C_2 and G_3, with two manometric capsules, and gently sounding the pipe so that only its prime is audible, we can show that G_3 is really present with C_2, although unheard. The flame-image corresponding to the fundamental note is shown in 1, Fig. 153. 3 is the flame-image of the twelfth, and shows that it executes just three times as many vibrations as its fundamental. Both flames combined give 1:3, which shows the components of the sound under analysis as well as if each partial were examined separately. For a similar reason a sonorous body, yielding in succession its prime and its octave, would give respectively the flame-images 1 and 2, Fig. 154. Both partials, sounding simultaneously, would yield a flame-image like 1:2 of the figure.

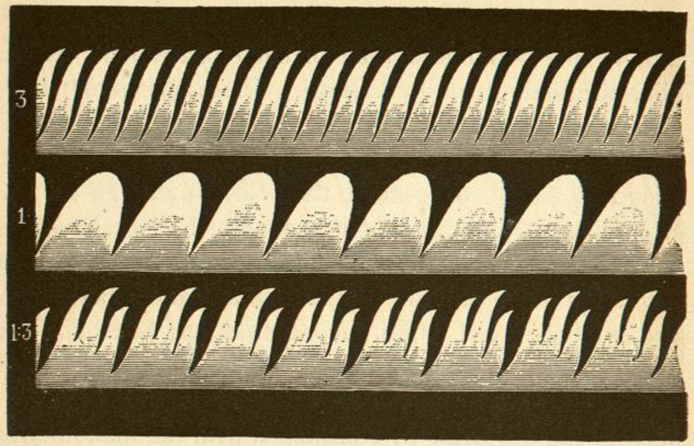


FIG. 153.

By employing a larger number of properly tuned resonators, it would be just as easy to show the flame-images corresponding to five or six partials as it is to show those corresponding to two. I may here add, however, that neither resonators alone, nor resonators attached to manometric capsules, can be used for very acute sounds. They are practically useless for all sounds above C_5.

On the screen is a photograph of an instrument having eight resonators (Fig. 155), exactly like those we have been using, except that they are mounted on a stand. The nipple of each resonator is connected by a rubber tube with a capsule, whose jet is placed before a revolving mirror. The resonators are turned to the notes C_2, C_3, G_3, C_4, E_4, G_4, the seventh partial of C_2, and C_5. If a compound tone whose prime is C_2 is emitted before the opening of the resonators, the flame-images reflected from the mirror will at once disclose the number and the order of the upper partials of the sound. When an open organ-pipe, whose prime is C_2, is caused to speak, five or six flame-images declare the presence of as many upper partials in the compound tone. The flame-image corresponding to the third partial is very markedly agitated.

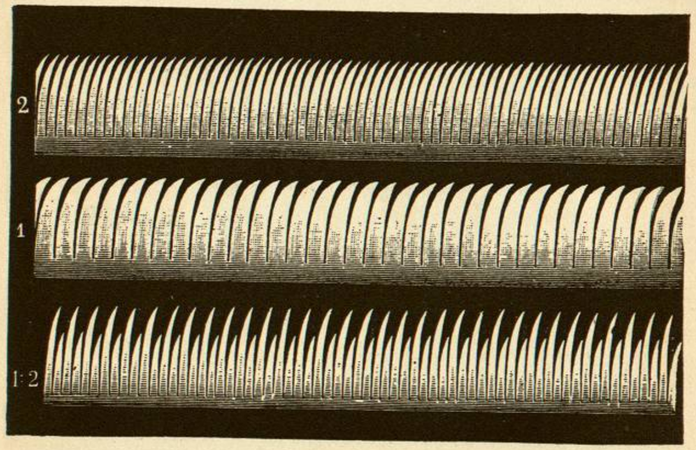


FIG. 154.

