heard when the two forks, C_2 and C_3, are sounded together, is quite different from the pure, simple tone emitted by C_2 alone. The second, as all can perceive, is fuller and richer than the first.

The prime C_2 and its first five upper partials, C_3, G_3, C_4, E_4, G_4, are now set in vibration. As with the two forks, the tones of the six forks now so coalesce that the resultant tone seems to proceed from one source of sound. So perfect is the combination that it is exceedingly difficult for the unaided ear to single out the notes that are emitted by the individual forks. With resonators, however, this could be done with the greatest facility, and in a way that would surprise those that have never had any experience with such appliances.

But what I wish specially to direct your attention to is the brilliancy and volume and harmoniousness of the tone you now hear, as compared with that produced by one fork, or by two forks. By exciting simultaneously all the forks in the series, except the seventh and ninth partials, we obtain a tone that is proportionally brighter. Introducing the seventh and ninth partials into the mass of sound now heard, the quality is at once changed. We have introduced elements of discord, although their influence in this case is not so great as they would be in sounding with one of the forks separately, because the volume of tone of the eight other forks is so great that it partially extinguishes the tones of the inharmonic intruders. We could not have a more striking or more beautiful illustration of the dependence of the quality of a tone on the number of partials accompanying a given fundamental, than that afforded by this experiment. The compound sound emitted by the series of forks — omitting the seventh and ninth — here used reminds one of the fulness, mellowness, and softness of the tones of a French horn in the hands of a *maestro*.

But for experiments on the synthesis of sounds, it is necessary to have, not only simple tones, but tones that can be sustained at will. Those afforded by the forks just used diminish rapidly, and for that reason are not well suited for the work of synthesis we now have in hand. And then, again, it is important that we should be able to regulate the intensities of the various simple tones introduced; and to do this accurately a special contrivance is necessary. In other words, if we would do exact work in the synthesis of sounds, a specially devised apparatus is almost indispensable.

Such an apparatus, as made by Koenig, is now before you. It is a modification of the one first devised by Helmholtz, and with which he carried on his celebrated researches on the quality of vowel and other compound sounds. It is one of the most ingenious of acoustic instruments, and enables us to effect, in a most striking manner, the composition of many compound sounds, and to show, what we have demonstrated analytically, how much the quality of a sound depends on the harmonic partials that are associated with the fundamental.

As seen in Fig. 161, this apparatus is composed of ten tuning-forks, giving the series of harmonic partials, starting from C_2, of one hundred and twenty-eight vibrations, as a prime. They are fixed vertically between the poles of electro-magnets which are traversed by an electric current that can be rendered intermittent by a tuning-fork so constructed as to close and break the circuit exactly one hundred and twenty-eight times per second. Each fork is provided with an accurately tuned cylindrical resonator, whose orifice, when the instrument is in use, is brought as near as possible to the vibrating prongs of its associated fork. The orifices of the various resonators can be more or less opened by keys in connection with them. When the resonators are closed, the tuning-forks, although vibrating, are scarcely audible, because the boards on which they rest are insulated from their common support by rubber tubes glued to their lower surface; and this has the effect of almost completely damping the sounds that would otherwise be heard with considerable intensity. As soon, however, as any of the resonators are opened, by pressing on the proper keys, the sounds of the tuning-forks burst forth with exceeding power and volume.

The best tones to select for imitation with the instrument before us are the vowel-sounds, because they are free from the various noises that always accompany other musical sounds. Even aside from this fact, I should now choose vowel-sounds, as a matter of convenience, and to show also

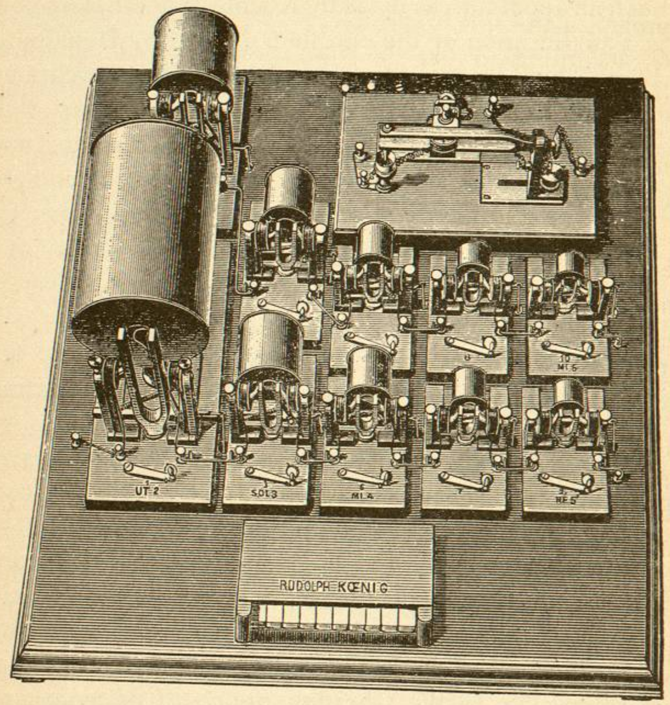

FIG. 161.

