CHAPTER III.

ON THE PRODUCTION OF MUSICAL SOUND IN TUBES.

§66. PRELIMINARY REMARKS ON THE MUSICAL VIBRATIONS OF AIR IN TUBES.—72. RESONATORS.—78. REEDS.—79. *THE FREE REED.* —80. *BEATING REEDS.*—84. THE PRODUCTION OF SOUND IN THE FLUTE AND ITS CONGENERS: *THE AIR-REED.*—90. *CHLADNI'S THEORY.*—91. *SIR J. HERSCHEL'S THEORY.*—92. *ITS QUALIFICATION.*—93. *THEORIES OF M. CAVAILLÉ-COLL.*—94. *PROFESSOR HELMHOLTZ.*—96. *PROFESSOR TYNDALL.*—99. *SIR G. B. AIRY.*—100. *MR. HERMANN SMITH AND HERR SCHNEEBELI.*—105. *THE SUBJECT PASSED OVER BY LORD RAYLEIGH.* —106. THE EFFECTS OF VARIATION IN THE FORCE AND THE DIRECTION OF THE AIR-REED.—112. RECIPROCAL ACTION OF THE AIR-REED AND THE COLUMN OF AIR.

66. Preliminary Remarks on the Musical Vibrations of Air in Tubes. The following outline of the laws which govern the musical vibrations of the air in a tube may, for the present, be taken for granted. Further details of the subject will be found in subsequent chapters, particularly in chapter IV. The preliminary account of these important laws, which is here given, is only intended to assist the general reader in the comprehension of the various modes in which the sounds of wind-instruments are produced.

67. The sounds of every wind-instrument are due to the vibrations of the air within its tube: this air is therefore in reality the sonorous body. Riccati (1767) not inappropriately calls it "the aerial string," but it is now usually termed the *column of air*. The vibrations of the air within the tube are to

a great extent independent of those of the tube itself, the main function of which is to determine the form and the dimensions of the air-column.

68. The musical vibrations of a column of air occur in a totally different manner to those of a string, being almost entirely longitudinal, but wind-instruments have, nevertheless, nodes, segments and antinodes, and therefore not only fundamental notes, but also harmonics, are producible from them, as well as from stringed instruments.

69. The air-column in a cylindrical or prismatic tube that is *wide open at both ends*, has but one node during the sounding of the fundamental note, and this node is situated in the centre of the length of the tube: the antinodes are at the open ends. The harmonics of such a column of air correspond in sound to those of a string.

70. The air-column in a cylindrical or prismatic tube that is *open at one end and perfectly closed at the other*, has a node at the closed end, and an antinode at the open one, during the sounding of the fundamental note. The harmonics of such a column of air correspond only to the uneven numbers of the table in §46.

71. The rapidity of the vibrations of an air-column depends chiefly on the length of that column. *Cæteris paribus, the rapidity varies inversely as the length.*

The opening of a lateral aperture in a tube is, in some measure and under certain circumstances, equivalent in effect to shortening the tube.

72. Resonators. Perhaps the most simple illustration of a sonorous air-column is afforded by an ordinary test-tube. Let a tuning-fork be selected which vibrates nearly in unison with the air in the tube. To suit a *c''* fork at our present pitch, the length of the tube will require to be nearly six inches and a quarter. The unison may be finally adjusted by pouring water into the tube to raise the pitch, or by partly closing the open end to render the sound flatter. Let the fork be struck, and the end of one of its prongs be held to the mouth of the tube, so that the vibrations of the fork shall be in the direction of the length of the tube. The air in the tube will then be heard to vibrate in sympathy with the fork, and the augmentation of sound may be taken as a test of the accordance of the vibrations of the fork with those of the air-column.

73. Tubes such as have just have been described, are termed *resonators*. These are made of various forms and materials. Savart tuned them by means of a slide. Those used by Professor Helmholtz were of globular form, and were provided with two tubular orifices, one broad for the reception of the vibrations, the other narrow so that it could actually enter the ear. Resonators are of great service in acoustical experiments.

