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LXVIII. Upon the production of sound by radiant energy

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volt. The reversal of the rods again produced a reversal of the deflection.

In corroboration of the theory above stated, it should be borne in mind that the chlorides of silver, copper, zinc, and iron, when fused, are electrolytes. The liquid chloride of tin is not an electrolyte; and it was found that on immersing tin in this liquid no deposition of crystals was observed when it was so arranged that one part of the liquid was kept at the heat of boiling water and another at the ordinary temperature for two days; nor was there the least action on a galvanometer when arrangements were made for testing by that instrument.

These experiments form a good lecture-table illustration of the conversion of heat into electricity and chemical force. They also seem to have a bearing on the theory of voltaic action, since, from the nature of the substances employed, it is difficult to imagine that chemical action in any way initiates the current.

LXVIII. *Upon the Production of Sound by Radiant Energy.* *By* Alexander Graham Bell *.

[Plates X. & XI.]

In a paper read before the American Association for the Advancement of Science last August, I described certain experiments made by Mr. Sumner Tainter and myself which had resulted in the construction of a "*Photophone*," or apparatus for the production of sound by light †; and it will be my object today to describe the progress we have made in the investigation of photophonic phenomena since the date of this communication.

In my Boston paper the discovery was announced that thin disks of very many different substances *emitted sounds* when exposed to the action of a rapidly-interrupted beam of sunlight The great variety of material used in these experiments led me to believe that sonorousness under such circumstances would be found to be a general property of all matter.

At that time we had failed to obtain audible effects from masses of the various substances which became sonorous in the condition of thin diaphragms; but this failure was explained

* From advance proofs of a paper read before the National Academy of Arts and Sciences, April 21, 1881, communicated by the Author.

† Proceedings of the American Association for the Advancement of Science, August 27th, 1880; see, also, American Journal of Science, vol. xx. p. 305; Journal of the American Electrical Society, vol. iii. p. 3; Journal of the Society of Telegraph Engineers and Electricians, vol. ix. p. 404; *Annales de Chimie et de Physique*, vol. xxi.

upon the supposition that the molecular disturbance produced by the light was chiefly a surface action, and that under the circumstances of the experiments the vibration had to be transmitted through the mass of the substance in order to affect the ear. It was therefore supposed that, if we could lead to the ear air that was directly in contact with the illuminated surface, louder sounds might be obtained, and solid masses be found to be as sonorous as thin diaphragms. The first experiments made to verify this hypothesis pointed towards success. A beam of sunlight was focused into one end of an open tube, the ear being placed at the other end. Upon interrupting the beam, a clear, musical tone was heard, the pitch of which depended upon the frequency of the interruption of the light, and the loudness upon the material composing the tube.

At this stage our experiments were interrupted, as circumstances called me to Europe.

While in Paris a new form of the experiment occurred to my mind, which would not only enable us to investigate the sounds produced by masses, but would also permit us to test the more general proposition, that *sonorousness, under the influence of intermittent light, is a property common to all matter.*

The substance to be tested was to be placed in the interior of a transparent vessel, made of some material which (like glass) is transparent to light, but practically opaque to sound. Under such circumstances the light could get in, but the sound produced by the vibration of the substance could not get out. The audible effects could be studied by placing the ear in communication with the interior of the vessel by means of a hearing-tube.

Some preliminary experiments were made in Paris to test this idea; and the results were so promising that they were communicated to the French Academy on the 11th of October, 1880, in a note read for me by M. Antoine Breguet*. Shortly afterwards I wrote to Mr. Tainter, suggesting that he should carry on the investigation in America, as circumstances prevented me from doing so myself in Europe. As these experiments seem to have formed the common starting-point for a series of independent researches of the most important character, carried on simultaneously, in America by Mr. Tainter, and in Europe by M. Mercadier †, Prof. Tyndall ‡,

* *Comptes Rendus*, vol. xcl. p. 595.

† "Notes on Radiophony," *Comptes Rendus*, Dec. 6 and 13, 1880, and Feb. 21 and 28, 1881; Phil. Mag. Jan. 1881, p. 78. See also *Journal de Physique*, vol. x. p. 53.

‡ "Action of an Intermittent Beam of Radiant Heat upon Gaseous Matter," Proc. Royal Society, Jan. 13, 1881, vol. xxxi. p. 307.

W. C. Röntgen *, and W. H. Preece †, I may be permitted to quote from my letter to Mr. Tainter the passage describing the experiments referred to:—

"Metropolitan Hotel,
Rue Cambon, Paris,
Nov. 2, 1880.

"Dear Mr. Tainter,— .... I have devised a method of producing sounds by the action of an intermittent beam of light from substances that cannot be obtained in the shape of thin diaphragms or in the tubular form; indeed, the method is specially adapted to testing the generality of the phenomenon we have discovered, as it can be adapted to solids, liquids, and gases.

"Place the substance to be experimented with in a glass test-tube, connnect a rubber tube with the mouth of the test-tube, placing the other end of the pipe to the ear. Then focus the intermittent beam upon the substance in the tube. I have tried a large number of substances in this way with great success, although it is extremely difficult to get a glimpse of the sun here, and when it does shine the intensity of the light is not to be compared with that to be obtained in Washington. I got splendid effects from crystals of bichromate of potash, crystals of sulphate of copper, and from tobacco-smoke. A whole cigar placed in the test-tube produced a very loud sound. I could not hear any thing from plain water; but when the water was discolored with ink a feeble sound was heard. I would suggest that you might repeat these experiments and extend the results," &c. &c.

Upon my return to Washington in the early part of January ‡, Mr. Tainter communicated to me the results of the experiments he had made in my laboratory during my absence in Europe.

He had commenced by examining the sonorous properties of a vast number of substances enclosed in test-tubes in a simple empirical search for loud effects. He was thus led gradually to the discovery that cotton-wool, worsted, silk, and fibrous materials generally, produced much louder sounds than hard rigid bodies like crystals, or diaphragms such as we had hitherto used.

