubt the existence of these conditions of condensation and rarefaction which alternate with each other in the pipes. The two pipes just used are replaced by two similar ones (Fig. 135), provided with manometric capsules at their middle nodes. These capsules are connected by rubber tubes to two jets placed one above the other in a vertical line and arranged in such a manner that when the gas is ignited, both flames will be reflected from an adjacent revolving mirror. When the mirror is rotated, and no sound is issuing from the pipes, we perceive two continuous bands of light, one above the other. As soon, however, as air is admitted into both pipes, these bands become at once similarly serrated, except that the elevations and depressions of the two bands alternate, the tooth of one corresponding exactly to the indentation of the other. Thus the evidence of the existence of pulses of condensation in one pipe, while opposite pulses of rarefaction prevail in the other, is as conclusive as the experiment on which it reposes is beautiful.

But supposing that while air is forced into both pipes, as in the preceding experiment, we connect the two capsules with a common jet, what will take place? A little reflection will tell us that there will be no agitation of the flame, for the simple reason that the pulses reaching the jet are in opposite phases, and therefore neutralize one

another. We make the necessary changes in the connections, and on admitting air, as before, into the two pipes, and revolving the mirror, the result is just as was anticipated, — perfect quiescence on the part of the flame, as indicated by the continuous band of light pictured in the mirror. The physical basis of sound, as we have learned,

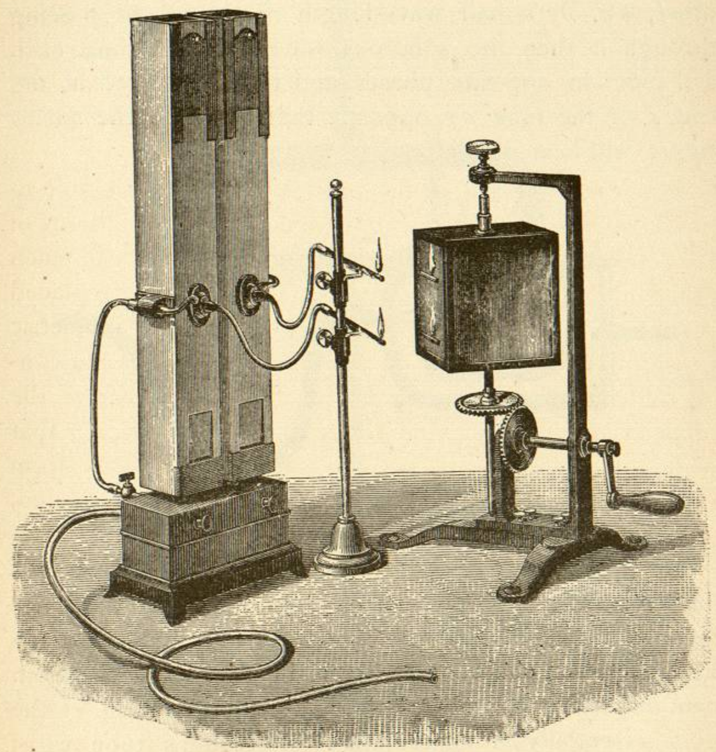

FIG. 135.

is motion. Here, as is evidenced by the aspect of the flame-image, there is no motion, therefore no sound.

Norremberg, acting upon a suggestion given by Sir John Herschel, demonstrated the existence of interference in a still different manner. He caused sonorous vibrations to enter a tube with two branches of different lengths, which afterwards reunited. Here is shown a simple form of this apparatus (Fig. 136), as modified by Quincke. A sound-wave enters one end, *o*, of the apparatus, and on reaching the two branches of the tube at *b*, is divided, to be again united on reaching the other end, *e*. If the branches are of equal length, the ear placed at one end, *s*, will hear undiminished any sound emanating from the other end. If, however, one of the branches, *c p q f*, is longer than the other, *a d*, by a half wave-length of the sound passing through it, then the sonorous waves, on reuniting at *e*, will meet in opposite phases, and the ear placed at the end, *s*, of the tube, *n r*, opposite that at which the sound enters, will hear nothing.