74. Sir Charles Wheatstone (1828) describes a very simple and interesting experiment in which a flute is converted into a resonator. "If one of the branches of a vibrating tuning-fork be brought near the *embouchure* of a flute, the lateral apertures of which are stopped so as to render it capable of producing the same sound as the fork, then the feeble and scarcely audible sound of the fork will be augmented by the rich resonance of the column of air within the flute. . . . To ensure success, it is necessary to remark that when a flute is blown into with the mouth, the under lip partly covering the embouchure renders the sound about a semitone flatter than the sound when the embouchure is entirely uncovered; and as the latter [sound] must be in unison with that of the fork, it is necessary, in most cases, to finger the flute for *B* when a *C* tuning-fork is employed."

75. The exact pitch of the flute when the mouth-hole is open, may be easily found by closing, with a smart tap, any one of those finger-holes which require to be closed for the production of the desired note, but absolute accuracy is not necessary for the success of Wheatstone's experiment, though the nearer the approach to perfect unison the more powerful will be the resonance of the air in the tube. It is worthy of special notice that whether the fork and the air-column are in perfect unison or not, the pitch of the sound of the fork is not altered, therefore the vibrations of the fork govern, to some extent, those of the column of air.

76. Sir Charles Wheatstone also writes, in the same paper: "It is evident, from experiment, that a column of air may vibrate by reciprocation, not only with another body whose vibrations are isochronous with its own, but also *when the number of its own vibrations is [any aliquot part] of those of the original sounding body*. The converse of this law does not hold."

Thus it is clear that the sympathetic vibrations of columns of air are governed by the same laws as those of strings.

77. Any sonorous body set in vibration at the mouth of a tube, or other vessel, the air in which can vibrate, either as a whole or in its aliquot parts, in unison with the vibrating body, will convert that vessel into a resonator. The vibrating plate of Chladni (§56) was used by Savart (1823) and by Wheatstone also (1832 A and B), to illustrate some exceedingly important facts which are particularly described in §§126 and 127. The last mentioned able experimenter contrived a method of producing the sounds of a wind-instrument, at any part of the column of air in its tube, by means of a hydrogen gas flame (1832 B). The details and results of these experiments will be found in §160.

78. Reeds. The tones of the majority of wind-instruments are produced by means of *reeds*. These are of several kinds, but they may all be classed under two heads: the *free* and the *beating*.

79. *The Free Reed* is a narrow, flat strip of very elastic metal, fixed at one end, and caused, by a current of air, to vibrate freely in a slit cut in a plate which is also of metal. It gives very nearly the same note whether plucked at the free end, or sounded by air being forced through the aperture. I am quite aware that I am contradicting the generally received opinion, when I state that a free reed is as truly a sonorous body as the string of an Æolian-harp or any other string. Free reeds do not strictly obey the law of isochronism which generally governs the vibrations of rods and strings. The regularity of motion in this kind of reeds, suffers from the interference of the exciting rush of air, which causes the vibrations to become slower in proportion to their amplitude; the resulting sound being, of course, lower in pitch. Free reeds are the sound producers in harmoniums and concertinas, as well as in the reed-pipes of most of the continental organs.

80. *Beating Reeds* are of two kinds, *single* and *double*. They are always associated with pipes, and their function is to break up the stream of air, as it enters the pipe, into a number of intermittent puffs, which, by reason of the rapidity of their succession, seem to the ear continuous, according to the principle explained in §§13 and 18. Beating reeds have little appreciable sound of their own, as have free reeds. The clarionet, the *corno-bassetto*, the saxophone, and other instruments of the same class, as well as many kinds of organ pipes, have single beating reeds. The English word clarionet is evidently a diminutive of clarion, a trumpet, it is therefore properly spelled as above, though it is now generally mis-pronounced *clarinet*. This instrument has a rigid mouth-piece, one side of which is nearly flat. The other side is tapered, so that the two meet at an angle of about 30°. In the flattened side is an oblong opening communicating with the bore. The reed consists of a thin plate of cane which is fastened to the lower end of the mouth-piece, so as to cover the opening and reach to the edge at the upper end. The reed at this end is very thin and flexible, and it is allowed to stand at a small distance from the mouth-piece. When in action, the reed beats against the mouth-piece, alternately closing and opening the orifice, thus giving rise to a succession of aerial impulses which combine to form the tone of the instrument.