The instrument just referred to, having only a small number of resonators, answers very well for demonstrations, but could not be employed in investigations in which other notes than those to which the resonators are attuned are submitted for examination. In the latter case a series of universal resonators would be required. Such an apparatus — one that was exhibited by Dr. Koenig at the Centennial Exposition at Philadelphia in 1876 — I now show you, in order that you may have a better idea of its *modus operandi*. The resonators of this splendid apparatus (Fig. 156) are like that described in our seventh lecture (Fig. 125). They are supported in a frame, *X C Y*, and are connected with manometric capsules whose jets are supplied with gas, entering through the tube *D*. The mirror *A B* is rotated before the jets by the crank *M*. The resonators can be so adjusted that all the upper partials between C_1 and C_5 can be studied. For the lower notes, the resonators are so arranged that as many as nine partials may be observed. These cylindrical resonators are fully as sensitive as those which are spherical, and, like the latter, they

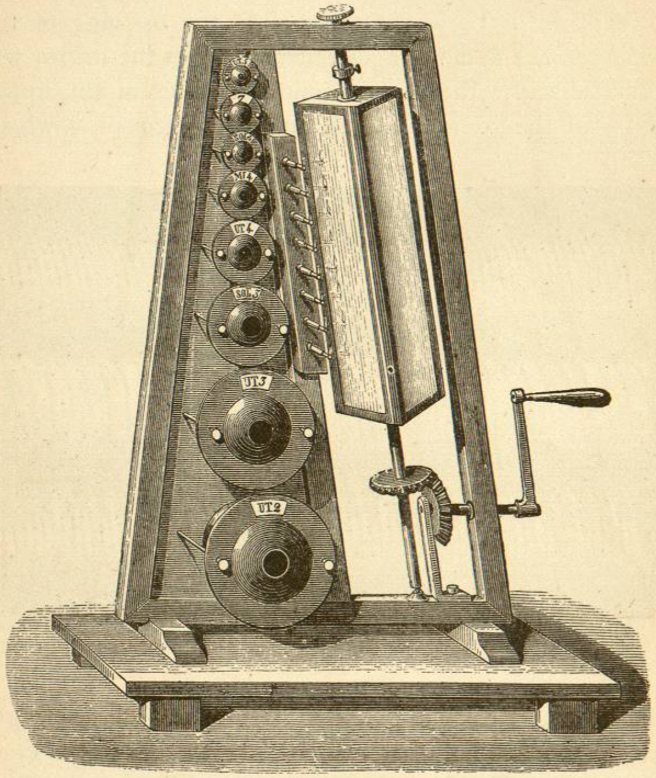


FIG. 155.

indicate the presence of partials as high as C_5. Such a series of resonant spheres or cylinders has been well likened to a set of chemical reagents. As such reagents enable the chemist to prove the presence of various elements and compounds, so do resonators afford the acoustician the means of analyzing any compound note into its constituent partials.

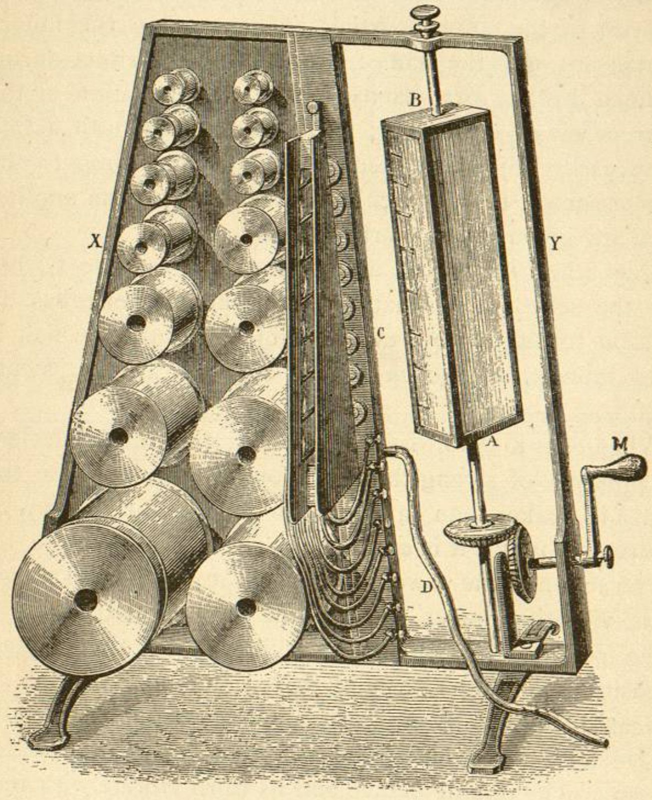


FIG. 156.