In order to study the effects under better circumstances, he enclosed his materials in a conical cavity in a piece of brass

* "On the Tones which arise from the intermittent illumination of a gas," see *Annalen der Phys. und Chemie*, Jan. 1881, No. 1, p. 155; Phil. Mag. April 1881, p. 308.

† "On the Conversion of Radiant Energy into Sonorous Vibrations,' Proc. Royal Society, March 10, 1881, vol. xxxi. p. 506.

‡ On the 7th of January.

closed by a flat plate of glass. A brass tube leading into the cavity served for connexion with the hearing-tube. When this conical cavity was stuffed with worsted or other fibrous materials, the sounds produced were much louder than when a test-tube was employed. This form of receiver is shown in figure 1.

Mr. Tainter next collected silks and worsteds of different colours, and speedily found that the darkest shades produced the best effects. Black worsted especially gave an extremely loud sound.

As white cotton-wool had proved itself equal, if not superior, to any other white fibrous material before tried, he was anxious to obtain coloured specimens for comparison. Not having any at hand, however, he tried the effect of darkening some cotton-wool with lampblack. Such a marked reinforcement of the sound resulted that he was induced to try lampblack alone.

About a teaspoonful of lampblack was placed in a test-tube and exposed to an intermittent beam of sunlight. The sound produced was much louder than any heard before.

Upon smoking a piece of plate-glass, and holding it in the intermittent beam with the lampblack surface towards the sun, the sound produced was loud enough to be heard, with attention, in any part of the room. With the lampblack surface turned from the sun, the sound was much feebler.

Mr. Tainter repeated these experiments for me immediately upon my return to Washington, so that I might verify his results.

Upon smoking the interior of the conical cavity shown in figure 1, and then exposing it to the intermittent beam, with the glass lid in position as shown, the effect was perfectly startling. The sound was so loud as to be actually painful to an ear placed closely against the end of the hearing-tube.

The sounds, however, were sensibly louder when we placed some smoked wire gauze in the receiver, as illustrated in the drawing, figure 1.

When the beam was thrown into a resonator, the interior of which had been smoked over a lamp, most curious alternations of sound and silence were observed. The interrupting disk was set rotating at a high rate of speed, and was then allowed to come gradually to rest. An extremely feeble musical tone was at first heard, which gradually fell in pitch as the rate of interruption grew less. The loudness of the sound produced varied in the most interesting manner. Minor reinforcements were constantly occurring, which became more and more marked as the true pitch of the resonator was neared. When at last the frequency of interruption corresponded to the frequency of the fundamental of the resonator, the sound produced was so loud that it might have been heard by an audience of hundreds of people.

The effects produced by lampblack seemed to me be very extraordinary, especially as I had a distinct recollection of experiments made in the summer of 1880 with smoked diaphragms, in which no such reinforcement was noticed.

Upon examining the records of our past photophonic experiments, we found in vol. vii. p. 57, the following note:—

"Experiment V.—Mica diaphragm covered with lampblack on side exposed to light.

"Result: distinct sound about same as without lampblack.—*A. G. B.*, *July* 18*th*, 1880.

"Verified the above, but think it somewhat louder than when used without lampblack.—*S. T.*, *July* 18*th*, 1880."

Upon repeating this old experiment we arrived at the same result as that noted. Little if any augmentation of sound resulted from smoking the mica. In this experiment the effect was observed by placing the mica diaphragm against the ear, and also by listening through a hearing-tube, one end of which was closed by the diaphragm. The sound was found to be more audible through the free air when the ear was placed as near to the lampblack surface as it could be brought without shading it.

At the time of my communication to the American Association I had been unable to satisfy myself that the substances which had become sonorous under the direct influence of intermittent sunlight were capable of reproducing the sounds of articulate speech under the action of an undulatory beam from our photophonic transmitter. The difficulty in ascertaining this will be understood by considering that the sound emitted by thin diaphragms and tubes were so feeble that it was impracticable to produce audible effects from substances in these conditions at any considerable distance away from the transmitter; but it was equally impossible to judge of the effects produced by our articulate transmitter at a short distance away, because the speaker's voice was directly audible through the air. The extremely loud sounds produced from lampblack have enabled us to demonstrate the feasibility of using this substance in an articulating photophone in place of the electrical receiver formerly employed.

The drawing, fig. 2, illustrates the mode in which the experiment was conducted. The diaphragm of the transmitter (A) was only 5 centimetres in diameter; the diameter of the receiver (B) was also 5 centimetres; and the distance between the two was 40 metres, or 800 times the diameter of the transmitting diaphragm. We were unable to experiment at greater distances without a heliostat, on account of the difficulty of keeping the light steadily directed on the receiver. Words and sentences spoken into the transmitter in a low tone of voice were audibly reproduced by the lampblack receiver.

In fig. 3 is shown a mode of interrupting a beam of sunlight for producing distant effects without the use of lenses. Two similarly-perforated disks are employed, one of which is set in rapid rotation, while the other remains stationary. This form of interrupter is also admirably adapted for work with artificial light. The receiver illustrated in the drawing consists of a parabolic reflector, in the focus of which is placed a glass vessel (A) containing lampblack or other sensitive substance, and connected with a hearing-tube. The beam of light is interrupted by its passage through the two slotted disks shown at B; and in operating the instrument, musical signals like the dots and dashes of the Morse alphabet are produced from the sensitive receiver (A) by slight motions of the mirror (C) about its axis (D).

In place of the parabolic reflector shown in the figure, a conical reflector like that recommended by Prof. Silvanus Thompson * can be used, in which case a cylindrical glass vessel would be preferable to the flask (A) shown in the figure.

In regard to the sensitive materials that can be employed, our experiments indicate that in the case of solids the physical condition and the colour are two conditions that markedly influence the intensity of the sonorous effects. *The loudest sounds are produced from substances in a loose, porous, spongy condition, and from those that have the darkest or most absorbent colours.*

The materials from which the best effects have been produced are cotton-wool, worsted, fibrous materials generally, cork, sponge, platinum and other metals in a spongy condition, and lampblack.