81. The hautboy, or *oboe*, the *cor anglais*, the bassoon, and other instruments of like nature, are sounded by means of double reeds. A double reed consists of two blades of cane, the upper and thinner ends of which are flat. The lower ends are bound together, and form a cylindrical tube, through which

the air enters the instrument. The thin, flat ends of the blades of cane vibrate and strike each other when the reed is in action, with the same effect as that produced by the single beating reed.

82. The reeds of almost all wind-instruments blown by the breath, are under the control of the lips of the performer, who is able to modify the tone of the instrument, and to correct defective notes, by increasing or relaxing the pressure on the reed. A strong, stiff reed controls the vibrations of the column of air to a much greater extent than a weak and flexible one. The latter appears to be itself governed by the vibrating air-column.

83. The reeds of bagpipes are enclosed in air-chambers, and are quite uncontrolled by pressure. There once existed a large family of instruments of this kind which is now happily almost obsolete.

In the sounding of brass instruments with cupped mouth-pieces, the lips of the player form a double reed.

84. The Production of Sound in the Flute and its Congeners. *The Air-reed.* The important family of instruments of which the flute may be taken as the type, embraces also whistles, flageolets, the flute-pipes of organs and the semi-barbarous instruments known as the *Pandean pipes;* the Chinese *yo*, *tsche* and *hinen;* the *nay* of Arabia, Persia and Turkey; the Egyptian *man*, or *men*, and some others of less importance. In all these the sound is due to a jet of wind which passes across either a lateral aperture, or the open end of the instrument, and strikes against the opposite edge of the opening. This jet is now generally regarded as a free aerial reed, and is often called an *air-reed*.

85. The best known amongst the earlier of the above named instruments is the Pandean pipes, or σύριγξ, a series of small tubes, of different dimensions, stopped at one end. These are bound together in a row, and their upper and open ends are ranged in a straight line. The performer blows across the open ends.

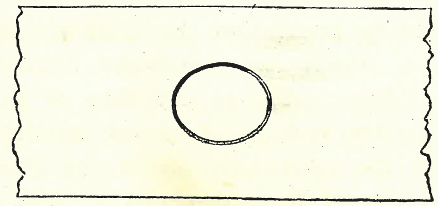
86. The following account of the Eastern instruments is condensed from *Mendel and Reissmann's Musical Dictionary* (1880), article "*Flöte*." The *yo* is a tube of bamboo, open at both ends. One end is sharpened at the edge, and this serves for the mouth-hole, as in the Pandean pipes. The *tsche* is a tube of bamboo, closed at both ends. It is sounded at a lateral hole in the centre of the instrument. The *hinen* is made of clay, in the form of a sugar-loaf, the mouth-hole being at the apex. The *nay* and the *man* are sounded in the same manner as the *yo*.

In the museum of the Paris *Conservatoire de Musique* there is an instrument of the same description as the *yo*, which is named in the catalogue of that institution (1884) "*guesba ou gosba*."

87. The flute of the present day may be described as a tube open at one end, and partially open at the other, for although one end of this instrument is always veritably stopped, yet the proximity of this end to an open hole, converts the tube into what is virtually an open one, and therefore the harmonic sounds of a flute are the same as those of a string. The flute is provided with a variable number of lateral apertures, that nearest the closed end being properly termed the *mouth-hole*, but often the *embouchure*; the others are closed or opened, more or less directly, by the fingers, and therefore have the general name, *finger-holes*. The instrument is held parallel to the lips of the player, with the nearer edge of the mouth-hole pressing against the under lip. A small, flat stream of breath, the air-reed, is directed across the hole, at the opposite edge of which the sound is formed. The jet of breath, passing, as it must, immediately from the lips to the edge of the hole, is under the direct control of the performer as to size, shape, direction and speed. It would appear that the *tsche* is sounded in precisely the same manner.

