directly. The same result is obtained when both sonorous bodies are at a distance from the ear and from each other, and when the sounds they emit are conveyed to the ear by different conductors, and heard by means of separate telephones. With such an arrangement, the formation of a resultant sound-wave, competent to generate the beat-tone perceived, seems to be impossible.

But it is time to conclude. We have been discussing one of the most difficult and warmly-debated questions connected with the subject of sound. Not only have Koenig and Helmholtz entered the lists against each other, but several other physicists, almost equally distinguished, have made the matter an issue of considerable moment. Among these may especially be mentioned, W. Preyer, G. Appunn, R. H. M. Bosanquet, and Lord Rayleigh. I have endeavored, without entering too much into detail, to give you what may be regarded as experimentally proved regarding this most vexed question of beats and beat-tones. Those of you who may be desirous of knowing more about the subject, I must refer to the researches of the investigators just mentioned. I commend especially to your consideration the account of the very elaborate series of experiments of Dr. Koenig on beats and beat-tones, as given in his admirable "Quelques Expériences d'Acoustique."

CHAPTER IX.

QUALITY OF SOUND.

SOUNDS, as we have learned, differ one from another in three ways, — in loudness, in pitch, and in quality. Loudness, as we saw, depends on the amplitude of vibration of the particles of the sonorous body, and pitch is due to the rapidity of their vibration. What, then, is the cause of quality? The answer to this most interesting, and, I may add, most difficult question, I shall endeavor to give you in to-day's lecture. I shall ask you to give me your closest attention, as we are entering upon a question which, to all except the few who have made it a matter of special investigation, is either entirely misunderstood, or known only by name.

We are all aware, as a matter of experience, that the tone of a violin, even when the pitch is the same, differs from the tone of a flute, a clarinet, a guitar, or a pianoforte. So, too, may the tone of one violin differ from that of another violin, or the tone of one pianoforte differ from that of another pianoforte, and that, too, when the pitch and loudness of the notes sounded are the same. The tone of a Steinway "Grand" is different from that of a Weber or a Chickering "Grand;" and the tones of a modern violin are vastly different from those emitted by an Amati, or a Guadagnini, or a Stradivarius. Even different players evoke different tones from the same instrument. No beginner can call forth from a pianoforte the purity of tone that responded to the touch of a Liszt, a Chopin, or a Rubinstein, nor can a tyro on the violin draw from the instrument the sweet, smooth, soul-stirring notes that it would yield to a Joachim, a Remeyni, or a

Paganini. The nature of the tones, then, varies with the instrument used, and varies, too, according to the method of manufacture, the materials used, and the way in which they were seasoned or tempered, and according as the performer is a master or a beginner in the art of music. More than this. The nature of the tones elicited from an instrument may depend even on the mood or the condition of health of the performer. Thus, as is obvious, the differences arising from various causes are almost infinitely varied and variable.

It is to these very marked differences of tone, emanating from different causes, and produced by different performers, that we give the general name "quality." The word "character" is also used to express the same thing. The French word *timbre* is likewise employed. The Germans use the very expressive term *klang-farbe*, which, literally translated, means, "clang-color," or "clang-tint." I do not think, however, that we can well improve on the time-honored word "quality," — a word that is familiar to you all, as designating those differences of tone about which we are now speaking.

Knowing, then, what is meant by quality of tone, we proceed now to investigate its origin. And in order that we may have a better understanding of the subject under consideration, it will be well to take a hasty review of the ground over which we have travelled.

It had long been suspected that the quality of tone depended on the mode of vibration of the sonorous body, — that is, on the form of the wave corresponding to the tone emitted; but nothing certain was known about the matter until Helmholtz took up the subject, about thirty years ago. His profound "Lehre von den Tonempfindungen," published in 1863, cleared up what until that time had been an enigma that had baffled all attempts at its solution.

In this great work he proves that the quality of a tone is due to the number and relative intensity of the partial tones that accompany the fundamental. The way for this grand generalization had been paved by several other investigators, but Helmholtz was the first to give it expression, and experimentally to demonstrate its truth. One of the first to throw light on this mysterious subject was the illustrious Father Mersenne. Speaking of Aristotle, he says, "He seems to have been ignorant of the fact that every string produces five or more different sounds at the same time, the strongest of which is called the natural tone of the string, and alone is accustomed to be taken notice of, for the others are so feeble that they are perceptible only to delicate ears. . . . Not only the octave and the fifteenth, but also the twelfth and major seventeenth are always heard, and, over and above these, the major twenty-third (the ninth partial), about the end of the natural sound."[1]

Sauveur, one of the founders of acoustics, made a special study of these sounds accompanying the fundamental. "On plucking a harp-string," he says, "a delicate and practised ear may, in addition to the fundamental, hear other and more acute sounds produced by portions of the string, which, as it were, separate themselves from the string vibrating as a whole, in order to start up vibrations of their own."

