emitting its fundamental tone. A little fine sand is strewn over the membrane, and as soon as it is introduced into the pipe, you hear the sand dancing about on the membrane; and if you were near enough you could also see, through the glass side of the pipe as the ring descends, that the agitation of the sand becomes less and less until it reaches the centre of the pipe, — which, as we have learned, is a nodal point, — where it becomes entirely quiescent. On lowering the membrane still further, the sand becomes more and more agitated until it approaches the embouchure, when the agitation, as at the upper end of the pipe, attains a maximum. This, as we have seen, is what should occur. The two ends of an open pipe yielding its prime are centres of ventral segments, and consequently places of maximum movement, while the middle of the pipe, where the direct and reflected pulses cross each other, must be a point where there is no motion whatever.

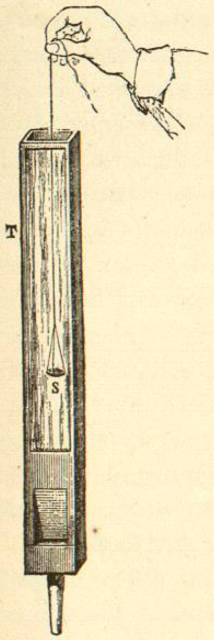

Fig. 85.

By increasing the pressure of the air so as to elicit from the pipe some of its upper partials, we should by the same simple means be able to locate the positions of the nodes and ventral segments of such partials as readily as we have found those corresponding to the fundamental.

Fixed in the wind-chest are two organ-pipes, one stopped and the other open. The former is one half the length of the latter. But, as we have learned, they should both emit notes of the same pitch. Causing the pipe to speak, we find that such is the case.

The same fact may be more strikingly illustrated by the pipe, *T*, Fig. 86. By means of the slide, *A S*, which has a large hole in one end and moves in a groove in the middle point of the tube, the pipe may be made to speak

as an open pipe or as a closed one of half the length of the open pipe. Arranging the slide so that the hole in it permits the two semi-ventral segments corresponding to the prime tone of the pipe to be in communication with each other, the pipe is caused to yield its fundamental. The slide is now moved in so as to make a stopped pipe of one half the length of the open one. The note is still the same. Keeping the pressure of the air the same, the slide is moved to and fro several times in rapid succession, and the pitch of the notes corresponding to the open pipe and the closed one of one half the length, remains unchanged. You note, however, a difference in the quality of the sound, that yielded by the open pipe being brighter and richer than that emitted by the stopped one.

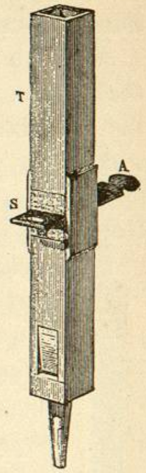

Fig. 86.

If a hole is made in the side of a pipe at a point occupied by a node, such a point is thereby changed at once into the centre of a ventral segment. This is well illustrated by the open pipe, Fig. 87, in one of the sides of which, at the middle point, is a hole which can be opened or closed by a small button. When this opening is closed and the pipe emits its fundamental note, there is a node at this point. As soon, however, as the button is turned to one side, this point becomes the centre of a ventral segment, as is evidenced by the change in the pitch of the sound now yielded. The reason is obvious. The middle point of the pipe is now in free communication with the external air, and hence there can be no variation in density, and consequently no nodal point where before there was one. But instead of one nodal point we now have two, — one midway between the aperture and the upper extremity of the tube, and the other at the same distance on the opposite side of

Fig. 87.

the opening. The note emitted under these circumstances should be an octave higher than that yielded by the pipe in the first instance. The musicians present can vouch for the fact.

A simple experiment will remove all doubt regarding the matter. A second open pipe, one half the length of the one with the aperture in it, is now mounted on the wind-chest, and both pipes are made to speak simultaneously. As was expected, the notes are in unison. Under the conditions of the experiment the small pipe yields its prime, and the larger one its first upper partial. This shows conclusively that the wave-length, and consequently the pitch, of the first upper partial of a pipe, *A*, is the same as that of the fundamental of a pipe, *B*, of one half the length of *A*.

FIG. 88.