The loud sounds produced from such substances may perhaps be explained in the following manner. Let us consider, for example, the case of lampblack—a substance which becomes heated by exposure to rays of all refrangibilities. I look upon a mass of this substance as a sort of sponge, with its pores filled with air instead of water. When a beam of sunlight falls upon this mass, the particles of lampblack are heated,

* Phil. Mag. April 1881, vol. xi. p. 286.

and consequently expand, causing a contraction of the air-spaces or pores among them.

Under these circumstances a pulse of air should be expelled, just as we would squeeze out water from a sponge.

The force with which the air is expelled must be greatly increased by the expansion of the air itself, due to contact with the heated particles of lampblack. When the light is cut off, the converse process takes place. The lampblack particles cool and contract, thus enlarging the air-spaces among them, and the enclosed air also becomes cool. Under these circumstances a partial vacuum should be formed among the particles, and the outside air would then be absorbed, as water is by a sponge when the pressure of the hand is removed.

I imagine that in some such manner as this a wave of condensation is started in the atmosphere each time a beam of sunlight falls upon the lampblack, and a wave of rarefaction is originated when the light is cut off. *We can thus understand how it is that a substance like lampblack produces intense sonorous vibrations in the surrounding air, while at the same time it communicates a very feeble vibration to the diaphragm or solid bed upon which it rests.*

This curious fact was independently observed in England by Mr. Preece; and it led him to question whether, in our experiments with thin diaphragms, the sound heard was due to the vibration of the disk, or (as Prof. Hughes had suggested) to the expansion and contraction of the air in contact with the disk confined in the cavity behind the diaphragm. In his paper read before the Royal Society on the 10th of March, Mr. Preece describes experiments from which he claims to have proved that the effects are wholly due to the vibrations of the confined air, and that the *disks do not vibrate at all.*

I shall briefly state my reasons for disagreeing with him in this conclusion.

1. When an intermittent beam of sunlight is focused upon a sheet of hard rubber or other material, a musical tone can be heard, not only by placing the ear immediately behind the part receiving the beam, but by placing it against any portion of the sheet, even though this may be a foot or more from the place acted upon by the light.

2. When the beam is thrown upon the diaphragm of a "Blake transmitter," a loud musical tone is produced by a telephone connected in the same galvanic circuit with the carbon button (A), fig. 4. Good effects are also produced when the carbon button (A) forms, with the battery (B), a portion of the primary circuit of an induction-coil, the telephone (C) being placed in the secondary circuit.

In these cases the wooden box and mouth-piece of the transmitter should be removed, so that no air-cavities may be left on either side of the diaphragm.

It is evident, therefore, that in the case of thin disks a real vibration of the diaphragm is caused by the action of the intermittent beam, independently of any expansion and contraction of the air confined in the cavity behind the diaphragm.

Lord Rayleigh has shown mathematically that a to-and-fro vibration, of sufficient amplitude to produce an audible sound, would result from a periodical communication and abstraction of heat; and he says:—"We may conclude, I think, that there is at presemt no reason for discarding the obvious explanation that the sounds in question are due to the bending of the plates under unequal heating" ('Nature,' xxiii. p. 274). Mr. Preece, however, seeks to prove that the sonorous effects cannot be explained upon this supposition; but his experimental proof is inadequate to support his conclusion. Mr. Preece expected that if Lord Rayleigh's explanation was correct, the expansion and contraction of a thin strip under the influence of an intermittent beam could be caused to open and close a galvanic circuit so as to produce a musical tone from a telephone in the circuit. But this was an inadequate way to test the point at issue; for Lord Rayleigh has shown (Proc. of Roy. Soc. 1877) that an audible sound can be produced by a vibration whose amplitude is *less than a ten-millionth of a centimetre*; and certainly such a vibration as that would not have sufficed to operate a "make-and-break contact" like that used by Mr. Preece. The negative results obtained by him cannot, therefore, be considered conclusive.

The following experiments (devised by Mr. Tainter) have given results decidedly more favourable to the theory of Lord Rayleigh than to that of Mr. Preece:—

1. A strip (A) similar to that used in Mr. Preece's experiment was attached firmly to the centre of an iron diaphragm (B), as shown in figure 5, and was then pulled taut at right angles to the plane of the diaphragm. When the intermittent beam was focused upon the strip (A), a clear musical tone could be heard by applying the ear to the hearing-tube (C).

This seemed to indicate a rapid expansion and contraction of the substance under trial.

But a vibration of the diaphragm (B) would also have resulted if the thin strip (A) had acquired a to-and-fro motion, due either to the direct impact of the beam or to the sudden expansion of the air in contact with the strip.

2. To test whether this had been the case, an additional strip (D) was attached by its central point only to the strip under trial, and was then submitted to the action of the beam, as shown in fig. 6.

It was presumed that, if the vibration of the diaphragm (B) had been due to a *pushing force* acting on the strip (A), the addition of the strip (D) would not interfere with the effect; but if, on the other hand, it had been due to the longitudinal expansion and contraction of the strip (A), the sound would cease, or at least be reduced. The beam of light falling upon strip (D) was now interrupted as before by the rapid rotation of a perforated disk, which was allowed to come gradually to rest.

No sound was heard excepting at a certain speed of rotation, when a feeble musical tone became audible.

This result is confirmatory of the first.

The audibility of the effect at a particular rate of interruption suggests the explanation that the strip D had a normal rate of vibration of its own. When the frequency of the interruption of the light corresponded to this, the strip was probably thrown into vibration after the manner of a tuning-fork, in which case a to-and-fro vibration would be propagated down its stem or central support to the strip (A).

This indirectly proves the value of the experiment.

The list of solid substances that have been submitted to experiment in my laboratory is too long to be quoted here; and I shall merely say that we have not yet found one solid body that has failed to become sonorous under proper conditions of experiment*.

Experiments with Liquids.