how the results we have arrived at analytically are confirmed by the synthetic method. When making the analysis of sounds by means of resonators and manometric flames, we employed vowel-sounds. The results then obtained may now serve as a guide in our synthetic work, and allow us to pick out at a glance the upper partials found in the various vowels, and regulate their intensities according to the flame-images corresponding to the different vowels.

Thus we saw that when *u*, pronounced as *oo*, was sung before the resonators, there was, in addition to the fundamental, an indication of a strong second partial, and occasionally, of a very weak third partial. If then the forks C_2 and C_3 are sounded with their corresponding resonators wide open, and G_3 is sounded feebly, we should obtain a compound sound resembling *u*. The forks are sounded, and at once you hear a tone that certainly approaches the one sought.

O, according to our flame-reactions, is made up of a strong prime and strong third and fourth partials, while its octave is comparatively feeble, and its fifth partial feebler still. The forks required in this instance will be those emitting the prime C_2, and the partials C_3, G_3, C_4, E_4. Opening the resonators of the proper forks according to the indications given by the flame images, we obtain a tone that you must admit bears a striking resemblance to the sound of the vowel *o* as it is sung.

In the tone of the vowel *a*, according to its analysis, there are no fewer than seven partials. The prime, fourth, fifth, and the sixth are the strongest. The others are of various degrees of feebleness. The forks required for *a* are, therefore, C_2, C_3, G_3, C_4, E_4, G_4, and the seventh partial. Sounding these with their corresponding resonators more or less opened, according as they are to reinforce the tones of the forks strongly or feebly, we have as a resultant tone an imitation of the vowel *a*.

To imitate the sounds of the vowels *e* and *i* is less easily accomplished, because of the high pitch of their upper partials, and because of the difficulty in rendering the tones of their upper partials sufficiently intense.

In our flame-analysis of the vowel *e* we found the prime C_2 accompanied by an octave and a twelfth, the former feeble, the latter very loud. Besides these, there were present the fourth and fifth partials of medium intensity, and a trace of the seventh. Compounding the simple tones of the forks according to these reactions, we obtain a faint reproduction of the tone of the vowel *e*.

Analytically, *i* is composed of a prime and its octave, both of which are very intense. But the same difficulty that was in our way in the analysis of this vowel, and of sounds of high pitch generally, now confronts us in its reproduction, — the difficulty of getting resonators strongly to reinforce high partials. For this reason it is impossible to imitate the tone of *i* in a way that even approximates the fidelity of the imitations of the graver vowels, especially *u*, *o*, and *a*. But, you will say, in none of these cases is the imitation perfect. The resemblance of the artificial sounds to the natural ones is, at best, more or less fanciful.

I admit that we have not, in the experiments made, been able to reproduce the vowel-sounds with all their characteristic shades of difference. And what is said for vowel-sounds may be said of all other sounds. But even granting the impossibility of effecting such a composition, we have accomplished enough to show that we have discovered the foundation of quality in tone, and this is all that has been attempted.

Moreover, in addition to the effect that upper partials, of varying number and intensity, have in modifying the quality of their prime, and in the case of vowel-sounds, for instance, of impressing on the resultant tone that quality that characterizes it, we must not forget to take into consideration the conformation of the mouth, the condition of the vocal cords, the pressure of the air urged through the glottis, and a score of other conditions that it would be quite impossible exactly to reproduce by any artificial contrivance, however perfect.

And more than this. There is a factor of more or less influence in determining the quality of sound, about which I have yet said nothing, but which is of sufficient importance to merit serious consideration. I refer to difference of phase. Helmholtz, whose conclusions respecting the influence of upper partials in modifying the quality of tone have already been given, denies that quality is in any way affected by difference of phase. Indeed, the complex

apparatus that we have just used was partially devised to show that the quality of sound is entirely independent of difference of phase. In summing up the results of his investigations on this subject, he states explicitly that "the quality of the musical portion of a compound tone depends solely on the number and relative strength of its partial simple tones, and in no respect on their difference of phase."

