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Publisher: Routledge
Informa Ltd Registered in England and Wales Registered
Number: 1072954 Registered office: Mortimer House, 37-41
Mortimer Street, London W1T 3JH, UK

Proceedings of the Musical Association

Publication details, including
instructions for authors and
subscription information:
[http://www.tandfonline.com/loi/
jrma18](http://www.tandfonline.com/loi/jrma18)

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Published online: 28 Jan 2009.

To cite this article: William Grylls Adams F.R.S. (1875) On the Musical
Inventions and Discoveries of the Late Sir Charles Wheatstone, F.R.S.,
Proceedings of the Musical Association, 2:1, 85-93, DOI: [10.1093/
jrma/2.1.85](https://doi.org/10.1093/jrma/2.1.85)

To link to this article: <http://dx.doi.org/10.1093/jrma/2.1.85>

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MAY 1, 1876.

ALEXANDER JOHN ELLIS, Esq., B.A., F.R.S., F.S.A.,
IN THE CHAIR.

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*ON THE MUSICAL INVENTIONS AND DISCOVERIES
OF THE LATE SIR CHARLES WHEATSTONE, F.R.S.*

By PROFESSOR WILLIAM GRYLLS ADAMS, F.R.S.

THE work of the late Sir Charles Wheatstone was very varied in character, and was not limited to one, or even two, of the branches of physics. He investigated the laws of sound, of ordinary and polarised light, and he greatly advanced our knowledge of electricity and magnetism. But there is one characteristic, at least, which runs through all his investigations: he always sought to embody the results of his study of the laws of nature in a practical form, so that they might be beneficial to mankind. Thus he made use of the polarisation of the light of the sky to determine the correct solar time by means of his solar clocks; and again, in his electric instruments, he has enabled us to make electric measurements, and also to interchange ideas with our fellow-creatures all over the globe.

In the short time which is at my disposal this afternoon, I can only attempt to review a part of his work on sound, and its relation to music. I therefore propose to devote myself principally to one special branch of that work, in which he explained the modes of vibration, and the resonance of tubes and columns of air, and accounted for the distinct qualities of tone of various musical wind instruments.

If we take a tuning-fork and hold it in front of the opening of an organ pipe, suitable to sound to it, the sound produced by the fork will be reinforced. Thus, the sound of this fork can hardly be heard by itself, but when I bring it in front of a tube of proper length, we get a note very much reinforced by the pipe. If I take a pipe which does not resound to that tuning-fork, I shall not get that resonance. In this case we have an open pipe, about two feet in length, and as the tuning-fork is middle C, the two agree, and the pipe will reinforce the fork. If we take a tube of half this length and close one end of it, we shall also get resonance when we bring the same fork in front of the end of the tube. Now, the state of vibration of air within this open tube is this: the air in the middle is perfectly at rest, and at the two ends the air is moving in opposite directions at the same time. There is very great motion, comparatively, at the end; as we go down the tube there is less and less motion of the particles of air.

and at the middle none whatever. So that, if we place in an open pipe a disc in the middle to form a separation between the two parts, we shall form two such tubes as this one—closed at the end—and we get the same note produced. The state of vibration in a tube is represented on these diagrams: particles of air moving from each end towards the centre, so that when the density in the centre is greatest from an increase of pressure towards the centre, then the particles move outwards again, and there is a change of pressure and density in the middle of the tube greater than at any other part, but no change of density at all at the ends; so that where we have the greatest motion we have no change of pressure, and where we have no motion whatever, there we get the greatest change of density.