The sounds produced by liquids are much more difficult to observe than those produced by solids. The high absorptive power possessed by most liquids would lead one to expect intense vibrations from the action of intermittent light; but the number of sonorous liquids that have so far been found is extremely limited, and the sounds produced are so feeble as to be heard only by the greatest attention and under the best circumstances of experiment. In the experiments made in my laboratory, a very long test-tube was filled with the liquid under examination, and a flexible-rubber tube was

* Carbon and thin microscope glass are mentioned in my Boston paper as non-responsive, and powdered chlorate of potash in the communication to the French Academy (*Comptes Rendus*, vol. xcl. p. 595). All these substances have since yielded sounds under more careful conditions of experiment.

slipped over the mouth far enough down to prevent the possibility of any light reaching the vapour above the surface. Precautions were also taken to prevent reflection from the bottom of the test-tube. An intermittent beam of sunlight was then focused upon the liquid in the middle portion of the test-tube by means of a lens of large diameter.

Results.

Clear water....................	No sound audible.
Water discoloured by ink ...	Feeble sound.
Mercury	No sound heard.
Sulphuric ether*..............	Feeble but distinct sound.
Ammonia	" " " "
Ammonio-sulphate of copper	" " " "
Writing-ink	" " " "
Indigo in sulphuric acid ...	" " " "
Chloride of copper *	" " " "

The liquids distinguished by an asterisk gave the best sounds.

Acoustic vibrations are always much enfeebled in passing from liquids to gases; and it is probable that a form of experiment may be devised which will yield better results, by communicating the vibrations of the liquid to the ear through the medium of a solid rod.

Experiments with Gaseous Matter.

On the 29th of November, 1880, I had the pleasure of showing to Prof. Tyndall, in the laboratory of the Royal Institution, the experiments described in the letter to Mr. Tainter, from which I have quoted above; and Prof. Tyndall at once expressed the opinion that the sounds were due to rapid changes of temperature in the body submitted to the action of the beam. Finding that no experiments had been made at that time to test the sonorous properties of different gases, he suggested filling one test-tube with the vapour of sulphuric ether (a good absorbent of heat), and another with the vapour of bisulphide of carbon (a poor absorbent); and he predicted that, if any sound was heard, it would be louder in the former case than in the latter.

The experiment was immediately made; and the result verified the prediction.

Since the publication of the memoirs of Röntgen † and Tyndall ‡ we have repeated these experiments, and have ex-

† *Ann. der Phys. und Chem.* 1881, No. 1, p. 155.
‡ Proc. Roy. Soc. vol. xxxi. p. 307.

tended the inquiry to a number of other gaseous bodies, obtaining in every case similar results to those noted in the memoirs referred to.

The vapours of the following substances were found to be highly sonorous in the intermittent beam — water vapour, coal-gas, sulphuric ether, alcohol, ammonia, amylene, ethyl bromide, diethylamine, mercury, iodine, and peroxide of nitrogen. The loudest sounds were obtained from iodine and peroxide of nitrogen.

I have now shown that sounds are produced by the direct action of intermittent sunlight from substances in every physical condition (solid, liquid, and gaseous); and the probability is therefore very greatly increased that sonorousness under such circumstances will be found to be a universal property of matter.

Upon Substitutes for Selenium in Electrical Receivers.

At the time of my communication to the American Association, the loudest effects obtained were produced by the use of selenium, arranged in a cell of suitable construction, and placed in a galvanic circuit with a telephone. Upon allowing an intermittent beam of sunlight to fall upon the selenium, a musical tone of great intensity was produced from the telephone connected with it.

But the selenium was very inconstant in its action. It was rarely, if ever, found to be the case that two pieces of selenium (even of the same stick) yielded the same results under identical circumstances of annealing &c. While in Europe last autumn, Dr. Chichester Bell, of University College, London, suggested to me that this inconstancy of result might be due to chemical impurities in the selenium used. Dr. Bell has since visited my laboratory in Washington, and has made a chemical examination of the various samples of selenium I had collected from different parts of the world. As I understand it to be his intention to publish the results of this analysis very soon, I shall make no further mention of his investigation than to state that he has found sulphur, iron, lead, and arsenic in the so-called "selenium," with traces of organic matter, that a quantitative examination has revealed the fact that sulphur constitutes nearly one per cent. of the whole mass, and that when these impurities are eliminated, the selenium appears to be more constant in its action and more sensitive to light.

Prof. W. G. Adams * has shown that tellurium, like sele-

* Proc. Roy. Soc. vol. xxiv. p. 163.

nium, has its electrical resistance affected by light; and we have attempted to utilize this substance in place of selenium. The arrangement of cell shown in fig. 7 was constructed for this purpose in the early part of 1880; but we failed at that time to obtain any indications of sensitiveness with a reflecting galvanometer. We have since found, however, that when this tellurium spiral is connected in circuit with a galvanic battery and telephone, and exposed to the action of an intermittent beam of sunlight, a distinct musical tone is produced by the telephone. The audible effect is much increased by placing the tellurium-cell with the battery in the primary circuit of an induction-coil, and placing the telephone in the secondary circuit.

The enormously high resistance of selenium and the extremely low resistance of tellurium suggested the thought that an alloy of these two substances might possess intermediate electrical properties. We have accordingly mixed together selenium and tellurium in different proportions; and while we do not feel warranted at the present time in making definite statements concerning the results, I may say that such alloys have proved to be sensitive to the action of light.

It occurred to Mr. Tainter, before my return to Washington last January, that the very great molecular disturbance produced in lampblack by the action of intermittent sunlight should produce a corresponding disturbance in an electric current passed through it, in which case lampblack could be employed in place of selenium in an electrical receiver. This has turned out to be the case; and the importance of the discovery is very great, especially when we consider the expense of such rare substances as selenium and tellurium.

The form of lampblack-cell we have found most effective is shown in fig. 8. Silver is deposited upon a plate of glass; and a zigzag line is then scratched through the film, as shown, dividing the silver surface into two portions insulated from one another, having the form of two combs with interlocking teeth.