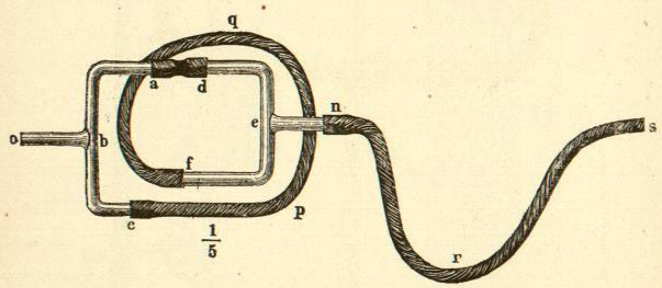

FIG. 136.

One may have a pleasing modification of this experiment by availing himself of Kundt's device, with which you are familiar, of showing, by means of a light powder, the presence of sonorous vibrations in tubes. The instrument employed for this purpose is before you (Fig. 137). It is essentially a combination of Kundt's tube with Quincke's apparatus. If the branches, *h g c* and *h o f n c*, of the tube are so adjusted as to differ from each other by exactly a half wave-length, or some odd multiple of a half wave-length, a sound excited by friction of the rod, *b a*, in one end, *d*, of the instrument will not give rise to any disturbance of the light powder in the other end, *h k*, of the tube. But should they, by sliding the tube *f* from *o n* to *o′ n′*, be made to differ from each other by more than a half wave-length, or some even multiple of a half wave-

length, the characteristic dust segments will at once appear, with greater or less distinctness, at the end of the tube opposite to that at which the sound-vibrations are generated.

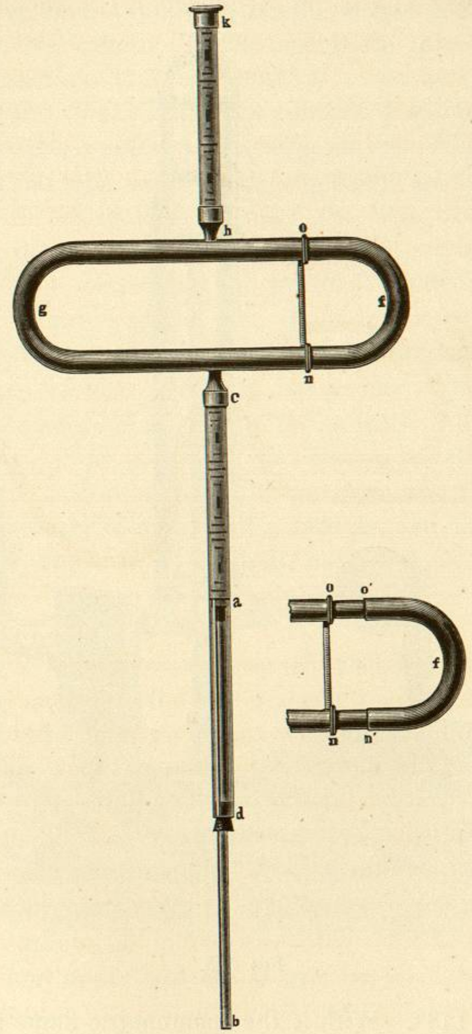

FIG. 137.

But probably the most elaborate and comprehensive method of exhibiting interference is that employed by

Koenig. It is essentially the same in principle as that proposed by Herschel, but in accuracy of results obtained is immeasurably superior to anything of which this great philosopher ever dreamed. Such an instrument is before