But we may carry our illustration still farther. Instead of using a tube with but one aperture in the side, let us take one in which there are four such openings. Fig. 88 shows such a tube. If the pressure of the air in the bellows be now so regulated that the pipe shall yield its third partial, the middle points of its corresponding ventral segments will be, as indicated, at the points *v* and *v*. These points may be put in communication with the external air by opening the holes at *v* and *v*, and the pitch of the note will remain unaffected. If, however, the apertures at *a* and *b* are uncovered, the nodal points are changed, and there is immediately produced a note of higher pitch. This same method is applicable in determining the positions of nodes and ventral segments in stopped as well as in open pipes.

From what has been said it is manifest that when a tube yields one of its upper partials the air-column within undergoes spontaneous subdivision into aliquot parts, each of which vibrates independently, but in unison with each of the others.

Let us, for instance, cause the long open pipe, called

the flute of Bernouilli (Fig. 89), to emit its fourth partial. The air-column within must now, according to what has been said, be subdivided into four columns of equal length, each of which, vibrating separately, would give the fourth partial, which you all hear. The centres of the ventral segments corresponding to the partials now sounding, are at *v*, *v*, *v*. If now the first, second, and third upper sections of the pipe are detached in succession, you will remark no change in the pitch. The lower section of the pipe alone yields the same note as was emitted by the whole pipe, or by a pipe whose length is twice or thrice that of each section taken separately. To show that this is the case, we may reverse the order of the experiment just made. While the lower section is yielding its fundamental note, we add in succession the three upper sections, and if the pressure of air is properly regulated, the pitch of the note will remain unchanged throughout.

FIG. 89.

The same fact can be shown in another manner. If we take, as did Bernouilli, a long tube, *T* (Fig. 90), and close its upper extremity by the piston, *p*, we shall have a stopped pipe. If now the tube is made to yield one of its upper partials, and the piston is slowly moved downward, you will observe a gradual change of pitch. But when the piston reaches one of the nodes corresponding to the partial first produced, the original note comes out loud and clear. We thus show that the same law obtains for the partials of stopped as for those of open pipes.

FIG. 90.

We are indebted to Dr. Koenig for a still more beautiful and delicate method of analyzing the condition of the air in sonorous tubes. For this purpose we use what is called a manometric flame. The apparatus for producing such a flame consists of a small wooden capsule (Fig. 91), one side of which is closed in with gold-beater's skin or a thin sheet of caoutchouc. Two openings are made in the capsule, — one at *a*, and the other at *b*. To the aperture *a* is attached a rubber tube, *T*, through which is admitted illuminating gas. At *b* is fastened a small gas-burner, at the end of which the jet of gas may be ignited.

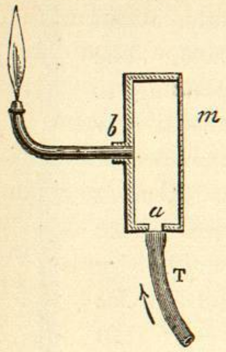

FIG. 91.

If now the gas be maintained at a uniform pressure, it is evident that its escape will be modified by any motion that may be imparted to the membrane, *m*. If the membrane is forced inwards, the gas will escape more rapidly, and the flame will be proportionally elongated. If the membrane move outwards, the gas will escape more slowly, and the flame will be correspondingly shortened. If the membrane be very suddenly and violently agitated, the flame will be extinguished. Such being the case, it is evident that this little apparatus affords a very delicate means of rendering visible the variations of pressure to which the gas within the capsule may be subjected. To render the device still more delicate,

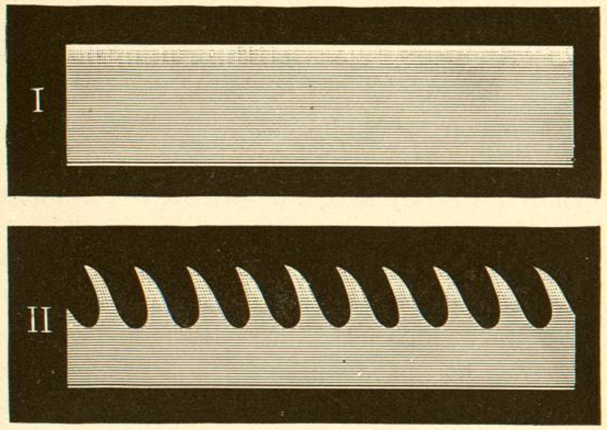

FIG. 92.

the flame is looked at in a cubical mirror which revolves in front of it. The use of such a revolving mirror in observing vibratory flames is due to Wheatstone.