There are several ways of exciting vibrations of air in tubes; one is by means of a sharp edge, as in the case of a diaphon organ pipe. The air comes out through a narrow slit against a sharp edge, and the tone produced will depend on the distance of the sharp edge from the opening, as well as on the length and size of the pipe. The air may also be set in vibration by means of a reed, or vibrating tongue, as in a clarinet or reed organ pipes, or by the vibration of the lips where the muscles of the lips act the part of the vibrating tongue, as in the trumpet and horn. In the case of the oboe and bassoon, the reed resembles the action of the lips. Only those vibrations are excited which the air in the tube is capable of maintaining; that is, the tube must be such that in one vibration of the fork, from its position of rest, the pulse would have travelled from one end of the open tube to the other, or in the closed tube down it and back again; so that in the complete vibration of the tuning-fork—that is, going to its extreme limit on both sides, and returning to its position of rest again—the length of the wave which will have been started at first from the tuning-fork will be twice the length of this open tube, or four feet. From such a pipe no intermediate sounds can be produced. If I take, for instance, this pipe, there is a certain amount of resonance from the air, but there is no increase when I bring the fork near to the end of the tube, because it is too sharp to respond to it. But if I take a pipe which corresponds to the fork, then we get the resonance as we did in the other case. The same may be shown with a closed organ pipe. But from such a pipe we may get more than one set of vibrations. We can get the fundamental note of the pipe, and by altering the rate at which the air enters the pipe we can divide it up into parts, which are represented on the diagram, thus making as it were two pipes each of half the length, and an opening may be made in the middle without producing any change at that point; so that the octave of the fundamental may thereby be produced. In this case we get it by increasing the pressure, but we may also divide it differently and have three divisions or nodal lines instead of two, and, in fact, any number. We may increase by 1, 2, 3, or 4, and so get separate vibrations dividing the tube

into lengths of one-half, one-third, one-fourth, one-fifth, and so on, and get notes with numbers of vibrations, or in those ratios. Suppose, for instance, we take a pipe sounding CC, and divide it into three parts, we shall get two notes related to one another, the number of vibrations of the one being three times the number of the other in the same time. There we get the 12th, the 3rd in the harmonic series, and the double octave where the number of double vibrations are in the ratio of 4 to 1 of the fundamental notes. We can see these are the divisions very readily by means of an organ pipe, where, at the position of the node in the first case, we have a gas jet, and at the position of the nodes of the second position, when the octave is produced, we have also two gas jets. When these are lighted, you will see how the pressure is altered according to the note which is sounded. When the fundamental is produced there is very little alteration in the pressure at the two outside points, but the one in the centre would go out, whilst, when the octave is sounded, the pressure would be altered most at the two ends, and there would be no alteration of pressure at the middle. Consequently, as the alteration of pressure will affect the gas flame when the octave is sounded, the gas flame will go out at the two ends, and in the middle there will be no alteration, and *vice versa*.

Sir Charles Wheatstone showed, by means of a circular tube, that the air is moving from the two ends towards the centre of the tube at the same time, which had not been done experimentally before. He did it by bringing the two ends of the circular tube over a vibrating plate, which, in vibrating, moved from one end of the tube and towards the other at the same time. Consequently, the air at one end would be compressed whilst the air at the other end is expanded, and there would not be a travelling of the air of the two ends towards the middle. In that case the two ends of the tube are over the same plate, but when it is turned halfway round, so that only one end is over the vibrating plate, then the tube will resound with the plate, just in the same way as one of these tubes; it corresponds to the treble C. It is difficult to show this experiment, because the vibrating plate itself would give out a note which is too powerful for the note of the tube to be heard distinctly at any distance.

If we took a closed pipe of three-quarters the length of the original, the note of that would be one in which the vibrations would be at the ratio of 4 to 3 of the original; and if we divide that so as to get the first harmonic to it, then the division is precisely the same as that for the octave in the first case. Thus the octave of an open pipe from the first harmonic and a closed pipe of three-quarters of the length give the same note. You can see readily from this that the harmonics from an open pipe are very different from those obtained from a closed one. In fact, the closed pipe can only give the odd harmonics 1, 3, 5, and 7. This difference between the open and closed pipes shows the difference between the harmonics we get from the flute or open

pipes, and from the clarinet or closed pipes of an organ, and would account in part for the difference in quality of tone produced from those stops. In the case of the clarinet, the vibrations are produced by means of a reed at the closed end of the pipe. In such a case the tones produced are more powerful than when the tone is produced in the same pipe from the open end, and the same would be the case in all reed instruments where the reed is at the closed end of the pipe.