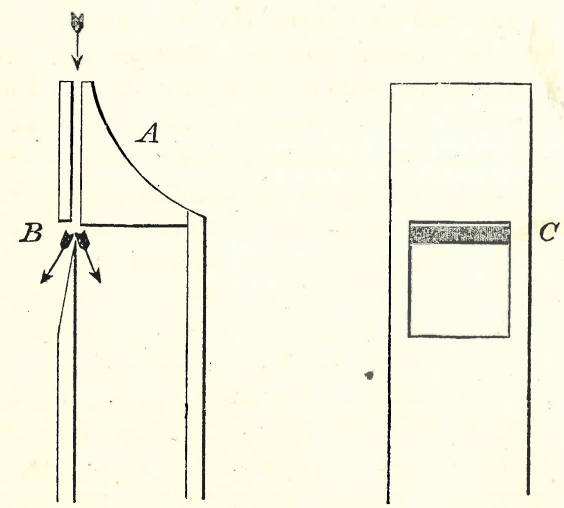
The annexed diagram shows the most desirable form and size of the mouth-hole of a flute.

FIG. 6.



88. In the common whistle the exciting wind passes, longitudinally to the pipe, through a slit at its upper end, and over a transverse opening in its side. The walls of the slit through which the wind passes are of wood, metal, or other rigid material; hence, though the strength of the tone can be somewhat modified, the size, shape and direction of the stream of air are unalterable. *Fig.* 7 shows the sound-producing apparatus of the whistle.

FIG. 7.



A The *Plug*. *B* The wind cutter.
C The opening across which the wind passes. The arrows show the directions of the wind-current, part of which passes alternately within and without the pipe. See § 91.

Many of the ancient pipes, as well as the comparatively modern *flûte-à-bec*, or *flûte douce*, differed in no essential particular from the whistle. The flageolet is but a whistle provided with a receptacle for the wind, somewhat similar in its action to that of the bagpipes, though not controlled by pressure from the outside. The flute-pipes of organs are also whistles. These are placed, in a vertical position, on a *wind-chest* which is fed with wind at a uniform pressure, consequently their tone is utterly inflexible.

89. The sounds of all the above mentioned instruments may be considered as being produced on the same principle. With regard to the theory of this sound-production, there is probably no subject in the whole range of the science of acoustics on which greater uncertainty and diversity of opinion prevail, but as it is a subject of peculiar interest to all who delight in wind-instruments, and to flute-players especially, I here cite the opinions of the most approved authorities.

90. *Chladni's Theory.* Chladni was the first to use the term *reed* in connection with the production of sound in flutes and flute-pipes. In the French edition only, of his work (1809) he says at page 73: "there is always something which may be regarded as a reed (*anche*) but this must always be more under the influence of the air-column than other reeds." Did this statement stand alone, it might be considered to have paved the way for some very important discoveries, hereafter to be mentioned, but, on the next page, Chladni speaks of the functions of the reed being performed by the lips of the player, as in brass instruments, a notion so erroneous that it may be dismissed without further comment.

91. *Sir John Herschel's Theory.* The ingenious theory of Sir John Herschel (1830) deserves to be more widely known than it appears to be: I believe it to be the only correct one, and I have therefore transcribed it *verbatim*.

"Let us consider what takes place when the vibrations of a column of air are excited by blowing over the open end of a pipe or an aperture in its side. To do it effectually the air

must be directed in a small current, not *into*, but *across* the aperture, so as to graze the opposite edge. By this means a small portion will be caught and turned aside down the pipe, thus giving a first impulse to the contained air and propagating down it, a pulse in which the air is slightly condensed. This will be reflected at the end [of the segment, *i.e.*, at the first node,] as an echo, and return to the aperture where the condensation goes off, the section condensed expanding into the free atmosphere. But in so doing, it lifts up, as it were, and for a moment diverts from its course, the impinging current, and thus, while it passes, suspends its impulse on the edge of the aperture. The moment it has escaped, the current resumes its former course, again touches the edge of the aperture, creates there a condensation, and propagates downwards another condensed pulse, and so on. Thus the current passing over the aperture is kept in a constant state of *fluttering* agitation, alternately grazing and passing free of its edge, at regular intervals, equal to those in which a sonorous pulse can run over twice the length of the pipe: or more generally, in which the condensations and rarefactions recur at its aperture in virtue of any of the modes of vibration of which the column of air in the pipe is susceptible

"The rationale of the continual sub-division of the vibrating column, as the force of the blast increases, is very obvious. A quick sharp current of air is not so easily driven aside by an external disturbing force; and when so driven, returns more rapidly to its original course than a slow and feeble one. A quick stream, when thrown into a ripple by an obstacle, undulates more rapidly than a slow one, consequently on increasing the force of the blast, a period will arrive when the current *cannot* be diverted from its course and return to it so *slowly* as is required for the production of the fundamental note. The next higher harmonic will then be excited, until, the force of the blast increasing, it becomes once more incapable of sympathising with the excursions of the aerial molecules and so on."