Such an instrument puts us in possession of an admirable means of investigating the nature and composition of vowel-sounds. Why does one vowel-sound differ from another; or why is it that the same pair of vocal cords are capable of sounding more than one vowel at all? The pitch and the loudness of two vowels sung to the same note may be identical. The only way in which the vowels can differ from one another is that in which the sound of the violin, for instance, differs from that of the clarinet. Vowels accordingly differ from one another because their quality is different; because the number and relative intensities of the upper partials accompanying the fundamental are not the same; because the various forms assumed by the oral cavity in the pronunciation of the different vowels are unlike; and because the mouth, acting as an easily adjustable resonator, tends, according to the form assumed, to reinforce one partial more than another when any given vowel is articulated.

Thus when *u*, like *oo*, as in "toot," is sung to C_1 before the series of resonators just exhibited, one has, in addition to the prime, evidence of the octave, which is quite intense, and occasionally also of a very feeble twelfth.

When *o*, as in "no," is sung, the vibrating flames declare the presence of strong third and fourth partials, while the octave is weaker than in *u*. Even a fifth partial may be observed in *o*, but it is extremely weak.

The action of the vowel *a*, as in "ah," extends, as is shown in the vibrating flames, as far as the seventh partial; but it is the fourth, fifth, and sixth that vibrate with the greatest intensity. Singing *e*, as in "there," the fundamental, as indicated by the flame-images, is accompanied by the octave and the twelfth, — the former feeble, the latter intense. The double octave and its third vibrate with medium intensity. In addition to these, there is also a trace of the seventh partial.

I, as in "machine," sung to C_2, shows that the prime is accompanied only by its first octave.

No more beautiful nor convincing proofs could be desired than those furnished by carefully tuned resonators and manometric flames, that the different vowels, like all musical sounds of different quality, are the result, not of any peculiar action of the vocal cords, but depend solely

on the varying admixture of certain partials, of varying intensities, with the fundamental.

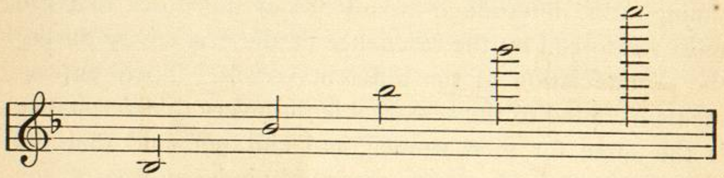
But what are the notes that specially distinguish the five vowels just mentioned from each other? Donders first paved the way for an answer to this delicate question by his discovery that the cavity of the mouth for different vowels is attuned to different pitches. Helmholtz, Koenig, and others took up these investigations, and, by means of tuning-forks, determined the pitches of the notes that are most reinforced by the resonance of the oral cavity during the pronunciation of the different vowels. Their experiments have led to the remarkable discovery that resonance is the same for men, women, and children, and that the proper tones of the mouth are nearly independent of age or sex.

From a series of forks prepared for researches on vowel-sounds, I select one which excites the maximum resonance in the mouth when it is shaped for articulating the vowel *u* as pronounced in Italian, viz., as *oo*. Holding the fork before my mouth thus formed, the resonance, as you observe, is very marked. Holding the same fork before a suitably tuned resonator, I obtain a similarly reinforced sound, and one identical in quality.

I try another fork somewhat smaller, and find that this resounds most strongly before the mouth when it assumes the form required for the pronunciation of the vowel *o*. When the form of the mouth is changed, its resonance for this particular fork is much diminished.

Taking another fork, and adjusting the mouth, you hear it distinctly resounding to the fork as in the previous instances; but the sound now heard is that of broad *a*, as in "father."