Vibrations may be excited in columns of air by means of gas. This also was investigated by Sir Charles Wheatstone more than 40 years ago, and he found that, provided the flame were of suitable size, then the note of the tube could be produced when the flame was quite at the end of the tube, if it was not too long; and that as the flame is passed up the tube it could be more and more easily excited until the position of the node is reached. In the case of long tubes usually the note produced is not the fundamental, but some harmonic. Here is an apparatus for producing these tones, and if the gas flame could be watched in a mirror, it would be seen that the gas almost goes out at each vibration of the air. Sir Charles Wheatstone found that on removing the gas jet nearly to a node in the tube, the intensity of the note was increased, and it was also necessary to increase the size of the flame in order to produce it. The note was produced with the smallest flame at the end of the tube, and it could be gradually enlarged in passing from the end towards the centre. He used very short tubes, so as to avoid the harmonics which are produced in the long ones. An instrument was constructed by Sir Charles Wheatstone of this description. There was a succession of tubes of different lengths, and gas flames which might be raised to the proper point by means of keys like a piano keyboard, so that each one might be sounded and the flames then caused to fall down again, and so any succession of sounds might be played by that instrument. He remarks that it is probable that organs may be constructed in which columns of air excited by flames of hydrogen gas might be substituted for the organ pipes now employed, and that instruments might be made possessing greater power in crescendos and diminuendos than any we are at present acquainted with. About three weeks ago I saw in the *Times* that there had been a meeting of scientific men in Paris who had been invited to witness the qualities of a musical instrument which had been introduced as a new invention, where gas flames were made use of to excite the tubes.

If, instead of taking cylindrical tubes, we make use of conical ones, then a note may also be obtained from these, and the succession of harmonics which may be produced from such tubes will be the same as the succession from open cylindrical tubes of the same length. Those from this cylindrical open pipe, and this other closed cone, we get the same note produced; it responds to the same tuning-fork. If we take a cone which is not complete, but open at both ends, of the same length, then

also from that we get the same note produced as from the cylindrical one. The resonance of the column of air is the same whichever end of the tube we take, although the amount of air set in vibration will not be the same; so that there may be a difference of intensity according to which end we set the air in vibration from. Thus, if we take a cone four feet in length, closed at the end, the fundamental note of that cone will be an octave below middle C. That will be the fundamental note when the whole of the air in the tube will be moving in the same direction at the same time. The vibrations are excited at the end, and the pulse travels down to the other end; when it reaches the other end all the particles of air begin to move backwards, so that whether they are going in or out they are all moving in the same direction at the same time. We saw that in the cylindrical pipe that was not the case, and if we took off the closed end of this cone it would not be the case, because then the pipe is open at both ends, and we then have a node between the two ends of the pipe. If we cut this in half again we shall have a note produced the octave of the original, the tube being just half the length. However we subdivide it, we shall get a similar arrangement, and whichever part we take we get the same note enforced. In such a conical pipe we may expect to get the same harmonics as in the case of open cylindrical pipes.

Professor Adams then showed a number of conical pipes fitting one into the other, and the mode in which the vibrations took place in such pipes—which were illustrated by a diagram—pointing out particularly that as you approached the apex of the pipes the nodal line moved further and further from the ventral section, until at the end the nodal line was found at the apex. He then continued as follows:—The greater the difference between the diameters of the two ends of the conical tubes, the greater will be the difference between the notes produced, and the note of the highest pitch will be produced when the open end is the largest of the two. If the open end is four times the diameter of the smallest one, then the note produced is an octave below the cylindrical closed pipe; so that from the same tube it is possible to produce two octaves. Here are some of the pipes made use of by Sir Charles Wheatstone in his experiments on cones, showing the different intervals between two notes. The production of different harmonics of conical tubes may be illustrated in a more pleasant way, as follows:—Dr. Stone has kindly consented to illustrate this fact by giving the different harmonics with the same fingering on the contrabassoon. The one great object in musical instruments generally is to avoid having a mixture of notes, and with the clarinet generally it is not possible to produce harmonics. With this instrument, however, Dr. Stone, as you hear, is able to produce the fundamental, the octave, and the twelfth from the same fingering, and in this case the instrument is a perfect cone. It illustrates perfectly Sir Charles Wheatstone's statement with regard to conical pipes, and shows

that the harmonics are the same as those obtained from a cylindrical tube.

