from the tube is not only lowered in pitch by the reduction of the bore at the lower extremity, but the depression goes on increasing, as the bore is reduced progressively from this end, until the place of mean amplitude of vibration is reached. After that, the pitch gradually rises until the size of the tube is reduced from the node downwards, when the sound is exactly the same as that given by the wide open tube. On continuing the reduction of the bore, the pitch rises constantly until the tube becomes smaller from end to end.

This experiment produces effects which are rather startling. It may be conveniently performed in either a cylindrical or a prismatic tube, by the insertion of a rod of sufficient thickness to reduce the diameter of the bore appreciably. The above account refers to the fundamental sound; the behaviour of the harmonics is still more curious. The same experiment may be so conducted as to afford conclusive proof of the truth of the statements given in §§ 154 and 155, and also of the following important facts: *the enlargement of the upper part of an open flute-tube flattens the pitch: the enlargement of the lower part has a contrary effect.* This rule applies to harmonics as well as to fundamentals.

170. The last subject of this chapter is a very obscure one, and its theoretical explanation has never, I believe, been attempted. Under certain circumstances, the natural law of isochronism is unable to assert itself; an ill-proportioned tube may set it at defiance, and cause the segments of the air-column to vibrate at different rates. The flute is peculiarly liable to this defect, as the delicate air-reed has not the power to control the vibrations of the column of air to the same extent as can the more ponderous reeds of other instruments: see §§ 82, 84, 112 and 134.

171. Falseness in a string (§ 47) affects the harmonics more than the fundamental, but deviation from the true proportions of the bore of a flute has often a contrary effect: the harmonics may even be improved, while the fundamental may be destroyed. The "horrid sound" of an ill-bored flute is technically termed a *rattle*, and when once heard, in full development, is not likely to be forgotten.

CHAPTER V.

ON SIMPLE AND COMPOSITE SOUNDS.

§172. SIMPLICITY AND COMPLEXITY OF SOUND.—174. PARTIALS. —192. LOWER ATTENDANT SOUNDS.—194. GRAVE HARMONICS.— 195. BEATS.

172. Simplicity and Complexity of Sound. There appears to be such good reason to doubt the possibility of the existence of an absolutely simple sound, that we may, perhaps, be justified in considering that all the sounds we hear are of necessity more or less complex, although the ear may sometimes fail to distinguish their component parts. Rameau (1737) went so far as to assert that a perfectly simple sound would be inappreciable to the ear, an assertion which he afterwards modified (1749) by saying that a simple sound is only noise, while musical tone is invariably composite. With these opinions which, however, rest on but a shadowy basis, Estève (1750) generally agreed.

173. Lord Rayleigh (1877) says that a tuning-fork gives a sound which becomes *nearly* simple, after the cessation of certain higher sounds which die rapidly away. Professor Helmholtz (1885, p. 69) tells us that "such musical tones as are not decomposable, but consist of a single, simple tone, are most readily and purely produced by holding a struck tuning-fork over the mouth of a resonance tube." On the next page we read: "Simple tones, accompanied only by the noise of rushing wind, can also be produced . . . . . . by blowing over the mouths of bottles with necks." He also speaks of wide stopped organ-pipes giving simple sounds. Probably the nearest approach to perfect simplicity is attained by the method of Lord Rayleigh, above mentioned. The first plan of Professor Helmholtz could only produce a sound inherently composite, and necessarily consisting of the tones of the fork and of the air-column in the tube. Besides, it is impossible to consider a sound pure, which is "accompanied by the noise of rushing wind."

174. Partials. It may be regarded as almost certain that every fundamental musical sound is associated with some, at least, of its harmonics; but, with harmonics themselves, when they are the principal sounds, are probably always joined other harmonics, though these are generally fewer and fainter than those which accompany fundamentals; the term "*partials*," first applied in this sense by Perrault, will therefore be used, for the sake of distinction, to designate the simultaneous accessory tones that contribute to, and form parts of, the general composite mass of sound, whether the principal tone of the latter, which gives the pitch and character to the whole, be fundamental or harmonic. The German word *Obertöne*, overtone, appears to be applied to harmonic sounds of all kinds, whether simultaneous or not.

175. The manner in which the vibrations of the partials are formed in a solid body is not difficult to understand: the smaller curves are simply superposed upon the larger ones. Thus, on the curve described by an entire string in the production of its fundamental (see *fig.* 1, chap. II), are superposed two smaller curves (*fig.* 2) which give the octave. On these smaller curves, others yet smaller are placed, and so on, indefinitely.

176. The interweaving, or incorporation, of the smaller with the larger segments of a column of air is not so easy to realize, but it is quite certain that it does occur, as may be roughly and readily proved by exposing the strings of a pianoforte; lifting the dampers by means of the pedal, and sounding a strong, firm, low note on a flute near the strings. On the cessation of the sound of the flute, some of its component parts will be heard to vibrate sympathetically in the form of a chord on the strings.

177. The reader will now do well to remember the general

law of Chladni, before quoted. "The air by which the sound is propagated makes neither more nor less vibrations than the body which produces the sound." It therefore follows that the air in which the sound is generated cannot add to the number of the sounds of a sonorous body.

