fifth and octave, the result is a major chord, the sound of which is very different from that of a single note or of a note with its octave. If the third be diminished by a semitone, there is a different quality, which is peculiar to minor chords. In this way a great variety of musical sounds may be made upon a single instrument, as the piano; and by the harmonious combinations of the notes of different instruments and of different registers of the human voice, as in choral and orchestral compositions, shades of effect, almost innumerable, may be produced. The modification of sounds in this way constitutes harmony; and an educated ear not only experiences pleasure from these musical combinations, but can distinguish their different component parts.

A chord may convey to the ear the sensation of completeness in itself or it may lead to a succession of notes before this sense of completeness is attained. Different chords of the same key may be made to follow each other, or by transition-notes, may pass to the chords of other keys. Each key has its fundamental note, and the transition from one key to another, in order to be agreeable to the ear, must be made in certain ways. These regular transitions constitute modulation. The ear becomes fatigued by long successions of notes or chords always in one key, and modulation is essential to the enjoyment of elaborate musical compositions; otherwise the notes would not only become monotonous, but their correct appreciation would be impaired, as the appreciation of colors becomes less distinct after looking for a long time at an object presenting a single vivid tint.

Laws of Sonorous Vibrations.—Sound is produced by vibrations in a ponderable medium; and the sounds ordinarily heard are transmitted to the ear by means of vibrations of the atmosphere. A simple and very common illustration of this fact is afforded by the experiment of striking a bell carefully arranged *in vacuo*. Although the stroke and the vibration can readily be seen, there is no sound; and if air be gradually introduced, the sound will become appreciable, and progressively more intense as the surrounding medium is increased in density. The oscillations of sound are to and fro in the direction of the line of conduction and are said to be longitudinal. In the undulatory theory of light, the vibrations are supposed to be at right angles to the line of propagation, or transversal. A complete oscillation to and fro is called a sound-wave.

It is evident that vibrating bodies may be made to perform and impart to the atmosphere oscillations of greater or less amplitude. The intensity of sound is in proportion to the amplitude of the vibrations. In a vibrating body capable of producing a definite number of waves of sound in a second, it is evident that the greater the amplitude of the wave, the greater is the velocity of the particles thrown into vibration. It has been ascertained that there is an invariable mathematical relation between the intensity of sound, the velocity of the conducting particles and the amplitude of the waves; and this is expressed by the formula, that the intensity is proportional to the square of the amplitude. It is evident, also, that the intensity of sound is diminished by distance. The sound, as the waves recede from the sonorous body, becomes distributed over an increased area. The propagation of sound has been reduced also to the formula, that the intensity diminishes in proportion to the square of the distance.

Sonorous vibrations are subject to many of the laws of reflection of light. Sound may be absorbed by soft and non-vibrating surfaces, in the same way that certain surfaces aborb the rays of light. By carefully arranged convex surfaces, the waves of sound may readily be collected to a focus. These laws of the reflection of sonorous waves explain echoes and the conduction of sound by confined strata of air, as in tubes. To make the parallel between sonorous and luminous transmission more complete, it has been ascertained that the waves of sound may be refracted to a focus, by being made to pass through an acoustic lens, as a balloon filled with carbon dioxide. The waves of sound may also be deflected around solid bodies, when they produce what have been called by Tyndall, shadows of sound.

Any one observing the sound produced by the blow of an axe can note the fact that sound is transmitted with much less rapidity than light. At a short distance the view of the body is practically instantaneous; but there is a considerable interval between the blow and the sound. This interval represents the velocity of sonorous conduction. This fact is also illustrated by the interval between a flash of lightning and the sound of thunder. The velocity of sound depends upon the density and elasticity of the conducting medium. The rate of conduction of sound, by atmospheric air at the freezing-point of water, is about 1,090 feet (332 metres) per second. This rate presents comparatively slight variations for the different gases, but it is very much more rapid in liquids and in solids.

Noise and Musical Sounds.—There is a well defined physical as well as an æsthetic distinction between noise and music. Taking as examples, single sounds, a sound becomes noise when the air is thrown into confused and irregular vibrations. A noise may be composed of musical sounds, when these are not in accord with each other, and sounds called musical are not always entirely free from discordant vibrations. A noise possesses intensity, varying with the amplitude of the vibrations, and it may have different qualities depending upon the form of its vibrations. A noise may be called dull, sharp, ringing, metallic, hollow etc., these terms expressing qualities that are readily understood. A noise may also be called sharp or low in pitch, as the rapid or slow vibrations predominate, without answering the requirements of musical sounds.