Each comb is attached to a screw-cup, so that the cell can be placed in an electrical circuit when required. The surface is then smoked until a good film of lampblack is obtained, filling the interstices between the teeth of the silver combs. When the lampblack-cell is connected with a telephone and galvanic battery, and exposed to the influence of an intermittent beam of sunlight, a loud musical tone is produced by the telephone. This result seems to be due rather to the physical condition than to the nature of the conducting material employed, as metals in a spongy condition produce similar effects. For instance, when an electrical current is passed through spongy platinum while it is exposed to intermittent sunlight, a distinct musical sound is produced by a telephone in the same circuit. In all such cases the effect is increased by the use of an induction-coil; and the sensitive cells can be employed for the reproduction of articulate speech as well as for the production of musical sounds.

We have also found that loud sounds are produced from lampblack by passing through it an intermittent electrical current, and that it can be used as a telephonic receiver for the reproduction of articular speech by electrical means.

A convenient mode of arranging a lampblack cell for experimental purposes is shown in fig. 9. When an intermittent current is passed through the lampblack (A), or when an intermittent beam of sunlight falls upon it through the glass plate B, a loud musical tone can be heard by applying the ear to the hearing-tube C. When the light and the electrical current act simultaneously, two musical tones are perceived, which produce beats when nearly of the same pitch. By proper arrangements a complete interference of sound can undoubtedly be produced.

Upon the Measurement of the Sonorous Effects produced by Different Substances.

We have observed that different substances produce sounds of very different intensities under similar circumstances of experiment; and it has appeared to us that very valuable information might be obtained if we could measure the audible effects produced. For this purpose we have constructed several different forms of apparatus for studying the effects; but as our researches are not yet complete, I shall confine myself to a simple description of some of the forms of apparatus we have devised.

When a beam of light is brought to a focus by means of a lens, the beam diverging from the focal point becomes weaker as the distance increases, in a calculable degree. Hence, if we can determine the distances from the focal point at which two different substances emit sounds of equal intensity, we can calculate their relative sonorous powers.

Preliminary experiments were made by Mr. Tainter during my absence in Europe, to ascertain the distance from the focal point of a lens at which the sound produced by a substance became inaudible. A few of the results obtained will show the enormous differences existing between different substances in this respect.

Distance from Focal Point of Lens at which Sounds become Inaudible with Different Substances.

		millim.
Zinc diaphragm (polished)		1·51
Hard-rubber diaphragm		1·90
Tin-foil ”		2·00
Telephone ”	(japanned iron)	2·15
Zinc ”	(unpolished)	2·15
White silk	(in receiver shown in fig. 1)	3·10
White worsted	” ” ”	4·01
Yellow worsted	” ” ”	4·06
Yellow silk	” ” ”	4·13
White cotton-wool	” ” ”	4·38
Green silk	” ” ”	4·52
Blue worsted	” ” ”	4·69
Purple silk	” ” ”	4·82
Brown silk	” ” ”	5·02
Black silk	” ” ”	5·21
Red silk	” ” ”	5·24
Black worsted	” ” ”	6·50
Lampblack. In receiver the limit of audibility could not be determined on account of want of space. Sound perfectly audible at a distance of		10·00

Mr. Tainter was convinced from these experiments that this field of research promised valuable results; and he at once devised an apparatus for studying the effects, which he described to me upon my return from Europe. The apparatus has since been constructed; and I take great pleasure in showing it to you today.

(1) A beam of light is received by two similar lenses (A, B, fig. 10*), which bring the light to a focus on either side of the interrupting-disk (C). The two substances whose sonorous powers are to be compared are placed in the receiving vessels (D, E) (so arranged as to expose equal surfaces to the action of the beam) which communicate by flexible tubes (F, G), of equal length, with the common hearing-tube (H). The receivers (D, E) are placed upon slides, which can be moved along the graduated supports (I, K). The beams of light passing through the interrupting-disk (C) are alternately cut off by the swinging of a pendulum (L). Thus a musical sound is produced alternately from the substance in D and from that in E. One of the receivers is kept at a constant point upon its scale; and the other receiver is moved towards or from the focus of its beam until the ear decides that the sounds pro-

[* The letters in this figure were omitted by the author, and the omission unfortunately was not detected until after the Plate was printed; the reader can easily supply them.—ED. *Phil. Mag.*]

duced from D and E are of equal intensity. The relative positions of the receivers are then noted.

(2) Another method of investigation is based upon the production of an interference of sound; and the apparatus employed is shown in fig. 11. The interrupter consists of a tuning-fork (A), which is kept in continuous vibration by means of an electromagnet (B).

A powerful beam of light is brought to a focus between the prongs of the tuning-fork (A); and the passage of the beam is more or less obstructed by the vibration of the opaque screens (C, D) carried by the prongs of the fork.

As the tuning-fork (A) produces a sound by its own vibration, it is placed at a sufficient distance away to be inaudible through the air; and a system of lenses is employed for the purpose of bringing the undulating beam of light to the receiving lens (E) with as little loss as possible. The two receivers (F, G) are attached to slides (H, I), which move upon opposite sides of the axis of the beam; and the receivers are connected by flexible tubes of unequal length (K, L) communicating with the common hearing-tube (M).

The length of the tube (K) is such that the sonorous vibrations from the receivers (F, G) reach the common hearing-tube (M) in opposite phases. Under these circumstances silence is produced when the vibrations in the receivers (F, G) are of equal intensity. When the intensities are unequal, a residual effect is perceived. In operating the instrument the position of the receiver (G) remains constant, and the receiver (F) is moved to or from the focus of the beam until complete silence is produced. The relative positions of the two receivers are then noted.

(3) Another mode is as follows:—The loudness of a musical tone produced by the action of light is compared with the loudness of a tone of similar pitch produced by electrical means. A rheostat introduced into the circuit enables us to measure the amount of resistance required to render the electrical sound equal in intensity to the other.

(4) If the tuning-fork (A) in fig. 11 is thrown into vibration by an undulatory instead of an intermittent current passed through the electromagnet (B), it is probable that a musical tone, electrically produced in the receiver (F) by the action of the same current, would be found capable of extinguishing the effect produced in the receiver (G) by the action of the undulatory beam of light, in which case it should be possible to establish an acoustic balance between the effects produced by light and electricity, by introducing sufficient resistance into the electric circuit.