The comprehension of these latter remarks will be facilitated by reference to the descriptions of the experiments of Bernoulli and Melde in §§52, 53, and 54.

92. *Qualification of Herschel's Theory.* Sir John Herschel's theory might, without qualification, lead to the supposition that the strength of the exciting air-current must necessarily be increased for the production of the harmonics of the flute. This is far from being the case: the necessary increase of the rapidity of the vibrations may be obtained with much greater facility by the reduction of the aperture between the lips of the player. By this means high notes may be produced with less expenditure of breath than low ones. This subject is treated in detail in Part III.

93. *M. Cavaillé-Coll* (1860) describes a paper which he presented to the *Académie Royale* in 1840, but which has never been printed. He says that in this paper he "demonstrated more clearly than had been shown before, the veritable function of the prime mover of the tone in flute-pipes, which was compared to a free aerial reed (*anche libre aerienne*)."

94. *Professor Helmholtz* (1863-1875) says that "the directed stream of air breaking across the edges, [*sic*] generates a peculiar hissing or rushing noise, which is all we hear when a pipe does not speak, or when we blow against the edges of a hole in a flat plate instead of a pipe. The narrower the opening and the stronger the blast, the higher will be this noise of the wind. Such a noise may be considered as a mixture of several inharmonic tones of nearly the same pitch. When the air chamber of the pipe is brought to bear upon these tones, its resonance strengthens such as correspond with the proper tones of that chamber, and makes them predominate over the rest, which this predominance conceals."

95. In the last edition of his work (1885) Professor Helmholtz has expunged the passage above quoted, and, as far as I can understand the exceedingly diffuse account of his views there given, he appears to have adopted a theory similar to Sir John Herschel's. His latest utterance on the subject

(1885, *Appendix*) is as follows: "The circumstances which affect the blowing of pipes . . . require a more extended investigation, which I hope soon to be able to give elsewhere."

96. *Professor Tyndall* (1867, etc.) has evidently founded his theory on the earlier opinions of Professor Helmholtz. He states, with scarcely a word of alteration in his latest edition, that out of a number of pulses which are generated by the breaking up of the stream of air from the lips against the sharp edge of the mouth-hole, the column of air in the tube has the power to select that pulse with which it is able to vibrate in unison. "The tube selects that pulse of the flutter which is in synchronism with itself and raises it to the dignity of a musical sound."

97. This theory has not met with general acceptance, and it appears open to grave objections. The air-column would not have the power to select one of several pulses which might be vibrating at nearly the same rate. The expression "selects that pulse" necessarily implies leaving the rest, but if several pulses, moving at different rates, could exist at the *embouchure* of a tube at the same time, the air in the tube would respond to all such pulses as might vibrate within a certain distance above or below its own rate of vibration, and the sounds would be the most discordant imaginable. If two tuning-forks, one sounding somewhat less than a semitone higher than the other, be held at the end of an air-column, whose normal rate of vibration is the mean of the rates of the forks, each fork will sound its own note, and the air-column will respond to both. Sir John Herschel (1830) drew attention to this fact, which agrees with what has been stated, in §75, as to there being no absolute necessity for perfect unison between the exciting sound and the air of the resonator. There appears to be no basis whatever for the assumption that the air-reed consists of several pulses, and such an assumption would seem to imply a leaning towards a popular but erroneous notion that the vibrations of the exciting stream of air are longitudinal, thus setting on one side the theory of Sir John Herschel and the free aerial reed. There is more accuracy in Professor Tyndall's remark (Edit. 1883, p. 183): "the pipe creates, as it were, its own tuning-fork by compelling the fluttering stream at its embouchure to vibrate in periods answering to its own," but this is certainly inconsistent with his previous utterances.

98. That confusion of pulses which Professor Helmholtz calls "vortices" and Professor Tyndall an "assemblage" may be considered as waste products, which are not formed until the steadily oscillating air-reed has performed its office, as may be easily proved by sounding a flute with one's mouth full of tobacco smoke. A premature "breaking up" of the stream of air prevents the production of any musical sound.