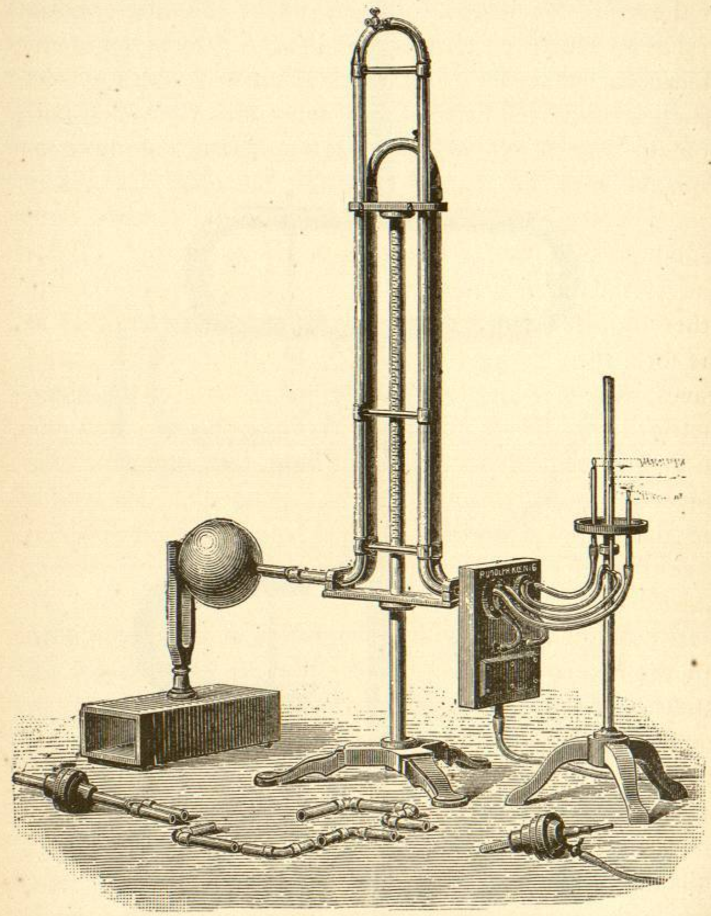

FIG. 138.

you (Fig. 138). With it the manometric flame fulfils the same function that is assigned to the ear in Quincke's apparatus, and subserves the purpose of the powder in Kundt's tube; but its indications are far more delicate than either ear or powder.

The tube and its branches are of metal, and divided into millimetres, *i. e.* twenty-fifths of an inch. By means of a draw-tube at its topmost part one of the branches is capable of being lengthened or shortened at will. In order to procure a proper tone, a tuning-fork with its resonator is used as the source of sound. To the end of the tube opposite to that at which the fork is stationed, is attached a manometric capsule. This, in turn, is connected with a gas-jet, which is supported before a revolving mirror. When both branches of the tube are of equal length, the sound issuing from the fork and passing through the tube declares its presence at the capsule end by the beautiful serrated band of light, which is seen when the mirror is rotated. But if one of the branches of the tube is made longer than the other by just a half wave-length of the sound emitted by the fork, then we have complete interference of the sound-waves, as is evidenced by the quiescent state of the manometric flame. For now, when the mirror is rotated, you no longer see a serrated band of light, indicating the existence of vibratory motion in the capsule, and the end of the tube to which it is attached, but we have, instead, a continuous ribbon, which is proof positive of total interference.

In order to render simultaneously visible the condition of vibratory motion at the end of each branch taken separately, and the result produced when the two tubes are combined, we may, after Koenig, attach a capsule to the end of each branch, and provide each capsule with two rubber tubes. These tubes are connected with three separate jets, all mounted on the same stand, and one placed immediately above the other. The middle jet is connected with both capsules as in the foregoing experiment, while the lower and upper jets are joined one to each capsule independently.

If now the sound of the tuning-fork be made to act on the three flames, when the branches of the tube are of the same length, the upper and lower jets, as viewed in the revolving mirror, are seen to give two similar indentated bands of light, *a* and *b* (Fig. 139), whilst the central jet gives a like serrated ribbon. But the latter being acted upon by the sum of the pulses affecting the upper and lower flames, its indentations, $a + b$, of the same figure, are correspondingly deeper. By so lengthening one of the branches that it differs from the other by an exact half wave-length, the result manifests itself instantly. The upper and lower flames, being, as before, under the influence of like but separate vibratory motions, remain unchanged, as is shown by the upper and lower flame-images at the right-hand side of the figure. The middle flame, on the contrary, as the middle image on the right of Fig. 139 declares, does not betray the slightest quiver. The contrast

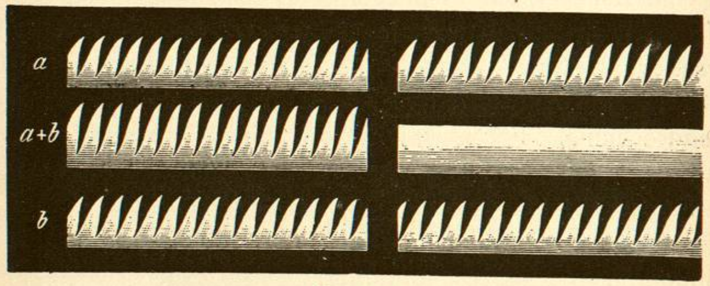

FIG. 139.

presented shows most strikingly the perfect interference that now prevails.