178. The composite nature of sound is by no means a modern discovery: Mersenne and Estève mention its having been known to Aristotle. Des Cartes (1618) makes some excellent remarks showing his intimate acquaintance with this subject. He lays especial stress on the harmonic octave, and says that no musical sound can be heard which does not appear to the ear to be accompanied by the octave above it, an assertion which is not quite correct, as will hereafter appear. He also wrote an interesting letter on this question to Mersenne.

179. The latter (1636) discourses pleasantly on the fact that "strings make many different sounds, or one sound composed of many at the same time," and he remarks that the accessory sounds are never lower than the natural sound of the string, but that they always "follow the same progress as the *sauts* of the trumpet." He, however, falls into grave error when, in attempting to account for this multiplicity of sounds, he says: "it is necessary to examine how it could be, that the same string could strike the air differently at the same time, for since the string makes the five or six sounds of which I have spoken, it seems absolutely necessary that it should strike the air two, three, four and five times in the same time that it strikes it once, which it is impossible to imagine, unless it should be said that the half of the string strikes it twice while the whole string strikes it once, and that in the same time the third, fourth and fifth parts strike it three, four and five times. This is contrary to experience, which shows clearly that all the parts of a string make an equal number of vibrations in the same time. . . . The air, having been struck by the string, divides itself first into two parts, then into three, four, five, etc., which give the above mentioned sounds." Estève (1750) adopts this opinion.

180. Mersenne thus amusingly censures the not more erroneous opinions of others: "Some persons have sought to explain the cause of all tnese sounds by suggesting that they are due to the different surfaces of the string, and saying that the middle of the string makes a sound different from that of the exterior surface, but there is no semblance of probability that the string can be divided into several concave cylinders which cover the convex central cylinder, as one skin of an onion covers another."

181. Perrault (1680) appears to have attached great importance to the partials. The ensuing quotations from his previously quoted work, I have almost literally translated:

182. "Each musical sound is composed of many other sounds, which appear but as one tone."

183. "When we listen attentively to the sound of a bell, or of a trumpet, which are the instruments of music that make the most noise, we remark an assemblage of many notes that form a chord, and which, as in the organ, seem to compose but one single tone."

184. "Every noise, although apparently simple, is in effect a system and an assemblage of an infinity of partial noises that compose a total, in which no confusion is remarked, on account of the affinity that all these partial noises have together, by reason of there always being one amongst them which, prevailing over the others, gives the total noise its specific character."

185. "The chief effect of this assemblage of different tones which compose but one, is on the grave notes, and it is not so easily perceived in high ones."

In the first edition of Perrault's work, there is a diagram showing how the smaller curves of the accessory vibrations are superposed on the larger curves.

186. It was not to be supposed that so interesting a subject

as this, would escape the penetrating research of Daniel Bernoulli; thus, we find (1753A) that after explaining, in his customary lucid manner, the "*mélange*" of the sounds of strings, he says: "The air is not exempt from this multiplicity of co-existing sounds; it often happens that we obtain two different sounds at once from a tube; but, what proves the best, how little the different undulations of the air interfere with each other, is that we hear distinctly all the parts of a concert, and that all the undulations caused by these different parts are formed in the same mass of air in mutual independence." In a subsequent paper (1753B) he treats the subject at great length.

187. La Grange (1759) regrets his inability to find a satisfactory solution of the problem, but disbelieves that the origin of "this multiplicity of harmonic sounds" can be in the same one string. He thinks that they ought rather to be attributed to other "bodies which respond to the sound of the principal one," but in a later paper (1760-1) he is careful to explain that "many different sounds can co-exist and spread in the same mass of air, without destroying each other."

188. Bernoulli again approaches the subject in these words, which terminate his immortal paper of 1762: "The same single sonorous ray may be moved at the same time by many species of vibrations which do not interfere with each other in any manner: in the place of a node, with regard to one species, a segment may be formed with regard to another species; in a word, each species of vibration may be formed independently of all other species, exactly as if there were no mixture at all. Many sonorous rays may also cross each other; whence it arises that we can hear distinctly many sounds at once, whether they approach from one or from many different places."

189. Chaldni (1809) calls attention to the facility with which two sounds may be obtained from a wind-instrument at the same time by blowing in a manner not quite appropriate for either; an unfortunate fact, only too well-known to beginners on the flute, and their teachers.

190. By a modification of the beautiful experiment described in §53, Dr. Melde (1864) rendered visible "the phenomenon of the simultaneous sounding of two or more of the harmonic sounds of a vibrating string."

191. Dr. Koenig, the eminent acoustician of Paris (1872), showed the co-existence of two sounds in the same column of air by means of the images of his celebrated "manometric flames" in a revolving mirror.