99. *Sir George Airy* (1868) seems rather divided in his opinions between the theory last given and that of the air-reed. His only decided utterances on the question are that it is "an obscure subject," and that "the matter demands more complete investigation."

100. *The Experiments of Mr. Hermann Smith* (1874B, 1874C) *and Herr Schneebeli*, as detailed in *Poggendorff's Annalen* for 1874, Vol. CLIII, appear to have been carried on independently. I have not seen Herr Schneebeli s paper, but I have very carefully studied Mr. Hermann Smith's, and also Mr. Ellis's excellent condensation and comparison of the two accounts, (1875, 1885) from which I have made the following extract:

101. "The source of tone, according to both Mr. Hermann Smith and Herr Schneebeli, is the formation of what the former calls an 'aeroplastic reed,' and also simply an 'air-reed,' and the latter a '*Luft-Lamelle*' (air-blade) which is produced outside the pipe and bends partly within it. For the formation of this reed, both agree that it is essential for the exciting air to pass the lip, [of the organ-pipe, or the edge of the mouth-hole of the flute], certainly not to enter the pipe. The existence of this reed is shown by Mr. Hermann Smith by interposing a thin lamina, a shaving, or crisp tissue paper, which is caught by the air, and vibrates as a reed, and by Herr Schneebeli by smoke

mixed with the air, which enables the experimenter to see its motion directly.

102. "Herr Schneebeli supposes the air-reed to act by producing condensation, but Mr. Hermann Smith's theory of its origin seems to be as follows: The air driven rapidly and closely from the slit past the mouth of the pipe, in a flat stream, just, and only just avoiding the edge of the lip [of the pipe], creates a vacuum . . . The air in the pipe under the action of the atmospheric pressure at the upper open end immediately descends to supply this vacuum, and by so doing not only bends the flat exciting stream of air outwards, but also of course produces a rarefaction in the tube, which by extending from the mouth upwards necessarily weakens the force of the outward rush of wind. The external (not the exciting) air, taking advantage of this relaxation of force, enters the tube at the lip, causing a condensation in the lower part of the pipe, and the resulting wave of condensation, before it has proceeded half way, meets the former wave of rarefaction, which continued to proceed from the further end of the tube, and thus forms a node. . . . . In the meantime the exciting stream of air rights itself, passes over the vertical, bends inwards, and a small portion of it enters the pipe with the external air, to be cast out again by the returning wave of rarefaction, and by this time the exciting stream of air has been converted into a vibrating air-reed. . . . . The external air of course passes continually, but intermittently, through the mouth of the pipe."

These views have attracted considerable attention, but it will be seen that with the exception of some manifest inconsistencies, they are very nearly in accordance with those of Sir John Herschel.

103. Mr. Hermann Smith's hypothesis of the entrance of the air at the open end of the pipe to fill the vacuum which he presumes to be created at the mouth, is certainly a weak point in his theory, and it involves the assumption that the sounds of open and stopped pipes are produced on different principles, which is contrary to reason and experience.

104. With regard to the new theory of the exciting air scarcely entering the pipe, it cannot be correct in the case of the flute, as is proved by the fact that in cold weather the breath of the performer can always be seen issuing from the end of the instrument.

105. *Lord Rayleigh* unfortunately expresses no opinion on this very interesting subject, except to mention (1878, p. 187) "our ignorance as to the mode of action of the wind."

106. The Effects of Variation in the Force and the Direction of the Air-reed. Mr. Hermann Smith (1874B) considers the action of the air-reed to be in opposition to the laws which govern all other vibrations. He says that "the aeroplastic reed has a law of its own, unique amongst the phenomena heretofore observed in musical vibrations. It may be stated thus: '*As its arcs of vibration are less, its speed is greater.* All our knowledge of rods and strings, of plates and membranes, would lead us to expect the usual manifestations of the law of isochronism, that in the air-reed considered as a free rod fixed at one end and vibrating transversely, the law would be observed, 'though the amplitude may vary, the times of vibration will be the same.' Yet here we meet with its absolute reversal, viz.: *the times vary with the amplitude.*"