As long as the pressure in the capsule is uniform, the image of the flame reflected from the mirror is in the form of a luminous ribbon, I (Fig. 92), of constant width and equal to the height of the flame. With rapid variations of pressure, however, the image becomes indentated, like II of the adjoining figure, each denticulation indicating an augmentation of pressure within the capsule.

To an open organ-pipe, *A B* (Fig. 93), mounted on the wind-chest, are attached three manometric capsules, *b*, *a*, *c*, communicating with a common reservoir, *D D*, into which illuminating gas is admitted through the tube, *T*. The capsule *a* is nearly at the middle of the pipe, and at the nodal point, therefore, of the pipe when sounding its fundamental. The capsules *b* and *c* are at the nodes corresponding to the second partial, or octave of the fundamental.

When air from this wind-chest is admitted into the pipe and the pipe yields its prime, there is, as we have learned, a variation of pressure in the vibrating air-column. This pressure is greatest at *a*, and diminishes on either side towards *b* and *c*, becoming zero at the open extremities. When the light from *a* is reflected from the revolving mirror, you observe a luminous band with deep indentations. Here the pressure is at a maximum. The indentations afforded by *b* and *c* are, by reason of the less pressure at these points, much less strongly marked. When the jet is small and the sound very intense, the agitation is sufficient to extinguish the flame.

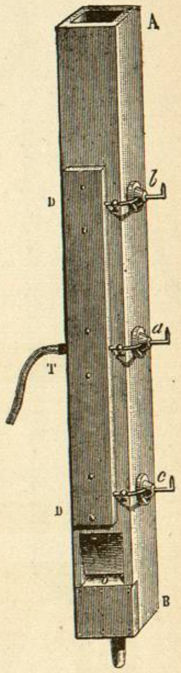

FIG. 93.

If we cause the pipe to yield the octave above the fundamental, the nodes are changed. They are now at *b* and *c*, *a* being the centre of a ventral segment where there is no variation of pressure whatever. This is indicated clearly by the action of the flames, that belonging to the capsule *a* being perfectly quiescent, whereas those at *b* and *c* give the same strong indentated ribbons as were seen at *a* when the pipe sounded its fundamental.

Let us now try a stopped pipe, *A B* (Fig. 94), provided with manometric flames. It is similar to the open one we have just employed, but, for reasons you are already familiar with, the nodes in this case occupy different positions from those of an open pipe. The stopped end of a pipe being always a node, one of the capsules is fixed at *b*. When the pipe yields its second partial it has a node both at *b* and at *c*, while *a* is then the middle of a ventral segment.

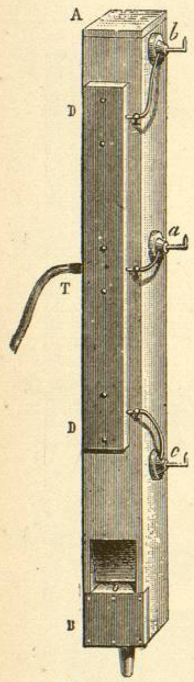

FIG. 94.

Causing the pipe to speak its fundamental, we observe in the reflected images that all the three flames are in a state of vibration. That at *b*, the nodal point corresponding to the prime tone, is most agitated; the agitation at *a* is less, and that at *c* is less still. At the embouchure, *o*, where the vibrating column is in contact with the external air, is the centre of a ventral segment, and here, consequently, a manometric flame would show that the pressure is constant, being always that of the atmosphere.

When the pipe sounds its second partial, *a* becomes the centre of a ventral segment. Here again, as declared by the motionless flame, the air is quiescent, because there are no variations of density. At *b* and *c*, on the contrary, the flames vibrate strongly, because at these points are the nodes corresponding to the second partial, which is now sounding.

Desiring to secure more accurate results than those afforded by the manometric pipes with which we have been experimenting, Dr. Koenig constructed one on a much larger scale. Such a one is now before you (Fig. 95).