Similarly, with smaller forks, I excite, by sympathetic resonance, in the air of the oral cavity, sounds corresponding to *e* and *i*. These latter tones, however, are much higher in pitch than those corresponding to the vowels *u*, *o*, and *a*, and their resonance is correspondingly less intense.

According to Koenig's investigations, the notes that are most strongly reinforced by the air in the cavity of the mouth during the articulation of the vowels *u, o, a, e, i*, are $B_2\flat$, $B_3\flat$, $B_4\flat$, $B_5\flat$, $B_6\flat$, respectively. These notes, as is obvious, differ from each other by an octave, and their respective vibration-numbers are 224, 448, 896, 1792, and 3584. In musical notation they would be written as follows: —

Vowels . .	*U*	*O*	*A*	*E*	*I*
Notes . .	$B_2\flat$	$B_3\flat$	$B_4\flat$	$B_5\flat$	$B_6\flat$
Frequency .	224	448	896	1792	3584

We have here a simpler form of instrument devised by Koenig for exhibiting the flame-images corresponding to the different qualities of the various vowel-tones sung to the same note, and for showing the transformations that these images undergo when the same vowels are sung to different notes. It is essentially a manometric capsule, like those we have been using, except that it is connected with a funnel-shaped mouthpiece (Fig. 157). *A* of the figure shows a cross-section of the capsule, and *M* is the revolving mirror in which the images of the flame are visible. When one sings into the mouthpiece connected with the manometric capsule, the flame is agitated, and the images seen in the revolving mirror disclose the slightest shades in the quality of the tones emitted; and as the number and intensity of the upper partials of any note vary with the pitch, the flame-images will show a corresponding change in form as the sound produced passes from a grave note to one more acute. For the lower notes, and particularly for the grave vowels, like *u, o, a*, there is an exuberance of partials that is entirely absent in notes of higher pitch, especially in those of the vowel *i*.

When *i* is sung to C_3, the flame-image produced shows that it is practically a simple tone, and unaccompanied, therefore, by any partials whatever.

The qualities of different vowel-sounds, and their transformations for the various notes from C_1 to C_3, are beautifully depicted in Fig. 158, which gives, in a compendious form, the results of the careful and laborious observations of Dr. Koenig on the subject of vowel-sounds as studied with manometric flames. *O U*, at the head of the first column, is intended to give the Italian sound of *u*, while the names of *ut, re*, etc., are given according to the French style, instead of that which we have adopted in these lectures.

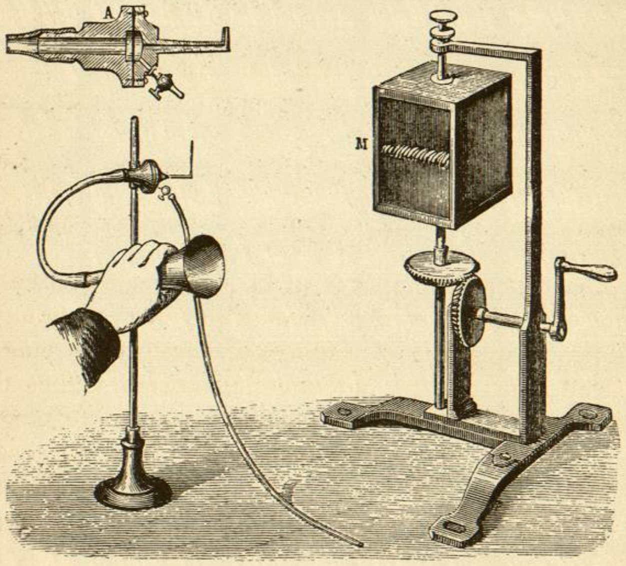


FIG. 157.

Many consonants, as well as the vowels, give characteristic flame-images. The so-called semi-vowels, *m* and *n*, give images that are so nearly alike they are practically indistinguishable. Fig. 159 exhibits their images for the notes C_2, E_2, G_2, C_3. In Fig. 160 we have the very remarkable image that characterizes the peculiar sound of the letter *r*.

The dependence of the quality of tone on the number and relative intensity of the upper partials that accompany their prime, can be very strikingly shown by a simple experiment that any one can make on the pianoforte.