Later on Chladni took up the subject, and showed that compound sounds are produced by organ-pipes, wind instruments, and bells, as well as by strings. Rameau, the eminent French composer, made it, in 1722, the basis of his system of musical harmony.

In his admirable article on Sound, written for the "Encyclopædia Metropolitana," Sir John Herschel says, "It was long known to musicians that besides the principal or fundamental note of a string, an experienced ear could detect in its sound other notes, related to this fundamental one by fixed laws of harmony, and which are called, therefore, harmonic sounds. They are the very same, which by the production of distinct nodes may be insulated, and, as it were, cleared from the confusing effect of co-existent

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[1] Harm., Lib. IX. Prop. 33.

sounds. They are, however, much more distinct in bells and other sounding bodies than in strings, in which only delicate ears can detect them."

From a communication made to the French Academy in 1875, it appears that Monge, the famous French mathematician, was one of the first to divine the true cause of the quality of sounds. Speaking of the sounds emitted by vibrating strings, Monge asserted it as his belief that their quality was due to the order and number of the vibrations of the aliquot parts of the string in question. And he added, further, that if one could succeed in suppressing the vibrations of these aliquot parts, all strings, of whatever material made, would yield tones of the same quality.

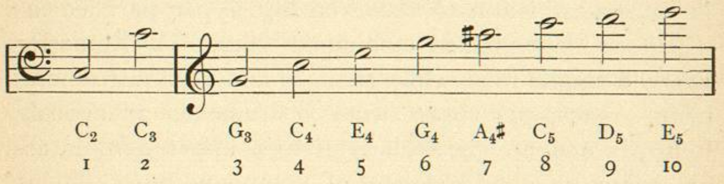
In 1817, Biot, who had been a pupil of Monge about twenty years previous, reproduced in his "Précis Élémentaire de Physique Expérimentale" the theory of his master in a somewhat modified form.

"All sonorous bodies," he says, "yield simultaneously an infinite number of sounds of gradually decreasing intensity. This phenomenon is similar to that which obtains for the harmonics of strings; but the law for the series of harmonics is different for bodies of different forms. May it not be this difference which produces the particular character of sound, called *timbre*, which distinguishes each form of body, and which causes the sound of a string and that of a vase to produce in us different sensations? May it not be owing to the diminution of the intensity of harmonics of each series that we find agreeable certain concords that would be intolerable if produced by sounds equally loud? And may not the quality of each particular substance — of wood or metal, for instance — be due to the superior intensity of one or another harmonic?"

In the first edition of his excellent "Traité de Physique," published in 1855, eight years before the appearance of Helmholtz's great work, M. Daguin has the following paragraph: "In musical instruments *timbre* is due most frequently to feeble sounds which accompany the fundamental. Sometimes these concomitant sounds arise from

the vibrating parts themselves, which thus render audible several sounds at the same time. At other times the vibrating body transmits these tremors to other parts of the instrument. . . . *Timbre* may also be due to the manner in which the velocity of the parts in the vibrating body varies during each oscillation. The curves representing sonorous waves may be of variable form, and the wave of rarefaction may be different from that of condensation. It may even be that there are interruptions between the successive waves."

To get a clear idea of the order of sequence of these harmonic sounds, or upper partials, as we have been calling them, let us write out in musical notation the first nine upper partials of C_2:[1] —



The seventh note, represented approximately by $A_4\sharp$, — it is, in fact, a little higher than $A_4\sharp$, — although called an harmonic in acoustics, is not considered as such in music. The same is true of D_5, the ninth partial. Either of these sounded simultaneously with the prime with sufficient intensity would cause the most jarring discord.[2]

Having thus refreshed our memories regarding a few points developed in the preceding lectures, we are now prepared to follow Helmholtz in his investigations as to the quality of sound. He tells us, as has already been stated, that the quality of a sound depends on the number of upper partials present, and their relative intensity. Mersenne, Sauveur, Chladni, and others tell us what these partials are, and when they are generated. In order to produce all the different modifications of quality ascribed to them, they should possess considerable intensity as com-

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[1] Compare the notes here given with those in Chapter IV.

[2] See Chapter X.

pared with their primes. We should, in a word, be able to hear them and distinguish them from the prime note which they accompany, and to which they give their characteristic quality.

In order to hear these upper partials it is not necessary, as might be supposed, to have a particularly acute ear. An ordinary ear, when the attention is properly directed, can perceive them in many instances, and a little practice will enable one to single out one or more of them from any sound that may contain them.