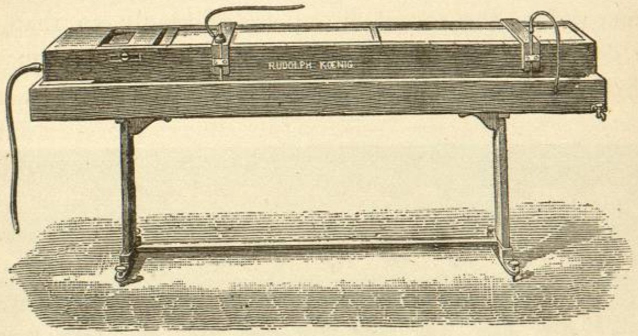

FIG. 95.

It is over seven and one half feet in length, and about five inches in depth and width. It is brought to a perfectly horizontal position by means of levelling screws in the feet of the support. Its prime note is C_1. Figure 96 exhibits a cross section of the pipe. A narrow, cleft-like opening extends the whole length of the bottom of the pipe. This is to permit the exploring tube, *a c d b*, attached to the support, *m n*, to be moved at will to any point along the axis of the pipe. The opening of the pipe is closed by partially filling the trough, in which it rests, with water. The upper side of the pipe is made of glass, so that the observer can see what is going on within.

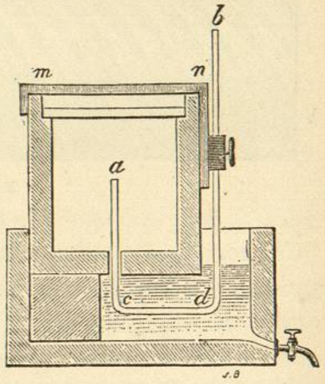

FIG. 96.

Passing the exploring tube along the length of the pipe, while it is emitting a note, and bringing the end, *b*, of the tube into communication with the ear, we are apprised of an augmentation of sound at the nodes, and of a diminution of it at the middle of the ventral segments. What is surprising is that it is easier to locate exactly the centre of a ventral segment than the position of the nodes. At the former points the sound disappears suddenly, so that we can determine the middle points of the ventral segments with the greatest ease and exactness.

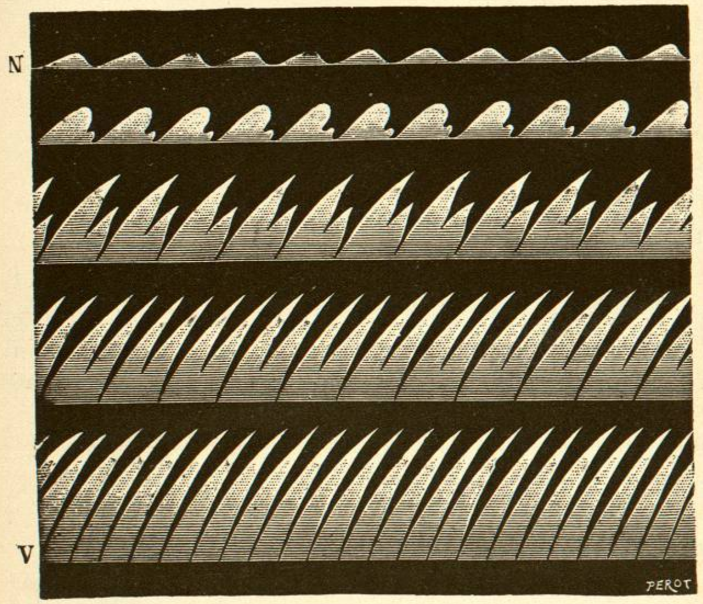

FIG. 97.

Connecting a manometric capsule with the end, *b*, of the exploring tube, and employing a short flame, we get results, if anything, more exact than those afforded by observations with the ear. At the centre of each ventral segment the flame suddenly becomes very luminous, while at all other points it is quite bluish and but faintly visible. Fig. 97 shows the appearance of the flame at the node, *N*, at the centre *V*, of a ventral segment, and at intervening points.