There are one or two other points I should have liked to have touched upon, but time has gone very rapidly. One point I must mention, namely, that the resonance of a tube is such that it will only give a note when its length is such as to give one of the harmonics of the fundamental sounding body. That may be seen if we take a tuning-fork and alter this length of tube, which we may do by moving the piston from one point to another along the inside of the tube. At the open end there is a jew's-harp, which has this great advantage over a tuning-fork—the sound of the jew's-harp itself is not loud enough to interfere with the sound of the pipe. At present there is very little sound heard, but if I alter the length of the tube so as to give a note which is one of the harmonics of the jew's-harp, there will be a reinforcement of the note. The number of vibrations of this instrument, the fundamental note, would be that of a closed pipe four feet long, or two octaves below the present position of the piston, and that position being such, the tube will respond to the treble C. Now, if I alter the position and place it at the position of the 3rd harmonic, we get a certain amount of reinforcement; and so with the higher harmonics, though not so distinctly. In the intervals between no note is sounded, though when the position of the piston is near the right point the tone is sounded rather weaker than when in its proper position.

There is one other point which bears a close relation to the resonance of the column of air, and that is the reinforcement or transmission of sound along rods of wood, or other materials, and it is well known that Sir Charles Wheatstone made many experiments of that kind, connecting a musical instrument in one room with the sounding-board of another instrument in another room; and although the instruments might be of different kinds—for instance, a clarinet or harp attached to the sound-board of a piano—if the clarinet or harp were played the sound-board of the piano would give out the quality of tone of the instrument played. One experiment of this kind I may make this afternoon, showing the transmission of sound through what may be considered to correspond to various rooms. Here I take a musical box and wrap it up carefully in flannel, which will not conduct sound readily. I place it inside one box and cover it up, and then place it in another, and no sound will be heard until we establish a communication with it. As soon, however, as I make a connection with that musical box, by putting a rod of wood attached to a sound-board through a hole in the enclosing box, so as to touch it, the sound is distinctly heard. That shows the direct relation of the resonance produced in the air by means of a sounding-board such as this or other sounding instruments.

The CHAIRMAN asked which in particular of the matters spoken of by the lecturer were those brought forward by Sir Charles Wheatstone.

Professor ADAMS replied that the cylindrical pipes, the motion of the air from the ends towards the middle, and at the same time from the middle towards the ends, and the whole theory of conical tubes, was entirely due to Sir Charles Wheatstone. In fact, the whole theory of harmonics when applied to wind instruments might be said to be made out by Sir Charles Wheatstone.

DISCUSSION.

Mr. R. H. M. BOSANQUET said this occasion was very important for musicians in connection with certain points of musical theory. The late Sir Charles Wheatstone formed certain opinions at an early time of his life, and illustrated them in the peculiarly clear manner which was his own, but he never changed those opinions or admitted any modification which might afterwards come forward. Of course, anything he continued to maintain had much in its favour, and any ideas of his ought to be very seriously considered, and not lightly put aside. At the *soirée* of this Association last summer he had the honour to be introduced to Sir Charles Wheatstone, when he was astonished at several things which fell from him. Amongst other things, he considered that Helmholtz was all wrong, and that the problem of the resonance of tubes was to be solved on the principle which he discovered years before, and described under the name of reciprocation. He had some difficulty in finding the papers referred to by Sir Charles Wheatstone, they being mostly in the journal of the Royal Institution about the years 1828 and 1830, but he had since read them with great care, and felt that they required a deal of consideration. This was a point which seemed to require an authoritative settlement very much, but of course he was not prepared to give one. Sir Charles Wheatstone believed that when you had a simple pendulum vibration produced in air by means of a tuning-fork, that was capable, mechanically, of reinforcing vibrations having multiple periods in pipes and resonators of suitable length. The evidence brought forward was that of the remarkable experiment which had just been shown, on which he must make one observation—namely, that the sounding part was not a tuning-fork, but a jew's-harp, which was a very different thing. No doubt it was analogous to a tuning-fork, but had much larger vibrations, and the tongue was enclosed between two jaws of metal, so that it was more like a harmonium reed. It was quite clear there must be some deviation from the simple law of motion of a vibrating plate under these circumstances, and he believed it was to this circumstance to a great extent that the production of these harmonics was due. No one supposed that the harmonics were in the rods, or that they could vibrate in octaves and twelfths. As he had mentioned at the last meeting, he had made some experiments with

a large fork of Kœnig's, not subject to such conditions as these, but simply by presenting it to the mouths of suitable organ pipes, when he had clearly heard the first seven harmonics beyond the possibility of a doubt. The question was, what the phenomenon was due to? Was it true that the fork would so act upon the resounding body? Was it mechanically possible that the simple vibration of a resonant body could excite vibrations 1, 2, 3, 4, 5, 6, 7 times, and so on, per second of the vibrations of the fork? That was a question for mathematicians and mechanicians; but hitherto they had considered it impossible, and that the solution must be sought from another source. He believed it simply arose from the properties of the air, which did not admit of its transmitting to any extent or distance simple pendulum vibrations without transforming them, but really he could not give any authoritative statement on the subject, and perhaps this was not the place to attempt it. Still, this was one of the most grave questions to be considered at the present time, especially considering that Sir Charles Wheatstone's opinion was, to say the least, not on that side which was most generally taken by theorists.