Upon the Nature of the Rays that produce Sonorous Effects in Different Substances.

In my paper read before the American Association last August, and in the present paper, I have used the word "light" in its usual rather than its scientific sense; and I have not hitherto attempted to discriminate the effects produced by the different constituents of ordinary light—the thermal, luminous, and actinic rays. I find, however, that the adoption of the word "photophone" by Mr. Tainter and myself has led to the assumption that we believed the audible effects discovered by us to be due entirely to the action of luminous rays. The meaning we have uniformly attached to the words "photophone" and "light" will be obvious from the following passage, quoted from my Boston paper:—

"Although effects are produced as above shown by forms of radiant energy which are invisible, we have named the apparatus for the production and reproduction of sound in this way the 'photophone,' *because an ordinary beam of light contains the rays which are operative.*"

To avoid in future any misunderstandings upon this point, we have decided to adopt the term "*radiophone,*" proposed by M. Mercadier, as a general term signifying an apparatus for the production of sound by any form of radiant energy, limiting the words *thermophone*, *photophone*, and *actinophone* to apparatus for the production of sound by thermal, luminous or actinic rays respectively.

M. Mercadier, in the course of his researches in radiophony, passed an intermittent beam from an electric lamp through a prism, and then examined the audible effects produced in different parts of the spectrum (*Comptes Rendus*, Dec. 6th, 1880).

We have repeated this experiment, using the sun as our source of radiation, and have obtained results somewhat different from those noted by M. Mercadier.

(1) A beam of sunlight was reflected from a heliostat (A, fig. 12) through an achromatic lens (B), so as to form an image of the sun upon the slit (C).

The beam then passed through another achromatic lens (D) and through a bisulphide-of-carbon prism (E), forming a spectrum of great intensity, which, when focused upon a screen, was found to be sufficiently pure to show the principal absorption-lines of the solar spectrum.

The disk interrupter (F) was then turned with sufficient rapidity to produce from five to six hundred interruptions of the light per second, and the spectrum was explored with the receiver (G), which was so arranged that the lampblack surface exposed was limited by a slit, as shown.

Under these circumstances sounds were obtained in every part of the visible spectrum, excepting the extreme half of the violet, as well as in the ultra-red. A continuous increase in the loudness of the sound was observed upon moving the receiver (G) gradually from the violet into the ultra-red. The point of maximum sound lay very far out in the ultra-red. Beyond this point the sound began to decrease, and then stopped so suddenly that a very slight motion of the receiver (G) made all the difference between almost maximum sound and complete silence.

(2) The lampblacked wire gauze was then removed, and the interior of the receiver (G) was filled with red worsted. Upon exploring the spectrum as before, entirely different results were obtained. The maximum effect was produced in the green, at that part where the red worsted appeared to be black. On either side of this point the sound gradually died away, becoming inaudible on the one side in the middle of the indigo, and on the other at a short distance outside the edge of the red.

(3) Upon substituting green silk for red worsted, the limits of audition appeared to be the middle of the blue and a point a short distance out in the ultra-red. Maximum in the red.

(4) Some hard-rubber shavings were now placed in the receiver (G). The limits of audibility appeared to be, on the one hand, the junction of the green and blue, and, on the other, the outside edge of the red. Maximum in the yellow. Mr. Tainter thought he could hear a little way into the ultra-red; and to his ear the maximum was about the junction of the red and orange.

(5) A test-tube containing the vapour of sulphuric ether was then substituted for the receiver (G). Commencing at the violet end, the test-tube was gradually moved down the spectrum, and out into the ultra-red, without audible effect; but when a certain point far out in the ultra-red was reached a distinct musical tone suddenly made its appearance, which disappeared as suddenly on moving the test-tube a very little further on.

(6) Upon exploring the spectrum with a test-tube containing the vapour of iodine, the limits of audibility appeared to be the middle of the red and the junction of the blue and indigo. Maximum in the green.

(7) A test-tube containing peroxide of nitrogen was substituted for that containing iodine. Distinct sounds were ob-

tained in all parts of the visible spectrum, but no sounds were observed in the ultra-red.

The maximum effect seemed to me to be in the blue. The sounds were well-marked in all parts of the violet; and I even fancied that the audible effect extended a little way into the ultra-violet; but of this I cannot be certain. Upon examining the absorption-spectrum of peroxide of nitrogen, it was at once observed that the maximum sound was produced in that part of the spectrum where the greatest number of absorption-lines made their appearance.

(8) The spectrum was now explored by a selenium-cell; and the audible effects were observed by means of a telephone in the same galvanic circuit with the cell. The maximum effect was produced in the red. The audible effect extended a little way into the ultra-red, on the one hand, and up as high as the middle of the violet, on the other.

Although the experiments so far made can only be considered as preliminary to others of a more refined nature, I think we are warranted in concluding that *the nature of the rays that produce sonorous effects in different substances depends upon the nature of the substances that are exposed to the beam, and that the sounds are in every case due to those rays of the spectrum that are absorbed by the body.*

The Spectrophone.

Our experiments upon the range of audibility of differen substances in the spectrum have led us to the construction of a new instrument for use in spectrum analysis, which was described and exhibited to the Philosophical Society of Washington last Saturday *. The eye-piece of a spectroscope is removed; and sensitive substances are placed in the focal point of the instrument, behind an opaque diaphragm containing a slit. These substances are put in communication with the ear by means of a hearing-tube; and thus the instrument is converted into a veritable "spectrophone," like that shown in fig. 13.

Suppose we smoke the interior of our spectrophonic receiver, and fill the cavity with peroxide of nitrogen gas. We have then a combination that gives us good sounds in all parts of the spectrum (visible and invisible), except the ultra-violet. Now pass a rapidly-interrupted beam of light through some substances whose absorption-spectrum is to be investigated, and bands of sound and silence are observed upon exploring the spectrum, the silent positions corresponding to the absorption-

* Proc. of Phil. Soc. of Washington, April 16, 1881.

bands. Of course, the ear cannot for one moment compete with the eye in the examination of the visible part of the spectrum; but in the invisible part beyond the red, where the eye is useless, the ear is invaluable. In working in this region of the spectrum, lampblack alone may be used in the spectrophonic receiver. Indeed the sounds produced by this substance in the ultra-red are so well-marked as to constitute our instrument a most reliable and convenient substitute for the thermopile. A few experiments that have been made may be interesting.