There are, of course, some tones that are practically devoid of upper partials. Such tones are emitted by stopped organ-pipes, and by certain specially constructed tuning-forks. These, as has been stated, are called simple tones, in contradistinction to those having upper partials, and which are denominated compound tones. The flute gives nearly a simple tone, while stringed and reed instruments, open organ-pipes, brass wind instruments, as also the human voice, are particularly rich in upper partials, and are, therefore, good instances of compound tones.

Here, too, we must distinguish between *single* and *composite* tones. A single tone, which may be simple or compound, is a tone emitted by one sounding body. A composite tone is made up of tones — simple or compound — from several sources of sound. Simple tones are characterized by purity and softness, whereas compound tones are distinguished for richness and brilliancy. But simple tones, however pure, are dull, and appear to be more grave than they really are. Compound tones, on the contrary, are bright and crisp, and often partake, in a marked manner, of the acuteness of their upper partials. For this reason even musicians often make a mistake of an octave in estimating the pitch of a given compound sound, taking the pitch of the first upper partial for that of its prime.

Upper partials are most easily heard when they are inharmonic, as in the case of bells. I strike the large Japanese gong on the table, and you at once hear distinctly several tones of quite different pitch. The lowest is deep, mellow, and powerful, and resembles the tone of a cathedral bell. The upper partials are clear and pure, and although not all constituting harmonic intervals with their prime, they still combine in such a way as to produce a pleasing effect. I excite another gong, similar to the first, and while sounding alone the result is similar to that obtained with the first gong; but the bell, being smaller, its prime and upper partials have a higher pitch. When I sound both together you perceive a certain jarring and harshness that disclose, in a most striking manner, the influence of the inharmonic partials. The primes of the two gongs form a comparatively good concord, making very nearly the interval of a fourth; but the upper partials are so far from harmonizing with each other or with their primes that they generate discord. That, however, to which I wish especially to direct your attention is the number of different notes — five or six at least — which can be distinctly separated from the general mass of sound.

The inharmonic upper partials heard so well in bells are also given forth with remarkable intensity by most tuning-forks and metal bars. I give the fork I hold in my hand a vigorous blow with an ivory hammer, and, in addition to the prime note of the fork, you hear distinctly the tinkle of high upper partials. They are, however, quite evanescent, while the prime tone persists for some length of time.

On the table is an instrument called the metallophone. It consists, as you know, of a number of steel bars, which, when struck, vibrate in the same manner as the tuning-fork. When I strike one of these bars, you hear the upper partials as distinctly as in the case of the tuning-fork. If I strike in succession a number of bars separated from each other by harmonic intervals, the primes of these bars will give a pleasing sensation; but the upper partials, not harmonizing with each other, will produce a jingle that is anything but agreeable. But, as in the case of the gongs and tuning-forks just used, the number of separate notes that can be distinguished in the very composite note produced is much greater than the number of sonorous bodies originating the sounds.

There is, then, no difficulty in hearing inharmonic upper partials. But just now we are more interested in detecting the presence of harmonic upper partials. They are, indeed, found in specially constructed bells and tuning-forks along with inharmonic partials; but we shall turn our attention to sounds in which harmonic partials so predominate over those that are inharmonic that the latter are practically imperceptible.

I hold in my hand a long, narrow, open organ-pipe, made of copper. It differs from wider pipes in the fact that it is capable of giving, with differences of pressure, a series of upper partials of remarkable purity and intensity. By forcing air through the pipe, we can, at will, produce any harmonic desired, or the pressure of wind can be so regulated as to cause two partials to sound at the same time. You now hear the fundamental and its octave, and in such a way that you have no difficulty whatever in recognizing the presence of both notes.

We now try a pipe that is exactly similar to the last one, except that it is stopped, instead of open. This pipe, as you know, will also readily yield upper partials. But, unlike the open pipe, whose partials follow in the order both of even and odd numbers, — 1, 2, 3, 4, 5, etc., — the stopped pipe will give only such partials as correspond to the odd numbers 1, 3, 5, etc. As with the open pipe, we can, by varying the pressure of air admitted into the pipe, elicit from it, at pleasure, any of the partials that it is capable of yielding. In like manner we can cause it to emit two notes simultaneously. Just now it is sounding its prime and its twelfth, both of which you can distinguish with ease.

It is scarcely possible to render the upper partials of strings audible to all of you, as they are, in most instances, much less distinct than those to which you have been listening. I shall, however, show you how they may be detected, and leave any of those present who may be sufficiently interested in the matter to make the experiments at their leisure.