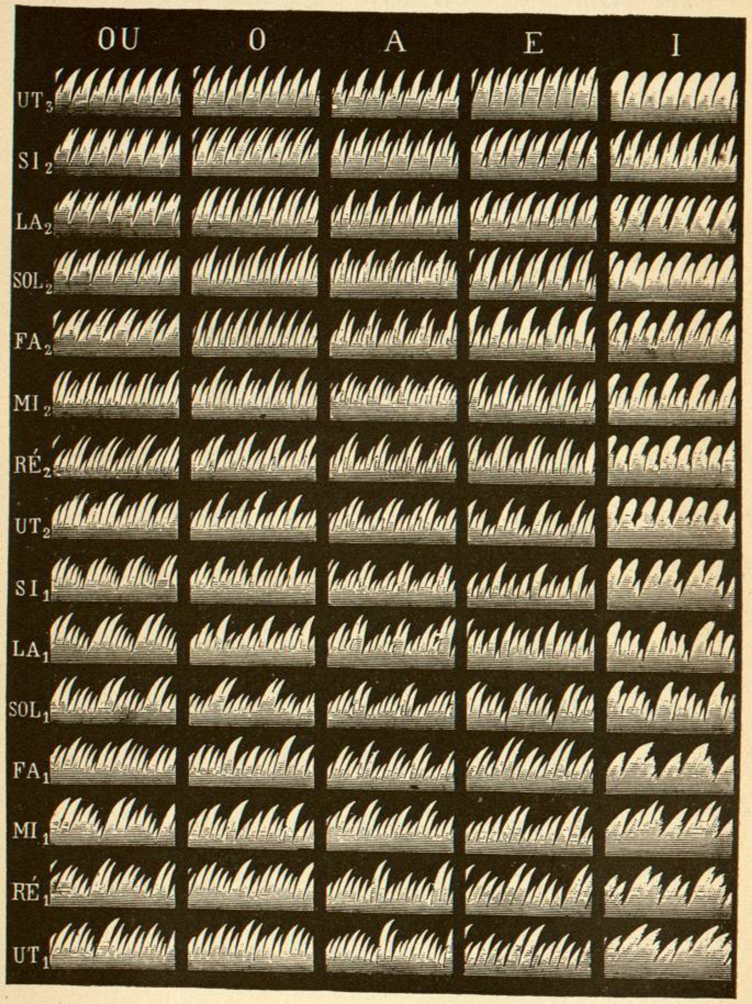


FIG. 158.

Raise all the dampers of the instrument, and directing the voice towards the sounding-board, sing loudly the vowel *a*, as in "ah," and you will hear the sound of the same *a* distinctly repeated by the strings that emit notes corresponding to the fundamental and upper partials of the voice. In like manner sing *o*, as in "oh," and the echo will give back with surprising clearness a full, sonorous *o*. *A*, as in "bay," is likewise re-echoed with astonishing exactness. *E*, *i*, and *u* are also heard, but not so loud as *a* or *o*.

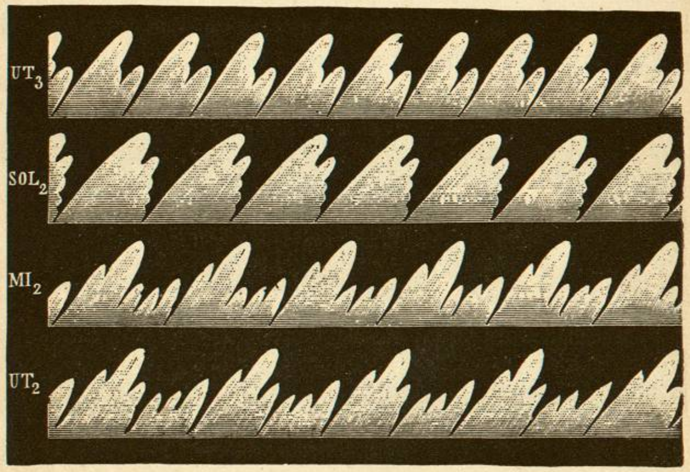


FIG. 159.