MR. WILLIAM CHAPPELL remarked that Sir Charles Wheatstone, in his papers, said that he had made the experiments with a tuning-fork as well as with a jew's-harp. He had a perfect recollection of that, because Sir Charles had ordered one to be made for him which would be shown at the International Exhibition of Scientific Instruments.

The CHAIRMAN said he was reading Sir Charles Wheatstone's papers a fortnight before his death, and was struck by the sentence Mr. Chappell interpreted to mean that he had tried the experiment with a tuning-fork. After reading the sentence with great care, he could not make up his mind as to whether he really meant to state that or not, and he wrote to Sir Charles Wheatstone to inquire; unfortunately Sir Charles was in Paris at the time and died before it was possible to answer the question, so that he was afraid it remained at present rather in doubt whether he really did get these harmonics with a tuning-fork or not.

Professor ADAMS thought, from Sir Charles Wheatstone's paper, that he had tried the experiment with a tuning-fork, but it would be very easy to do so, although he had not a fork with him sufficiently large to try the experiment properly, the lowest he had being a middle C, which was a long way above the tone of the jew's-harp.

MR. CHAPPELL said Sir Charles Wheatstone proposed to him to try circular cards to make the sound more audible, and therefore he presumed it could be produced in any way. He himself had not had time or the convenience for trying it, but he thought that anything which would set the air in vibrations at the mouth of the tube would produce the same effect.

MR. BOSANQUET said there was no doubt the tone could be got.

The way he had set to work was to take various organ pipes corresponding to the pitch of the large fork he had spoken of out of an organ, and lay them side by side on a table. He made the observation himself with Mr. Parratt, of Magdalen, and they found that with this large fork and a disc of wood about four inches in diameter fastened to it, so as to increase the agitation of the air, they could hear distinctly up to the seventh harmonic. The tierce was exceedingly strong, and could be heard plainly without a disc.

Professor ADAMS said he had noticed in this sliding tube that the odd harmonics were much stronger than the even ones.

The CHAIRMAN asked what was the amplitude of vibration of the fork used by Mr. Bosanquet?

Mr. BOSANQUET: About a third of an inch.

The CHAIRMAN thought that might have something to do with it. Mr. W. W. Parkinson, in writing to him recently, stated that he had got beats from two tuning-forks a fifth apart. He did not know whether he had taken means to get rid of any combinational tone, so that he could be quite sure there were two simple tones. If you could produce so many harmonics as those Mr. Bosanquet mentioned, there would be no difficulty in getting beats with the interval of a fifth. This was evidently a case which required very strict examination.

Mr. BOSANQUET said by far the greatest series of experiments in this direction were those recounted in a paper by Kœnig in the last number of *Poggendorf*. He appeared to be fully satisfied that he had obtained perfectly pure tones, and if that were so, certainly the results were most startling and entirely contradicted Helmholtz's proposition as to the absence of beats. He thought, however, there could be no doubt the sounds were not pure, for what investigations he had been able to make left no doubt on his mind that it was quite impossible to produce a pure simple tone in air.

Mr. LEA SOUTHGATE, referring to the singing flames, said M. Kostner had made an instrument, to which he gave the name of Pyrophone, by which musical notes could be obtained from a key-board similar to a pianoforte.

The CHAIRMAN said this instrument was noticed in an appendix to his translation of Helmholtz. The peculiarity of it was that the tone was produced and stopped, not by raising the flame, but by a number of coincident flames, which were made to come together or separate. It was tried at the Society of Arts, but it was found extremely difficult to get it in tune, and the result was not very satisfactory. It was also shown at the Royal Institution, but there there was not sufficient gas, and they could not get any tone out of it at all.