107. The above remarks, as far as the simple facts are concerned, are incontrovertible, but I venture to think that the air-reed should not be regarded as a rod quite free at one end, and that therefore the idea of the reversal of the acknowledged laws of vibrating rods is imaginary. The same principle of interference which has been mentioned in the description of the action of free metal reeds (§79) is at work here also. The part of the jet of wind which describes the arc, and which Mr. Hermann Smith considers to be free, is continually receiving fresh lateral impulses from the vibrations of the air in the tube; impulses, be it observed, given by the concussion of the air itself, the same material as that of which the air-reed is formed. The influence of these concussions may be compared to that on a vibrating solid rod continually struck by a mass of similar material. The following homely experiment will serve to illustrate this principle of interference. If a knife with a long flexible blade be held loosely, at such a distance from the end of its handle that it can vibrate freely when the end of the blade is smartly struck against a slab of some hard material, arcs similar to those of which Mr. Hermann Smith speaks, will be described by the end of the blade in its excursions to and from the slab. Of course these arcs will become less, as the force of the original impulse becomes weaker, and *as the arcs of vibration become less, the speed will be greater.* If the process be reversed, by striking the slab against the knife, the result will be the same. A blade of less flexibility, but of the same length, held in a corresponding place, and struck with the same force, will describe smaller arcs, and consequently have an increased speed of vibration.

108. It is to this principle of interference that Sir John Herschel alludes in the words already quoted: "A quick sharp current of air is not so easily driven aside by an external disturbing force, and, when so driven, returns more rapidly to its original course than a slow and feeble one." On no other principle does it appear possible to account for the well-known fact that the sound of a flute rises in pitch when the force of the exciting air-current is increased. The "quick sharp current of air" which strikes the edge of the mouth-hole of the flute when a note is blown strongly, is not so easily driven aside by the vibrations of the air-column as a weak one, therefore its arcs of vibration are smaller, its speed is greater, and in proportion to the rapidity of the vibrations, the pitch of the flute of course rises.

109. The *direction* of the air-reed has also an important influence on the pitch of the sound of a flute. It has been shown to be necessary for the air-reed to pass the edge of the orifice, across which it is directed, at every oscillation, and as the more nearly its direction on entering approaches to the perpendicular, the greater distance it must traverse before it can escape: so, its arcs being larger, its rate of vibration will be less. It is obvious that the converse of this theory must be equally true.

110. The sounds of the flute are slightly raised or lowered when the exciting air-current is diverted from its true transverse direction, towards the open or the closed end of the instrument. This may perhaps be explained by the assumption that the vibrations of the air-column are not strictly longitudinal, and that the change of pitch is due to a greater or less amount of tortuosity in the vibrations. It is a difficult problem to solve, and I am not aware that it has ever been attacked.

111. All flute-players are aware of the necessity for correcting the influence of variation in the strength of the exciting blast on the pitch of the notes of the flute. According to the force of the breath the performer alters its direction; the skilful flute-player is thus able to maintain perfect steadiness of pitch by careful regulation of the opposing forces under his command.

112. Reciprocal Action of the Air-reed and the Column of Air. It has been stated (§82) that a solid reed and a column of air excited by it, influence each other to an extent depending on the strength of the former. The air-reed and the air-column of the flute have the same reciprocity. Every flute-player must have noticed the sense of vibration experienced by the lips while the flute is sounding; a sensation totally different to that caused by the mere passage of the air when no instrument is present to respond to it. On attempting to sound a bad flute, or to unduly force a note on even a good one, the performer feels a slight though unmistakable shock to the lips, and the tone sometimes stops quite suddenly. Sometimes, however, greater pressure of the lips against each other, which causes an increase of density in the stream of breath equivalent in its effect to that of a stronger reed, will compel the flute to sound, thus coercing into obedience the refractory column of air.

113. The practical application of the theories set forth in

this chapter will be conveniently deferred, but it must already be abundantly clear that the flute stands superior to all other instruments in sympathetic responsiveness to the efforts of the performer, in fact, the really skilful flute-player and his flute are one, just as much as the singer and his voice, hence the unique beauty and flexibility, the variety of tone and expression, and the general indescribable charm, which are the well-known attributes of this exquisite instrument.