With this pipe Koenig showed, as Wertheim had demonstrated by other means, that the indications of theory as regards the vibrations of pipes are not realized by experiment. It is the old story over again, — the discrepancy between the observations of the experimenter and the demands of the mathematician.

The length of a pipe, whether open or stopped, emitting its fundamental note is less than that assigned by theory. Again, when a pipe yields one of its partials, it is found that the nodes next the embouchure, and the end opposite, in an open pipe, are nearer the extremity than theory calls for, and that the same discrepancy obtains for the middle of the ventral segment next to the closed end of a stopped pipe. It is nearer the end of the pipe than it should be according to theory. These variations are due to what are called terminal perturbations. For these reasons the prime note of a pipe is graver than that which the length of the pipe calls for.

Again, as Koenig has demonstrated, the partial sounds of an ordinary pipe do not follow the law of harmonic partials. According to his observations, the eighth partial may in any moderately large pipe have very nearly the same pitch as the ninth partial. Wertheim had previously remarked that in endeavoring to determine the fundamental of an organ-pipe by means of one of the upper partials he always obtained a value that was greater than that indicated by theory, in proportion as he employed a higher partial.

Savart has shown, however, that when the pipe is long and of very small diameter, and set in vibration by an oscillating plate, the number of vibrations is, as theory indicates, inversely proportional to the length of the pipe. In each case, too, the node corresponding to the fundamental is sensibly at the middle of the pipe, and the proper sounds of the pipe are true harmonic partials of the fundamental.

When, as in the case of ordinary pipes, the length is between six and twelve times the diameter, there is a slight divergence of experimental from theoretic values;

but as the transverse section increases, this divergence augments very rapidly.

By simply increasing the diameter of a pipe, and leaving its length unchanged, Mersenne succeeded in lowering the fundamental by seven whole tones. Taking a pipe seventy-two lines[1] in length, which we will suppose yielded the note C, — the note in fact would be many octaves higher, — and varying the diameter, he was able to get the results indicated in the following table: [2] —

Diameter in lines,	3	6	12	18	25	51
Notes emitted,	C	A_{-1}	G_{-1}	E_{-1}	$C\sharp_{-1}$	$A\sharp_{-2}$

The law governing the vibrations of similar pipes was discovered by Mersenne. It was afterwards verified by Savart, and extended to pipes of the most diverse forms. "If," says Mersenne, "we give to a pipe one foot in length a diameter of three digits, it will make exactly an octave with a similar pipe two feet in length and six digits in diameter."

The law of Mersenne and Savart may be expressed as follows: *Two similar pipes having similar embouchures emit notes whose pitch is inversely proportional to their lineal dimensions.* Thus, for instance, the prime tone of a square prismatic pipe twelve inches long and four inches wide will yield a note an octave lower than a similar pipe six inches long and two inches wide.

On the wind-chest of the acoustic organ are fixed eight pipes, of the forms shown in Fig. 98, the larger of which is in each case just twice the dimensions of the smaller. Causing them to speak, you observe that the smaller one in each instance gives a note an exact octave above that emitted by the larger ones. The law just enunciated was adverted to in our last lecture. We then learned that it was universal, and applied to all vibrating systems, solid, gaseous, or liquid.

In the manufacture of organ-pipes this law is of special practical value, as it enables the artisan to produce pipes which are in perfect accord. Their consonance is not changed by variations of temperature, inasmuch as pipes of different dimensions would be equally affected in proportion to their size.

Owing to the difference between the observed and the theoretic length of an organ-pipe for any determinate note, organ manufacturers have recourse to an empirical law which meets their wants and is found to hold true within quite wide limits. M. Cavaillé-Coll, the celebrated organ-builder of Paris, employs in the construction of open pipes the following formula: —

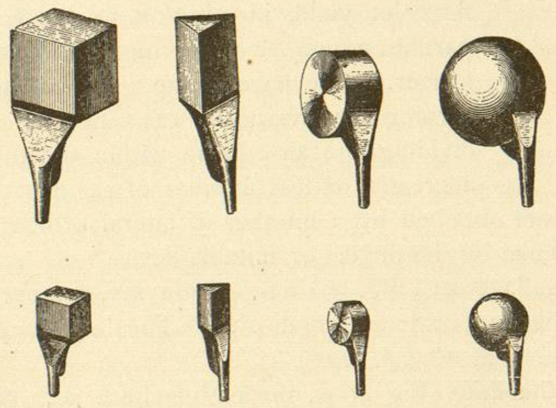

Fig. 98.