A musical sound consists of vibrations following each other at regular intervals, provided that the succession of waves be not too slow or too rapid. When the vibrations are too slow, there is an appreciable succession of impulses, and the sound is not musical. When they are too rapid, the sound is excessively sharp, but it is painfully acute and has no pitch that can be accurately determined by the auditory apparatus. Such sounds may be occasionally employed in musical compositions, but in themselves they are not strictly musical.

Musical sounds have the characters of duration, intensity, pitch and quality. Duration depends simply upon the length of time during which the vibrating body continues in action. Intensity depends upon the amplitude of the vibrations, and it has no relation whatsoever to pitch. Pitch depends absolutely upon the rapidity of the regular vibrations, and quality, upon the combinations of different notes in harmony, the character of the harmonics of fundamental tones and the form of the vibrations.

Pitch of Musical Sounds.—Pitch depends upon the number of vibrations. A musical sound may be of greater or less intensity; it may at first be quite loud and gradually die away; but the number of vibrations in a definite note is invariable, be it weak or powerful. The rapidity of the conduction of sound does not vary with its intensity or pitch, and in the harmonious combination of the sounds of different instruments, be they high or low in pitch, intense or feeble, it is always the same in the same conducting medium. Distinct musical notes may present a great variety of qualities, but all notes of the same pitch have absolutely equal rates of vibration. Notes equal in pitch are said to be in unison. An educated ear can distinguish slight differences in pitch in ordinary musical notes; but this power of appreciation of pitch is restricted within well defined limits, which vary slightly in different individuals. According to Helmholtz, the range of sounds that can be legitimately employed in music is between 40 and 4,000 vibrations in a second, embracing about seven octaves. In an orchestra the double bass gives the lowest note, which has 40·25 vibrations in a second, and the highest note, given by the small flute, has 4,752 vibrations. In grand organs there is a pipe which gives a note of 16·5 vibrations, and the deepest note of modern pianos has 27·5 vibrations; but delicate shades of pitch in these low notes are not appreciable to most persons. Sounds above the limits just indicated are painfully sharp, and their pitch can not be exactly appreciated by the ear.

Musical Scale.—A knowledge of the relations of different notes to each other lies at the foundation of the science of music; and without a clear idea of certain of the fundamental laws of music, it is impossible to thoroughly comprehend the mechanism of audition.

It requires very little cultivation of the ear to enable one to comprehend the fact that the successions and combinations of notes must obey certain fixed laws; and long before these laws were subjects of mathematical demonstration, the relations of the different notes of the scale were established, merely because certain successions and combinations were agreeable to the ear, while others were discordant and apparently unnatural.

The most convenient sounds for study are those produced by vibrating strings, and the phenomena here observed are essentially the same for all musical sounds; for it is by means of vibrations communicated to the air that the waves of sound find their way to the auditory apparatus. Take, to begin with, a string vibrating 48 times in a second. If this string be divided into two equal parts, each part will vibrate 96 times in a second. The note thus produced is the octave, or the 8th of the primary note, called the 8th, because the natural scale contains eight notes, of which the first is the lowest, and the last, the highest. The half may be divided again, producing a second octave, and so on, within the limits of appreciation of musical sounds. If the string be divided so that $\frac{2}{3}$ of its length will vibrate, there are 72 vibrations in a second, and this note is the 5th in the scale. If the string be divided again, so as to leave $\frac{4}{5}$ of its length, there are 60 vibrations, which give the 3d note in the scale. These are the most natural subdivisions of the note; and the 1st, 3d, 5th and 8th, when sounded together, make what is known as the common major chord. Three-fourths of the length of the original string make 64 vibrations, and give the 4th note in the scale. With $\frac{8}{9}$ of the string, there are 54 vibrations, and the note is the 2d in the scale. With $\frac{3}{5}$ of the string, there are 80 vibrations, or the 6th note in the scale. With $\frac{8}{15}$ of the string, there are 90 vibrations, or the 7th note in the scale. The original note, which may be called C, is the key-note, or the tonic. In this scale, which is called the natural, or diatonic, there is a regular mathematical progression from the 1st to the 8th. This is called the major key. Melody consists in an agreeable succession of notes, which may be assumed, for the sake of simplicity, to be pure. In a simple melody every note must be one of those in the scale. When a different note is sounded, the melody passes into a key which has a different fundamental note, or tonic, with a different succession of 3ds, 5ths etc. Every key, therefore, has its 1st, 3d, 5th and 8th, as well as the intermediate notes. If a note formed by a string $\frac{5}{6}$ the length of the tonic instead of $\frac{4}{5}$, be substituted for the major 3d, the key is converted into the minor. The minor chord, consisting of the 1st, the diminished 3d, the 5th and the 8th, is perfectly harmonious, but it has a quality quite different from that of the major chord. The notes of a melody may progress in the minor key as well as in the major. Taking the small numbers of vibrations merely for convenience, the following is the mode of progression in the natural scale, which may be assumed to be the scale of C major:

	1st.	2d.	3d.	4th.	5th.	6th.	7th.	8th.
Note	C	D	E	F	G	A	B	C
Lengths of the string	1	$\frac{8}{9}$	$\frac{4}{5}$	$\frac{3}{4}$	$\frac{2}{3}$	$\frac{3}{5}$	$\frac{8}{15}$	$\frac{1}{2}$
Number of vibrations	48	54	60	64	72	80	90	96

The intervals between the notes of the scale, it is seen, are not equal. The smallest, between the 3d and 4th and the 7th and 8th, are called semitones. The other intervals are either full perfect tones or small perfect tones. Although there are semitones, not belonging to the key of C, between C and D, D and E, F and G, G and A, and A and B, these intervals are not all composed of exactly the same number of vibrations; so that, taking the notes on a piano, with D as the tonic, the 5th would be A. It is assumed that D has 54 vibrations, and A, 80, giving a difference of 26. With C as the tonic and G as the fifth, there is a difference of 24. It is on account of these differences in the intervals, that each key in music has a more or less peculiar and distinctive character.

Even in melody, and still more in harmony, in long compositions, the ear becomes fatigued by a single key, and it is necessary, in order to produce the most pleasing effects, to change the tonic, by what is called modulation, returning afterward to the original key.

Quality of Musical Sounds.—Nearly all musical sounds, which seem at first to be simple, can be resolved into certain well defined constituents; but with the exception of the notes of great stopped pipes in the organ, there are few absolutely simple sounds used in music. These simple sounds are pure, but are of an unsatisfactory quality and wanting in richness. Almost all other musical sounds have a fundamental tone, which is at once recognized; but this tone is accompanied by harmonics caused by secondary vibrations of subdivisions of the sonorous body. The number, pitch and intensity of these harmonic, or aliquot vibrations affect what is called the quality, or timbre of musical notes, by modifying the form of the sonorous waves. A string vibrating a certain number of times in a second, if the vibrations were absolutely simple, would produce, according to the laws of vibrating bodies, a simple, musical tone; but as the string subdivides itself into different portions, one of which gives the 3d, another, the 5th, and so on, of the fundamental tone, it is evident that the form of the vibrations must be considerably modified, and with these modifications in form, the quality, or timbre of the note is changed.

From what has just been stated, it follows that nearly all musical notes consist, not only of a fundamental sound, but of harmonic vibrations, subordinate to the fundamental and qualifying it in a particular way. These harmonics may be feeble or intense; certain of them may predominate over others; some that are usually present may be eliminated; and in short, there may be a great diversity in their arrangement, and thus the timbre may present an infinite variety. This is one of the elements entering into the composition of notes, and it affords a partial explanation of quality.

Another element in the quality of notes depends upon their re-enforcement by resonance. The vibrations of a stretched string not connected with a resonant body are almost inaudible. In musical instruments the sound is taken up by some mechanical arrangement, as the sound-board of the organ, piano, violin, harp or guitar. In the violin, for example, the sweetness of the notes depends chiefly upon the construction of the resonant part of the instrument, and but little upon the strings themselves, which latter are frequently changed; and the same is true of the human voice.