To this conclusion, which Helmholtz lays down as "an important law," Dr. Koenig takes exception, and by a number of cleverly devised apparatus, constructed especially for the purpose, he shows that difference of phase affects the quality of tone to such an extent that its influence cannot be neglected.

To appreciate Koenig's experiments, and understand the apparatus by which they were made, we must recall what was said in our seventh lecture about the combination of waves representing notes of the same and of different periods, and of notes of the same and of different phases. Then, however, only waves corresponding to notes whose periods were equal, or were to each other in the ratio 1 : 2, or 1 : 3, were combined. But it is possible, and even easy, by following the rules there laid down, to combine any number of simple waves, whether of the same or of different phases.

In Fig. 162, drawn by Professor Mayer, we have beautifully illustrated the combination of the six harmonic curves corresponding to the first six partials of a musical note. The elementary curves are shown in the upper part of the figure; the resultant in the lower part. In order to bring out the characteristic flexures of the resultant, the amplitudes of the curves are made to vary as their wave-lengths. But it must not be inferred that the intensities of the partials of a musical note vary according to the amplitudes here given. Neither must it be concluded that the amplitudes, as compared with the wave-lengths, are nearly so great in nature as in the curves in the diagram. As a matter of fact, in sonorous vibrations, the amplitude of vibration of the oscillating particles, as compared with the wave-lengths, must be infinitely small, in order that the law of the "superposition of displacements" may be rigorously true.

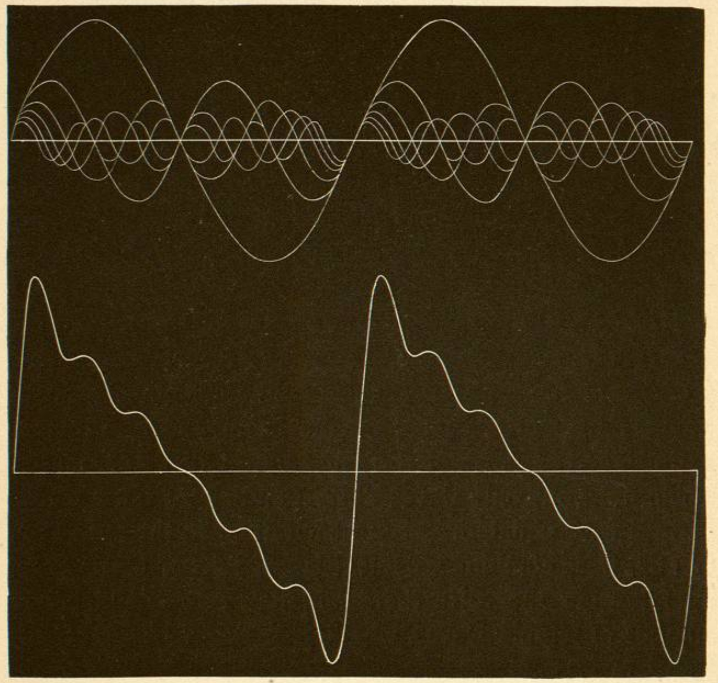

FIG. 162.

The resultant curve given in the foregoing illustration has a special interest from the fact that it closely resembles the vibrational figure executed by a violin-string, as determined by Helmholtz by means of a vibration-microscope. A comparison of the latter curve (Fig. 163) with the former, shows how nearly the two are alike. If the violin had yielded a tone of exactly six partials, and of the same intensities as indicated in Fig. 162, the two resultant curves would be identical in appearance.

Professor Mayer gives us another remarkable illustration of the coincidence of vibrational forms obtained by different

methods. In Fig. 164, *A* shows the indentations made in a sheet of tin when the vowel *a* is sung into the mouthpiece of a phonograph. *B* exhibits a transverse section of these indentations. *C* gives in outline the form of a manometric flame which has been set in vibration by the sing-

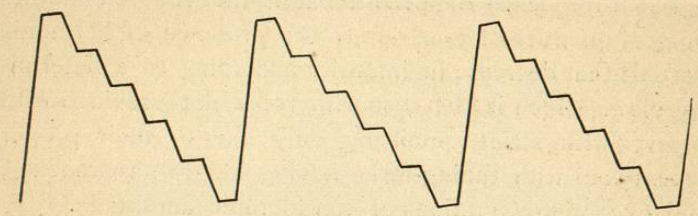

FIG. 163.

ing of the same vowel, *a*. The similarity of forms in the two cases is beyond question.