For rectangular pipes of a depth p, $L' = L - 2p$

For cylindrical pipes of a diameter d, $L' = L - \frac{5}{3}d$.

In both these formulæ L' denotes the actual, and L the theoretic length of the pipe for any given note. Similar empirical laws govern the manufacture of stopped pipes, and of pipes of varying depth, but of the same length. It is found that in pipes of the same length but of different widths, the pitch of the note is the same, — provided the embouchure extends across the entire width of the pipe. The only difference then observed in notes yielded by pipes of the same length and depth, but of different width,

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[1] A line is the one twelfth of an inch.

[2] Harm. lib. xi. Prop. 9.

is one of intensity, the wider pipe emitting the louder note.

Two pipes of equal length and depth, but of different widths, are now mounted on the wind-chest, and when they are made to speak, you are unable to distinguish any difference in the notes emitted, save the one mentioned. The larger pipe yields a note considerably louder than that emitted by the smaller one, but the pitch in both cases is identical.

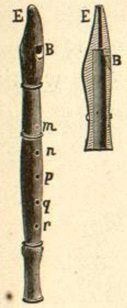

FIG 99.

Instruments like the flute, fife, piccolo, and flageolet yield, in addition to the harmonic partials, a number of intermediate notes. The former, as we have learned, are produced by varying the pressure of the wind, thereby subdividing the air-column within the tube into a greater or less number of segments. The latter are obtained by a number of lateral orifices closed or opened by the fingers or suitable keys.

The flageolet (Fig. 99) has, as you see, a mouthpiece, *E B*, like an ordinary organ-pipe. The lateral openings are shown at *m*, *n*, *p*, *q*, *r*.

FIG. 100.

In the flute (Fig. 100), the embouchure is an oval opening, *A*, at the side. The player places his lips above the orifice, and at a short distance from its sharp edge, which answers to the lip of a mouthpiece.

Taking, then, an instrument like the flute, whose fundamental is C_3, and which has six lateral openings between its open extremity and its embouchure, we produce by opening the holes in succession an effect analogous to that which would result from shortening the tube by cutting off in succession those portions between its open end and the different apertures, beginning with that which is farthest away from the embouchure. Thus, the prime tone being C_3, we obtain by opening in succession the six holes, beginning with the one nearest the open end of the tube, the notes D_3, E_3, F_3, G_3, A_3, B_3. By closing all the lateral orifices and increasing the pressure of the wind, we get C_4, an octave above the prime, and by opening the holes as before, we get the notes of the second octave. In a similar manner we elicit those of the third octave. The flats and sharps of the chromatic scale are obtained by suitable keys, which open and close holes intermediate between those yielding the notes of the diatonic scale. And what is here said of the flute applies to all instruments of its class.

We come now to the consideration of reed-pipes properly so-called. We have seen that flute-pipes may be considered as reed-pipes, and that the aërial column within them may be caused to vibrate by means of the "Luftlamelle," or air-reed; but it is probably better, in order to avoid confusion, to retain the old name of flute or flue pipe.

A reed-pipe may be defined as any kind of wind instrument in which the aërial column is excited by the vibratory motion of an elastic body called a reed. Under the action of this reed the air within the pipe forms pulses of condensation and rarefaction, as in flute-pipes. Nodes and ventral segments are also developed according to the laws which we have already considered.

In organs, harmoniums, concertinas, harmonicums, accordeons, and similar instruments the reed is made of metal, usually brass. The reeds of the clarinet, oboe, and bassoon are of thin cane. The vocal cords answer to reeds in the human larynx, while in such instruments as the horn, trumpet, trombone, and brass instruments generally, the work of reeds is performed by the lips. The vocal cords and the lips are, hence, frequently classed as membranous reeds. In the clarinet and organ and in all instruments generally in which metal reeds are employed, we have what are called single reeds; that is, there is only a single vibrating lamina for each pipe or note. The bassoon and the oboe have what are denominated paired or double reeds.