(1) The interrupted beam was filtered through a saturated solution of alum.

Result. The range of audibility in the ultra-red was slightly reduced by the absorption of a narrow band of the rays of lowest refrangibility. The sounds in the visible part of the spectrum seemed to be unaffected.

(2) A thin sheet of hard rubber was interposed in the path of the beam.

Result. Well-marked sounds in every part of the ultra-red. No sounds in the visible part of the spectrum, excepting the extreme half of the red.

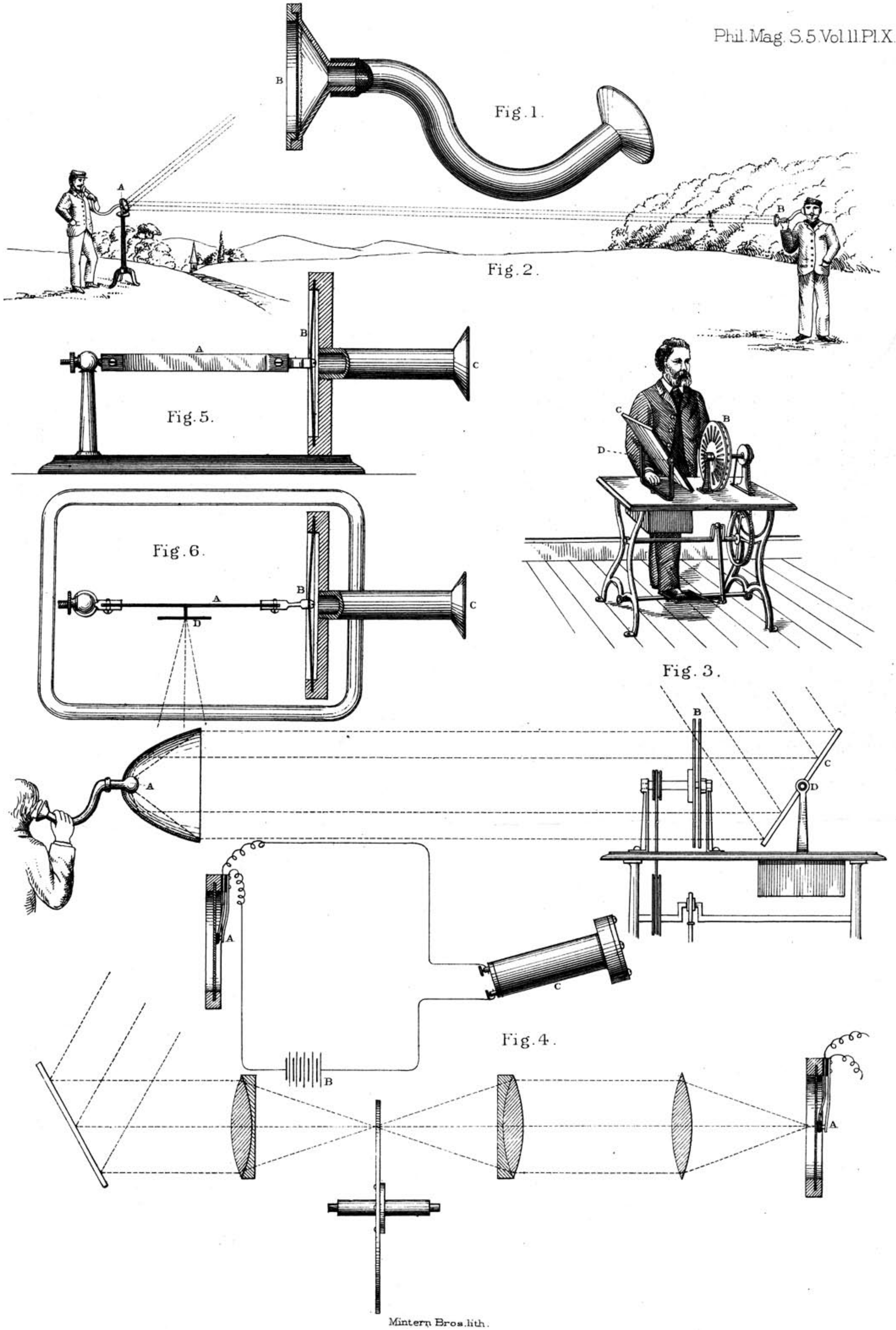
These experiments reveal the cause of the curious fact alluded to in my paper read before the American Association last August—that sounds were heard from selenium when the beam was filtered through both hard rubber and alum at the same time. (See table of results in fig. 14.)

(3) A solution of ammonia-sulphate of copper was tried.

Result. When placed in the path of the beam the spectrum disappeared, with the exception of the blue and violet end. To the eye the spectrum was thus reduced to a single broad band of blue-violet light. To the ear, however, the spectrum revealed itself as two bands of sound with a broad space of silence between. The invisible rays transmitted constituted a narrow band just outside the red.

I think I have said enough to convince you of the value of this new method of examination; but I do not wish you to understand that we look upon our results as by any means complete. It is often more interesting to observe the first totterings of a child than to watch the firm tread of a full-grown man; and I feel that *our* first footsteps in this new field of science may have more of interest to you than the fuller results of mature research. This must be my excuse for having dwelt so long upon the details of incomplete experiments.

I recognize the fact that the spectrophone must ever remain a mere adjunct to the spectroscope; but I anticipate that it has a wide and independent field of usefulness in the investigation of absorption-spectra in the ultra-red.