In Fig. 165, *a*, we have in the upper horizontal line four curves, whose periods are 1 : 2 : 3 : 4 : 5 : 6 : 7 : 8; and represent sounds whose intensities are equal. The four curves give the resultants of the eight simple curves, when they coincide at their point of departure, indicated by *o*,

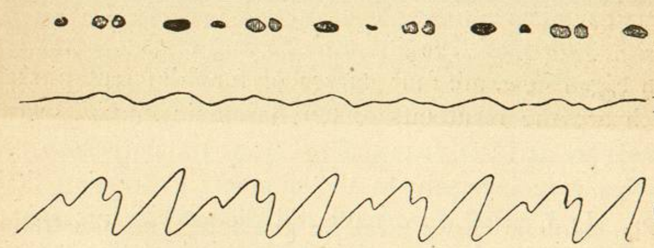

FIG. 164.

and when their difference of phase is equal to $\frac{1}{4}$, $\frac{1}{2}$, or $\frac{3}{4}$ of their wave-lengths. In the same figure, *b*, we have four curves, representing likewise curves of equal intensities, and having periods that are to each other as the odd numbers 1 : 3 : 5 : 7, etc. As in *a*, there are differences of phase corresponding to *o*, $\frac{1}{4}$, $\frac{1}{2}$, and $\frac{3}{4}$ of a wave-length.

Sounds in which all the upper partials have the same intensities as their fundamental are probably never produced by any of the natural sonorous bodies with which we are familiar. When required in music, they are produced by bringing out simultaneously a series of sounds bearing to each other the relations of harmonic partials, as in the compound stops of the organ.

But it frequently happens in nature that sonorous bodies possess qualities of tone due to the presence of harmonic partials that decrease in intensity according to a determinate law. Such is the case with reeds not provided with pipes; with strings emitting only one of their proper tones; and with tuning-forks having long, thin branches, and executing vibrations of considerable amplitude.

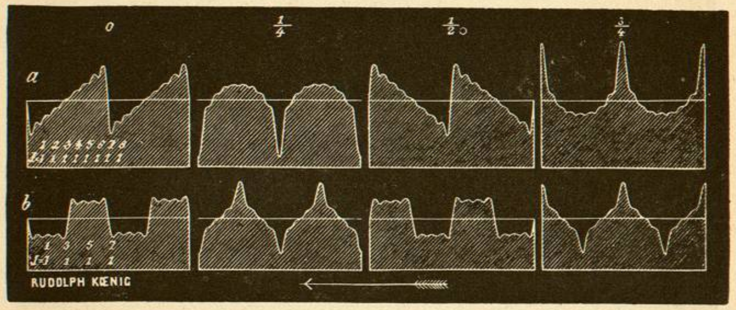

FIG. 165.

In Fig. 166, *a*, are four curves of four different phases, which are the resultants of ten harmonic curves, whose periods are as 1 : 2 : 3 : 4 : 5 : 6 : 7 : 8 : 9 : 10, and whose amplitudes vary inversely as the numbers expressing their order. In *b*, *c*, and *d* we have still different curves representing sounds whose partials, with their relative intensities, are indicated by the numbers given.

If, now, these curves are cut in the circumferences of metal disks, or on the margins of metal bands attached to wheels, we have reproduced, in a modified form, the wave-siren which we had occasion to use in studying the nature of beats and beat-tones. The principles employed in constructing a wave-siren for exhibiting beats and beat-tones, and one for showing the quality of tone produced by various harmonic partials, of the same or different phases, are identical.

A siren, as employed for the latter purpose, is now before you. As you observe, it consists essentially of three bands of brass, fastened to three wheels supported on a vertical axis (Fig. 167), which is caused to revolve by a crank. On the margins of the two lower bands are cut four curves, each corresponding to the first twelve partials of a sound, the intensities of which partials are inversely as the order of their sequence. The difference of phase exhibited by these four curves corresponds to the coinci-

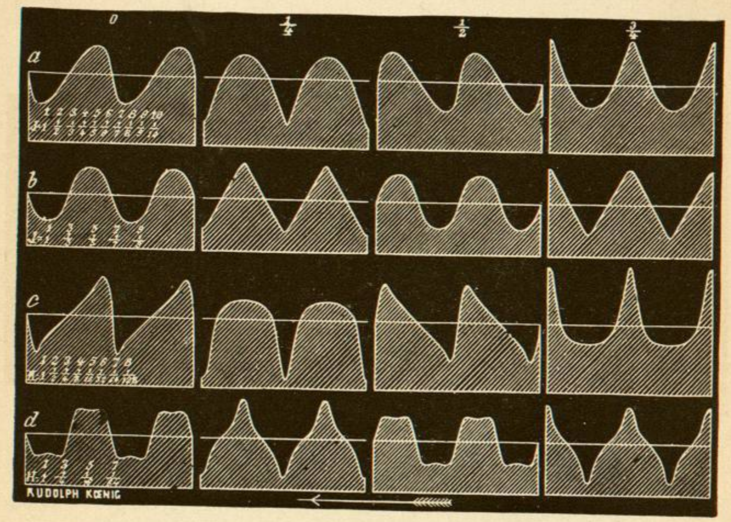

FIG. 166.

dence of origin in the first curve, *o*, and to differences of $\frac{1}{4}$, $\frac{1}{2}$, and $\frac{3}{4}$ of a wave-length in the three others.