In making such experiments, it will be well to look, first, for the upper partials corresponding to odd numbers, as they are most readily heard. Thus, it is easier to hear the third and the fifth partials than to perceive the second and the fourth. Sounding beforehand a note of the pitch of the partial one wishes to observe, will materially aid in hearing such partial when a compound tone containing it is produced.

Both the pianoforte and the harmonium are good instruments on which to study upper partials. Suppose, then, we employ the piano, and wish to hear G_3, which is the third partial of C_2. All that is necessary, in order to hear this note in the compound note C_2, is to strike gently the note G_3, and, after it dies out, to strike strongly C_2, when our ear, already prepared for the note G_3, hears it distinctly in the note C_2. In the same manner we may hear E_4, which is the fifth partial of C_2. A little practice will also enable one to hear the first and second octaves of the prime. On one of the louder stops of a harmonium one may hear, in addition to the preceding, even the seventh and the ninth partials. The two latter are inaudible on the pianoforte, because it is so constructed that they are either totally or partially eliminated.

On the sonometer we should proceed in a different way. If we wish to hear the third partial, for instance, we should gently press a feather on one of the corresponding nodes, and then excite the string by plucking it. In this way we can perceive distinctly the note that is due to the vibration of the third part of the string, as well as that caused by the string vibrating as a whole. In a similar manner, we could render audible several other partials. The third and fifth partials, thus excited, are sufficiently intense to be heard at some distance, with comparative facility. By employing thin strings, which are especially rich in loud upper partials, Helmholtz was able to recognize partials up to the sixteenth.

It is still more difficult to hear the upper partials of the human voice; but even these can be perceived with a little attention and practice. Let a powerful bass voice sing $E_2\flat$, to the word "awe;" then gently sound on the pianoforte $B_3\flat$, which is the third partial of $E_2\flat$, and after the note of the piano dies away, one will still continue to hear, in the voice of the singer, the continuation of the note emitted by the pianoforte. In the same way, if the note be sung to the broad sound of *a*, as in "father," one may hear G_4, which is the fifth partial of $E_2\flat$.

Under favorable circumstances, and by giving the matter special attention, one may hear some of the upper partials of the human voice without the assistance of any apparatus whatever. Rameau was thus able to distinguish them with the unaided ear. Seiler, of Leipsic, says that while listening to the voice of the night watchman at a distance, he was able to hear, first the third partial, and then the prime of the note uttered. Garcia relates that in listening to his own voice in the quiet of the night he could detect both the octave and the twelfth of the note he sang. I have heard the same two partials in the voice of a muezzin in Cairo calling the faithful to prayer. But when I heard them, the circumstances were especially favorable. The muezzin had a remarkably powerful, rich voice, the night was unusually still, and the minaret on which stood the servant of the Prophet was only a short distance from the place where I happened to be at the time.

To distinguish more clearly and more readily the upper partials existing in any compound tone, Helmholtz constructed the resonators with which you are already familiar. This is, in reality, only a modification of the resonant case first used by Marloye to strengthen the prime tone of a tuning-fork. Helmholtz's first resonators were made from bottles and from the spherical portions of glass retorts. He also employed conical forms made of pasteboard, tin, or zinc. But by far the best and most useful, as well as the most sensitive resonators, are such as are made by Koenig, and which are especially designed to reinforce strongly one tone only. The conical resonators sometimes used have the disadvantage of strengthening the intensity of all the upper partials at the same time that they augment the prime.

With a series of spherical resonators as made by Koenig, the dimensions of which are accurately calculated to give the maximum of resonance for only one particular note, any one, even though entirely unskilled in the study of musical sounds, is able at once, and without the slightest difficulty, to single out a number of the upper partials found in any compound tone of such instruments as the violin, harmonium, or pianoforte. These resonators enable those who have trained musical ears to detect the presence of partials that are entirely imperceptible to the unaided ear, and to extend their investigations in the study of compound sounds in a manner that would otherwise be quite impossible. By means of resonators as many as sixteen partials of the human voice have been heard, while in reed pipes the number has been swollen to twenty.

Koenig has increased the delicacy and extended the usefulness of the resonator by coupling it with the manometric capsule. In this way the experiment is made to appeal to the eye instead of to the ear. As a consequence, a person who is entirely deaf can analyze a compound tone as well as one who has a most delicate musical ear.

Let us connect this stopped organ-pipe, C_2, with the acoustic bellows. By suitably regulating the pressure of the air we can cause the pipe to speak separately either its prime, C_2, or its twelfth, G_3. Not only this, we can so adjust the pressure of the wind that we can detect without difficulty the presence of both these tones at the same time. By applying to the ear the resonator corresponding to the note G_3, one can readily hear the note, when without the resonator only the note C_2 would be audible.

By connecting the resonators corresponding to the notes