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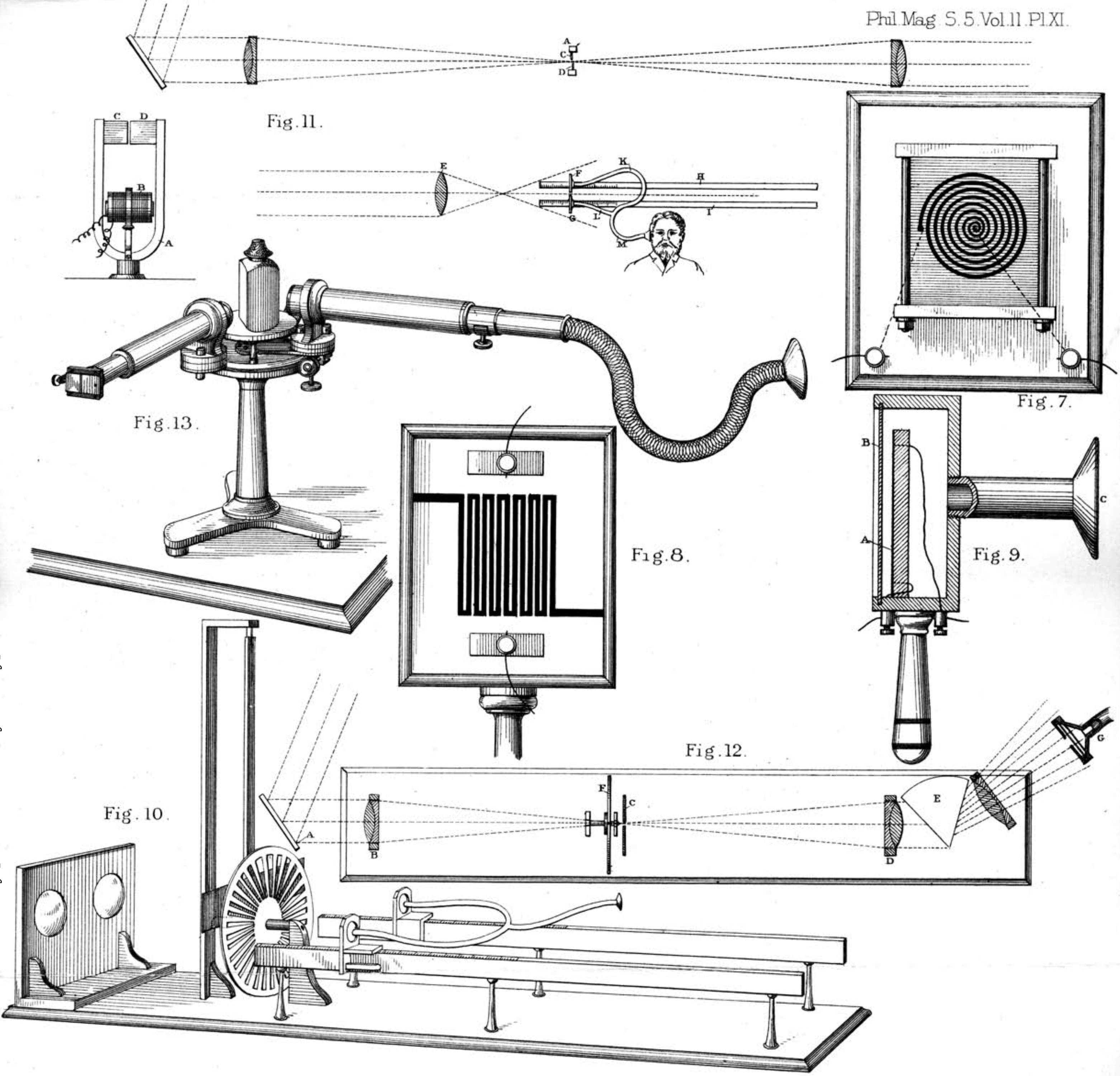

Fig.11. Fig.7. Fig.13. Fig.8. Fig.9. Fig.12. Fig.10.

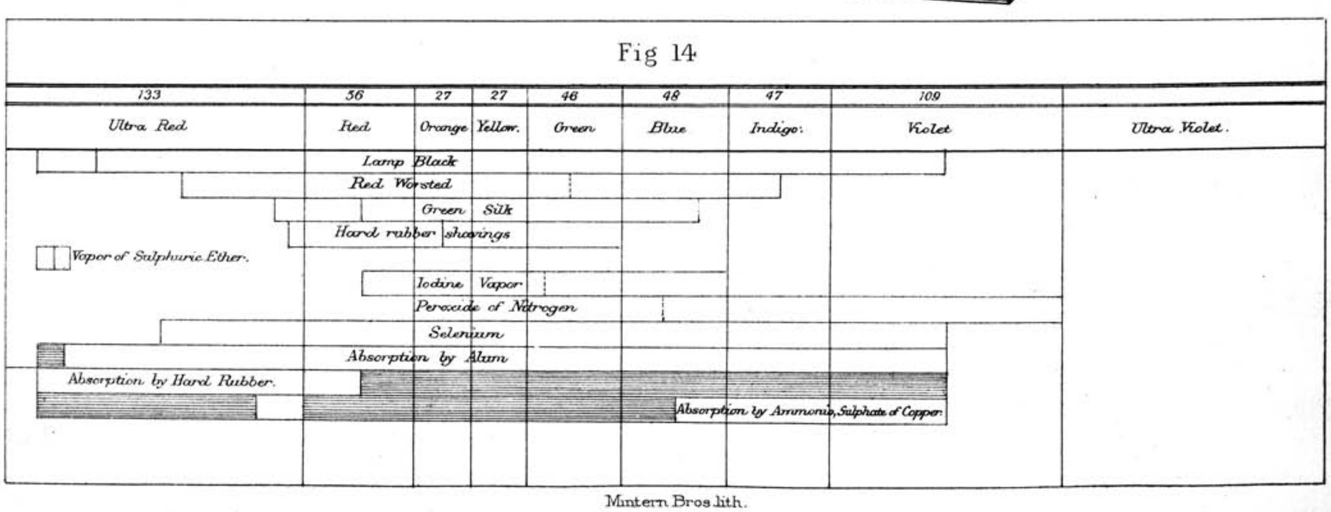

Fig 14

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