The same ingeniously fashioned apparatus is available for exhibiting interference of sonorous waves proceeding from other sonorous bodies as well as from those generated by tuning-forks.

It can also be utilized for measuring the velocities of sound in air and in gases. When we wish to employ it for determining the velocity of sound in air, we have only to secure perfect interference by properly adjusting the branches of the tube when a simple tone of a given number of vibrations is passing through it. The wave-length is twice the difference of the lengths of the paths travelled by the divided sonorous pulses. This, multiplied by the known rate of vibration of the fork, is

the velocity of sound in the air at the temperature of the atmosphere at the time of the experiment.

By means of the little stop-cocks fitted into the top part of the branches we can fill the tube with any gas we choose, and determine its velocity in the same manner as we find that of air. In this instance, however, we shall have to take the precaution of preventing the escape of gas at the ends of the tube, or at the joints, — an emergency that is neatly provided for in the construction of the instrument. Having done this, we shall find, in adjusting the branches so as to insure total interference, that the difference in the lengths of the branches of the tube will vary according to the gas with which the tube is filled, and, as a consequence, that as the length of the branches for the different gases varies, so will the velocity of sound in these gases vary.

It may be stated, in conclusion, that the phenomena of reinforcement and interference of vibratory motion apply to all kinds of wave-systems. They obtain in heat and light as well as in sound. Our experiments have shown us that sound added to sound may produce silence. Similarly, light added to light may cause darkness, and heat rays may interfere with each other in such wise as to cause a diminution of temperature. All that is necessary in either case is that the heat or light vibrations should meet each other in opposite phases.

More than this. According to Hertz's experiments, electric and magnetic vibrations may similarly interfere with each other as completely as those of light or of sound.

Nothing shows better than the experiments we have just witnessed the nature of these various forces, or proves more conclusively that they are, one and all, simply modes of motion. The germ of this grand generalization, — a generalization demonstrated experimentally, step by step, — is to be found in an experiment on the diffraction of light made by a Jesuit philosopher, Grimaldi, over two hundred years ago. This germ has been developed by the researches of Huygens, Young, Arago, Dr. Lloyd, Sir

William Hamilton, Maxwell, Hertz, and others, but above all by that brilliant young French physicist, Augustin Jean Fresnel. It was he that put the truth of the wave-theory of light beyond further question by his celebrated *experimentum crucis*, in which he obtained total interference of luminous rays both by reflection and refraction.

CHAPTER VIII.

BEATS AND BEAT-TONES.

IN our last lecture we dealt with vibrations that are so related to each other that their resultant effect is either resonance or total interference. We found that when two sounds are in unison, and in the same phase, they tend to reinforce each other; and that when the same sounds are in opposite phases, — their intensity being equal, — one cancels the other, and silence is the result. Under these conditions we discovered that the result must always be either augmentation or annihilation of sound, — no other result being possible.

It is, however, comparatively seldom that we deal with two sounds that are exactly in unison. We are more frequently called upon to consider notes whose rates of vibration differ from each other by a greater or less amount. What, then, is the result, when two notes differing more or less from each other in pitch are sounded simultaneously? This question — one that is of special interest to musicians — I shall endeavor to answer in to-day's lecture. What we have learned about resonance and interference has paved the way for our work to-day, — for the discussion, namely, of what we shall, after Koenig, designate as beats and beat-tones.

Before you are the two C forks used in our last lecture. I damp one of them by attaching a small pellet of wax to one of its prongs. On exciting it with the bow, you perceive that it gives a slightly lower note than it did before. The extra load it has to carry retards its motion, and it executes, in consequence, a smaller number of vibrations than previously, and a smaller number, too, than is made by its unencumbered companion.