In addition to the harmonic tones of sonorous bodies, various discordant sounds are generally present, which modify the timbre, producing, usually, a certain roughness, such as the grating of a violin-bow, the friction of the columns of air against the angles in wind-instruments, etc. All of these conditions have their effect upon the quality of tones; and these discordant sounds may exist in infinite number and variety. These sounds are composed of irregular vibrations and consequently are inharmonious. Nearly all notes that are spoken of in general terms as musical are composed of musical, or harmonic, aliquot tones with the discordant elements to which allusion has just been made.

Aside from the relations of the various component parts of musical notes,

the quality depends largely upon the form of the vibrations. To quote the words of Helmholtz, "the more uniformly rounded the form of the wave, the softer and milder is the quality of the sound. The more jerking and angular the wave-form, the more piercing the quality. Tuning-forks, with their rounded forms of wave, have an extraordinarily soft quality; and the qualities of sound generated by the zither and violin resemble in harshness the angularity of their wave-forms."

Harmonics, or Overtones.—As before stated, nearly all sounds are composite, but some contain many more aliquot, or secondary vibrations than others. The notes of vibrating strings are peculiarly rich in harmonics, and these may be used for illustration, remembering that the phenomena here observed have their analogies in nearly all varieties of musical sounds. If a stretched string be made to vibrate, the secondary tones, which qualify the fundamental, are called harmonics, or overtones.

While it is difficult at all times to distinguish by the ear the individual overtones of vibrating strings, their existence can be demonstrated by certain simple experiments. Take, for example, a string, the fundamental tone of which is C. If this string be damped with a feather at one-fourth of its length and a violin-bow be drawn across the smaller section, not only the fourth part of the string across which the bow is drawn is made to vibrate, but the remaining three-fourths; and if little riders of paper be placed upon the longer segment at distances equal to one-fourth of the entire string, they will remain undisturbed, while riders placed at any other points on the string will be thrown off. This experiment shows that the three-fourths of the string have been divided. This may be illustrated by connecting one end of the string with a tuning-fork. When this is done and the string is brought to the proper degree of tension, it will first vibrate as a whole, then, when a little tighter, will spontaneously divide into two equal parts, and under increased tension, into three, four, and so on. By damping a string with the light touch of a feather, it is possible to suppress the fundamental tone and bring out the overtones, which exist in all vibrating strings but are usually concealed by the fundamental. The points which mark the subdivisions of the string into segments of secondary vibrations are called nodes. When the string is damped at its centre, the fundamental tone is quenched and there are overtones an octave above; damping it at a distance of one-fourth, there is the second octave above, and so on. When the string is damped at a distance of one-fifth from the end, the four-fifths sound the 3d of the fundamental, with the second octave of the 3d. If it be damped at a distance of two-thirds, there is the 5th of the fundamental, with the octave of the 5th. Every vibrating string thus possesses a fundamental tone and overtones. Qualifying the fundamental there is first, as the most simple, a series of octaves; next, a series of 5ths of the fundamental and their octaves; and next, a series of 3ds. These are the most powerful overtones, and they form the common chord of the fundamental; but they are so far concealed by the greater intensity of the fundamental, that they can not easily be distinguished by the unaided ear, unless the fundamental be quenched in some way. In the same way the harmonic 5ths and 3ds overpower other overtones; for the string is subdivided again and again into overtones, which are not harmonious like the notes of the common chord of the fundamental.

The presence of overtones, resultant tones and additional tones, which latter will be described hereafter, can be demonstrated, without damping the strings, by resonators. It is well known that if a glass tube, closed at one end, which contains a column of air of a certain length, be brought near a resounding body emitting a note identical with that produced by the vibrations of the column of air, the air in the tube will resound in consonance with the note, while no other note will have this effect. The resonators of Helmholtz are constructed upon this principle. A glass globe or tube (Fig. 267) is constructed so as to produce a certain note. This has a larger opening (a) and a smaller opening (b), which latter is fitted in the ear by warm sealing-wax, the other ear being closed. When the proper note is sounded, it is re-enforced by the resonator and is greatly increased in intensity, while all other notes are heard very faintly. By using resonators graduated to the musical scale, it is easy to analyze a note and distinguish its overtones. The resonators of Helmholtz, which are open at the larger extremity, are much more delicate than those in which this is closed by a membrane.