Sound a clarinet near the sounding-board, and the quality of the tone of this instrument will be imitated with remarkable fidelity.

All the various sounds mentioned single out and excite to vibration certain strings that, by themselves, would give the elementary constituents of the compound tone in question. These simple experiments prove as conclusively as the more elaborate ones we have made that all compound tones are composed of simple ones, and that quality of tone, as demonstrated in so many ways, is intimately associated with the number and intensity of the partials existing in the tone examined.

Thus far the method we have employed in investigating the quality of sound has been analytical. We have learned the difference between simple and compound tones, and have seen how we can accurately determine the number and relative intensity of the simple tones that coexist in any given compound tone. We have studied particularly the methods of sound-analysis devised by Helmholtz and Koenig, and have found that, with one or two exceptions, all musical sounds are composed of two or more simple tones, and that it is mainly the presence of these partials that enables us to distinguish from each other the sounds proceeding from different sonorous bodies.

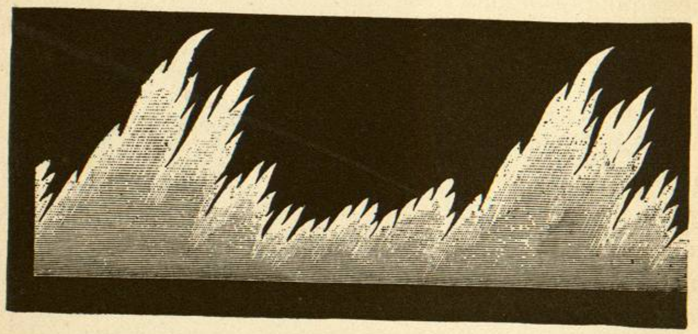


FIG. 160.

We are now prepared to make another step in advance, — to study the quality of sound synthetically. After Helmholtz had succeeded in effecting the analysis of sound, by the means just considered, he proceeded to confirm the results thus obtained by synthesis. By analysis he was able to determine the number and the relative intensity of the partials constituting a tone of determinate quality. His next problem was to take these partials, of the number and intensity revealed by his analysis, and put them together in such a manner as to obtain a tone of the same quality as that which had been subjected to analysis. The result was that the two processes — analysis and synthesis — corroborated each other in a most remarkable manner. The problem that had so long baffled musicians and acousticians was at last solved, and we are now able to account for the quality of a tone, as well as for its pitch and its intensity.

In investigating synthetically the quality of a sound, it is essential that we should have simple tones. Stopped organ-pipes, which, as we have learned, give nearly simple tones, might be used, and sometimes are used; but it is found more advantageous to use tuning-forks, whose tones are reinforced by suitable resonators. Tuning-forks thus made give us simple tones, whose vibrations are nearly pendular.

For the artificial production of tones of different qualities, quite a number of forks, of different pitches, are required. As is evident from what has been said regarding the components of compound sounds, we can employ only such tones as those whose frequencies are to each other as the whole numbers 1, 2, 3, 4, etc. Hence, the application of the method is limited to comparatively grave sounds. For should the prime of the compound tone to be studied be very acute, its upper partials would have such a high pitch that it would be impossible to reinforce them with resonators; and unless thus strengthened they would be useless for the purpose under consideration.

On the table is a series of ten tuning-forks placed in front of resonant cases. The larger fork, C_2, gives 128 vibrations, while the other nine forks are tuned to give exactly the nine upper partials of C_2. Starting with C_2 as the prime, these partials would be in the order of succession, C_3, G_3, C_4, E_4, G_4, seventh upper partial, — between $A_4\sharp$ and $B_4\flat$, — C_5, D_5, E_5.

When the prime C_2 is sounded, we have the pure, simple tone that is characteristic of a good tuning-fork. The tone heard in this case is as nearly a perfectly simple tone as it is possible to obtain. In addition to the prime, the octave is now excited, and the two tones blend together so perfectly that they appeal to the ear as only one note. Indeed, it requires considerable effort for the ear to separate one note from the other. But the compound tone