The upper band has cut into its edges two curves, produced by the combination of harmonic curves representing the first six odd partials, whose intensities also decrease inversely as the numbers denoting their order of succession. When revolving on their axes, these curves pass before the narrow openings of six tubes which are connected with a common reservoir, and which, by means of suitable keys, can be opened at will. When air is blown against any of these curves, and they are revolved with a sufficient rapidity, a sound is generated whose quality varies according to the number of the constituent harmonic curves in the resultant compound curve. With this apparatus, then, we are able to compare the results given by two series of different harmonic partials, and to compare also the results afforded by the same series of partials when their phases are different.

If we now direct a stream of air against the four lower serrations in succession while they are made to rotate with

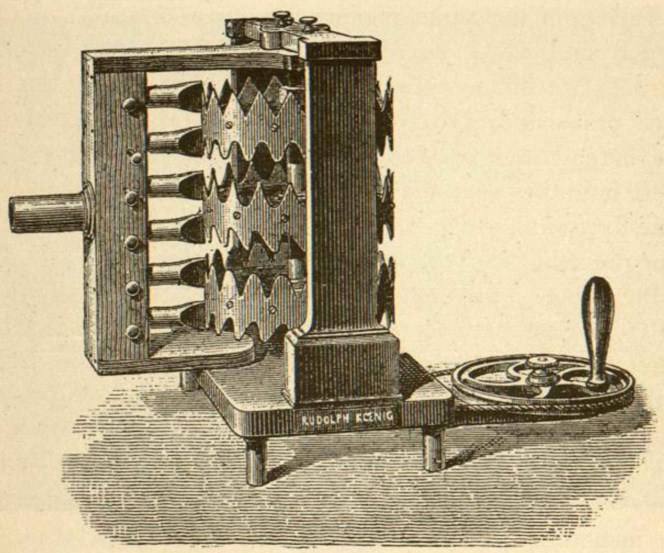

FIG. 167.

a suitable velocity, you immediately perceive that there is a marked difference in the quality of the sounds produced by the different serrated bands. The curve, having a difference of phase of $\frac{1}{4}$, is found to give a tone of greater power and brightness than any of the three others. The minimum of power and brightness is afforded by the curve whose difference of phase is $\frac{3}{4}$, while the two remaining curves, corresponding to differences of phase of *o* and $\frac{1}{2}$, yield a tone intermediate in quality between those furnished by the curves whose differences of phase are $\frac{1}{4}$ and $\frac{3}{4}$.

Here, then, we have curves corresponding to partials whose number and intensity, in the four cases considered, are precisely the same. The very marked difference observed in the quality of the tones cannot, therefore, depend on the number and intensity of these partials, but must be due to some other factor which is not common to the four curves. This factor is the difference of phase of the curves, and this alone it is that differentiates the quality corresponding to one curve from that given by any of the others.

Trying, in the same manner, the two serrations of the upper band, whose curves correspond to the first six odd partials, we obtain tones that are entirely different from each other, and entirely different from those afforded by the indentations of the two lower bands. We note that there is in this case, also, the same difference of quality of tone for the phases $\frac{1}{4}$ and $\frac{3}{4}$ as was observed in two of the four preceding curves.

But Koenig was not satisfied with the results afforded by these compound curves until he had verified them by other means. He had, indeed, constructed his curves with the greatest care, and on a large scale, reducing them afterwards by photography; and it would seem that the evidence furnished by the experiments made was conclusive. To prove, however, that the difference of quality in the instances just referred to was, without all peradventure, due solely to difference of phase, Koenig devised still another form of wave-siren.

The essential parts of this ingenious piece of mechanism (Fig. 168), — a photograph of which is projected on the screen, — are sixteen copper disks, mounted on a sort of cone-pulley, and connected by suitable tubes with a powerful wind-chest. The disks have cut in their edges sixteen simple harmonic curves, corresponding to the first sixteen partial tones, and they increase in diameter from the first to the last. A movement of rotation causes them to pass before the tubes attached to the wind-chest, and they can be so arranged that each disk will yield a simple