A very striking and instructive point in the present discussion is the following: All the overtones are produced by vibrations of divisions of the string, included between the comparatively still points, called nodes; and if a string be thrown into vibration by plucking or striking it at one of these nodal points, the overtones which vibrate from this node at a fixed point are abolished. It is readily understood that when a string is plucked at any point, it will vibrate so vigorously at this point that no node can be formed. This fact has long been recognized by practical musicians, although many are probably unacquainted with its scientific explanation. Performers upon stringed instruments habitually attack the strings near their extremities. In the piano, where the strings may be struck at almost any point, the hammers are placed at a distance of $\frac{1}{7}$ to $\frac{1}{9}$ of the length of the strings, from their extremities; and it has been ascertained by experience that this arrangement gives the richest notes. The nodes formed at these points would produce the 7ths and 9ths as overtones, which do not belong to the perfect major chord, while the nodes for the harmonious overtones are undisturbed. The reason, then, why the notes

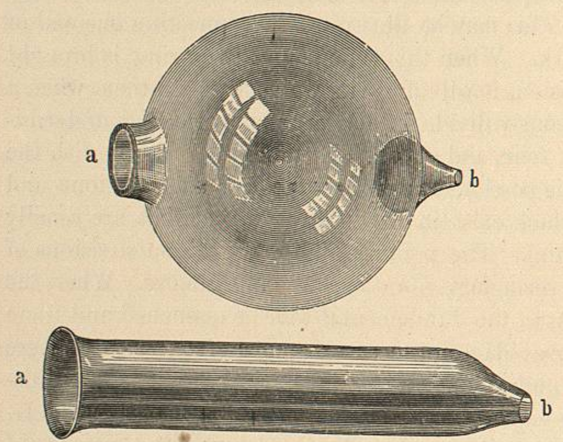

FIG. 267.—*Resonators of Helmholtz.*

are richer and more perfect when the strings are attacked at this point, is that the harmonious overtones are full and perfect, and certain of the discordant overtones are suppressed.

When two harmonious notes are produced under favorable conditions, one can hear, in addition to the two sounds, a sound differing from both and much lower than the lower of the two. This sound is too low for a harmonic, and it has been called a resultant tone. The formation of a new sound by combining two sounds of different pitch is analogous to the blending of colors in optics, except that the primary sounds are not lost. The laws of the production of these resultant sounds are very simple. When two notes in harmony are sounded, the resultant tone is equal to the difference between the two primaries. For example, C, with 48 vibrations, and its 5th, with 72 vibrations in a second, give a resultant tone equal to the difference, which is 24 vibrations, and it is consequently the octave below C. These resultant tones are very feeble as compared with the primary tones, and they can be heard under only the most favorable experimental conditions. In addition to these sounds, Helmholtz has discovered sounds, even more feeble, which he calls additional, or summation tones. The value of these is equal to the sum of vibrations of the primary tones. For example, C (48) and its 5th (72) would give a summation tone of 120 vibrations, or the octave of the 3d; and C (48) with its 3d (60) would give 108 vibrations, the octave of the 2d. These tones can be distinguished by means of resonators.

It is thus seen that musical sounds are complex. With single sounds there is an infinite variety and number of harmonics, or overtones, and in chords there are series of resultants, which are lower than the primary notes, and series of additional, or summation tones, which are higher; but both the resultant and the summation tones bear exact mathematical relations to the primary notes of the chord.

Harmony.—Overtones, resultant tones and summation tones of strings have been discussed rather fully, for the reason that in studying the physiology of audition, it will be seen that the ear is capable of recognizing single sounds or successions of single sounds; but at the same time certain combinations of sounds are appreciated and are even more agreeable than those which are apparently produced by simple vibrations. Combinations of tones which thus produce an agreeable impression are called harmonious. They seem to become blended with each other into a complete sound of peculiar quality, all of the different vibrations entering into their composition being simultaneously appreciated by the ear. The blending of tones which bear to each other certain mathematical relations is called harmony; but two or more tones, though each one be musical, are not necessarily harmonious. The most prominent overtone, except the octave, is the 5th, with its octaves, and this is called the dominant. The next is the 3d, with its octaves. The other overtones are comparatively feeble. Reasoning, now, from a knowledge of the relations of overtones, it might be inferred that the re-enforcement of the 5th and 3d by other notes bearing similar relations to the tonic would be agreeable. This is the fact, and it was ascertained empirically long before