192. Lower Attendant Sounds. Independently of the consequences of unskilful blowing, the harmonics of flutes and flute-pipes are always attended by one or more of the lower sounds of the same series; fundamental, harmonic, or both, as the case may be. These sounds, to which I have given the above name in default of a better one, appear to have escaped the notice of all writers on acoustics, and yet their presence may sometimes be detected even by the dullest ears. Louis Drouet (1830), the celebrated flute-player, casually mentions the fact that certain harmonics of the flute are accompanied by the *fifths* below them, and on that account he condemns the use of such notes. With this exception, I have never found even the most distant allusion to the sounds in question.

It is probable that a column of air vibrating in a flute-pipe invariably gives simultaneously all the sounds that could possibly be obtained from it, and therefore it may be right to consider that a harmonic is not produced from such a column of air, but rather that it is rendered prominent, while the sounds above and below it fall more or less into abeyance, though they are not entirely eliminated from the conglomerate mass of tone.

193. The opening of a vent-hole of sufficient size, cuts off some of these sounds, those only being possible which could be produced by using the vent-hole as a note-hole, or by so using the highest vent-hole in the case of more than one being open. I have not investigated the lower attendant sounds in any other than flute-pipes, but I have no doubt of their presence in the tones of all kinds of wind-instruments.

194. Grave Harmonics. The peculiar sounds just described have no affinity to the well-known *grave harmonics*, *combinational tones*, or *resultant tones*, as they are variously called. Chladni states that these sounds were discovered by Sorge of Hamburg in 1744, but in *The Harmonicon* for 1827 there is an interesting letter from Fayolle, in which the discovery is claimed for Tartini. The writer says that Tartini's pupils attested that although the great master's well-known treatise was not published until 1754, the discovery was made in 1714. Grave harmonics are invariably produced in the air surrounding the sonorous bodies which are their primary cause, and thus they limit the application of the law of Chladni, cited in §§20 and 177. Lower attendant sounds, on the contrary, are always produced inside the tube of a wind-instrument. Grave harmonics are the result of the difference between the rates of vibration of two sounds. They are sometimes exceedingly prominent during the sounding of the high notes of two wind-instruments. The effect of grave harmonics is always unpleasant, and sometimes actually painful.

195. Beats. When two notes, slightly differing from each other in pitch, are sounded at the same time, the sounds do not blend smoothly and continuously, but sudden augmentations of power occur, which are called beats. These beats are caused by the periodical coincidences of the vibrations of the two sounds. Sauveur (1700) appears to have been the first scientifically to investigate these phenomena. The beats caused by the imperfect unison of fundamental sounds may be easily understood.

196. Two fundamental sounds with a difference between them of one vibration in a certain time, will make one beat after the expiration of that time, and the vibrations will then make a fresh start together. If we sound, at the same time, two tuning-forks, one of which makes four hundred and fifty, and the other four hundred and fifty-one vibrations in a second, the result will be one beat in a second; and if two forks vibrate as four hundred and fifty to four hundred and fifty-two, the beats will occur twice in a second, and so on.

197. Beats are not due only to differences between fundamental notes, or to imperfect unisons. Dr. Pole (1877) thus writes: "Beats may arise (1) from two fundamental sounds that are nearly in unison: this kind may be called the *unison beat;* or (2) from two fundamental sounds which lie wider apart but the overtones [partials] of which approach each other within beating distance: this kind may be called the *overtone beat.* . . . There is, however, a third kind of beat which was pointed out by Dr. Smith of Cambridge, in his learned work on Harmonics published in 1749 [(1749 and 1759)] and was afterwards further explained by Mr. De Morgan in the Cambridge Philosophical Transactions for 1858. It differs from the first mentioned kind of beat, in that it arises from the imperfection, not of unisons, but of wide-apart consonances, such as the third, fourth, fifth, sixth and octave. It has been called the *beat of imperfect consonances.* It is well-known, practically, to organ-tuners, and is appreciable to any musical ear. . . . The theory of the consonance beat as explained by Smith and De Morgan, is too complicated to be given here, but it may be said in general terms to be a beat of the second order, depending, not like the unison beat, on a cycle of differing periods, but on a cycle of differing cycles."

198. Notwithstanding the disagreeable effect of beats on the ear, they have been of immense service to the cause of music, for they are proved to be the only satisfactory tests of intonation, as will be seen in chapter IX. Mr. Ellis has written a masterly and exhaustive treatise on this subject (1880B), a copy of which he was kind enough to present to me, and which I have found exceedingly useful.

CHAPTER VI.

ON QUALITY OF TONE, AND THE CAUSES OF ITS VARIETY.

199. General View of Quality of Tone. The plain English expression, quality of tone, will be used, throughout this work, to express those peculiar characteristics of musical sound, by means of which we are enabled, not only to distinguish the tones of different voices and instruments of music from one another, but to appreciate the finer and more delicate shades of variety in the tones elicited by different performers from the same instrument, and also the still more recondite differences between the sounds produced by the same performer from the same instrument at different times. The French word *timbre,* which originally meant "a bell struck on the outside by a hammer, instead of on the inside by a clapper," and which now has more meanings than letters, has lately been imported into this country as a substitute for the English term, but, as Mr. Ellis observes, it is "often odiously mispronounced, and not worth preserving." Professor Tyndall's new word "clang-tint,"