ART. XXXIV.—*On the Production and Reproduction of Sound by Light*; by ALEXANDER GRAHAM BELL, Ph.D.

[Read before the American Association for the Advancement of Science, in Boston, August 27, 1880.]

IN bringing before you some discoveries made by Mr. Sumner Tainter and myself, which have resulted in the construction of apparatus for the production and reproduction of sound by means of light, it is necessary to explain the state of knowledge which formed the starting point of our experiments.

I shall first describe that remarkable substance "selenium," and the manipulations devised by previous experimenters; but the final result of our researches has widened the class of substances sensitive to light vibrations, until we can propound the fact of such sensitiveness being a general property of all matter.

We have found this property in gold, silver, platinum, iron, steel, brass, copper, zinc, lead, antimony, german-silver, Jenkin's metal, Babbitt's metal, ivory, celluloid, gutta-percha, hard rubber, soft vulcanized rubber, paper, parchment, wood, mica, and silvered glass; and the only substances from which we have not obtained results, are carbon and thin microscope glass.*

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* Later experiments have shown that these are not exceptions.

We find that when a vibratory beam of light falls upon these substances *they emit sounds*, the pitch of which depends upon the frequency of the vibratory change in the light. We find farther, that when we control the form or character of the light, vibrations on selenium (and probably on the other substances), we control the quality of the sound, and obtain all varieties of articulate speech. We can thus, without a conducting wire as in electric telephony, speak from station to station wherever we can project a beam of light. We have not had the opportunity of testing the limit to which this photophonic effect may be extended, but we have spoken to and from points 213 meters apart; and there seems no reason to doubt that the results will be obtained at whatever distance a beam of light can be flashed from one observatory to another. The necessary privacy of our experiments, hitherto, has alone prevented any attempts at determining the extreme distance at which this new method of vocal communication will be available.

I shall now speak of selenium.

Selenium.—In the year 1817, Berzelius and Gottlieb Gahn made an examination of the method of preparing sulphuric acid in use at Gripsholm. During the course of this examination they observed in the acid a sediment of a partly reddish, partly clear brown color, which under the action of the blowpipe gave out a peculiar odor, like that attributed by Klaproth to tellurium.

As tellurium was a substance of extreme rarity, Berzelius attempted its production from this deposit, but he was unable after many experiments to obtain farther indications of its presence. He found plentiful signs of sulphur mixed with mercury, copper, tin, zinc, iron, arsenic and lead, but no trace of tellurium.

It was not in the nature of Berzelius to be disheartened by this result. In science every failure advances the boundary of knowledge as well as every success; and Berzelius felt that if the characteristic odor that had been observed did not proceed from tellurium, it might possibly indicate the presence of some substance then unknown to the chemist. Urged on by this hope he returned with renewed ardor to his work.

He collected a great quantity of the material and submitted the whole mass to various chemical processes. He succeeded in separating successively the sulphur, the mercury, the copper, the tin and the other known substances, whose presence had been indicated by his tests; and after all these had been eliminated, there still remained a residue, which proved upon examination to be what he had been in search of—*a new elementary substance.*

The chemical properties of this new element were found to resemble those of tellurium in such a remarkable degree that Berzelius gave to the substance the name of "selenium," from the Greek word *σελήνη*, the moon, ("tellurium," as is well known, being derived from *tellus*, the earth). Although tellurium and selenium are alike in many respects, they differ in their electrical properties; tellurium being a good conductor of electricity, and selenium, as Berzelius showed, a non-conductor.

Knox* discovered in 1837, that selenium became a conductor when fused; and Hittorff† in 1851, showed that it conducted at ordinary temperatures when in one of its allotropic forms.

When selenium is rapidly cooled from a fused condition it is a non-conductor. In this, its "vitreous" form, it is of a dark brown color, almost black by reflected light, having an exceedingly brilliant surface. In thin films it is transparent, and appears of a beautiful ruby red by transmitted light.

When selenium is cooled from a fused condition with *extreme slowness*, it presents an entirely different appearance, being of a dull lead color, and having throughout a granular or crystalline structure and looking like a metal. In this form it is opaque to light even in very thin films. This variety of selenium has long been known as "granular" or "crystalline" selenium; or as Regnault called it, "metallic" selenium. It was selenium of this kind that Hittorff found to be a conductor of electricity at ordinary temperature.

He also found that its resistance to the passage of an electrical current diminished continuously by heating up to the point of fusion; and that the resistance suddenly increased in passing from the solid to the liquid condition.‡

It was early discovered that exposure to sunlight § hastens the change of selenium from one allotropic form to another; and this observation is significant in the light of recent discoveries.

Although selenium has been known for the last sixty years, it has not yet been utilized to any extent in the arts, and it is still considered simply as a chemical curiosity. It is usually supplied in the form of cylindrical bars. These bars are sometimes found to be in the metallic condition, but more usually they are in the vitreous or non-conducting form.

It occurred to Willoughby Smith that, on account of the high resistance of crystalline selenium, it might be usefully employed at the shore-end of a submarine cable, in his system

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* Trans. Roy. Irish Acad. (1839). xix, 147; also Phil. Mag. III, xvi, 185.

† Pogg. Ann., lxxxiv, 214; also Phil. Mag., IV, iii, 546.

‡ See Draper and Moss in Proc. Roy. Irish Acad., Nov. 1873, II, vol. i, p. 529.

§ Gmelin's Handbook of Chemistry (1849,) ii, 235; see also Hittorff in the Phil. Mag. (1842,) IV, iii, 547.

of testing and signaling during the process of submersion. Upon experiment the selenium was found to have all the resistance required; some of the bars employed measuring as much as 1400 megohms—a resistance equivalent to that which would be offered by a telegraph wire long enough to reach from the earth to the sun! But the resistance was found to be extremely variable. Efforts were made to ascertain the cause of this variability, and it was discovered that *the resistance was less when the selenium was exposed to light than when it was in the dark!*

This observation was first made by Mr. May*—(Mr. Willoughby Smith's assistant, stationed at Valentia)—was soon verified by a careful series of experiments, the results of which were communicated by Mr. Willoughby Smith † to the Society of Telegraph Engineers, on the 17th of February, 1873. Platinum wires were inserted into each end of a bar of crystalline selenium, which was then hermetically sealed in a glass tube through the ends of which the platinum wires projected for the purpose of connection. One of these bars was placed in a box, the lid of which was closed so as to shade the selenium, and the resistance of the substance was measured.

Upon opening the lid of the box the resistance instantaneously diminished. When the light of an ordinary gas burner (which was placed at a distance of several feet from the bar,) was intercepted by shading the selenium with the hand, the resistance again increased; and upon passing the light through rock salt, and through glasses of various colors, the resistance was found to vary according to the amount of light transmitted. In order to be certain that temperature had nothing to do with the effect, the selenium was placed in a vessel of water so that the light had to pass through a considerable depth of water in order to reach the selenium. The effects, however, were the same as before. When a strong light from the ignition of a narrow band of magnesium was held about nine inches above the water, the resistance of the selenium immediately fell more than two-thirds, returning to the normal condition upon the removal of the light.

The announcement of these results naturally created an intense interest among scientific men, and letters of enquiry regarding the details of the experiment soon appeared in the columns of Nature, from Harry Napier Draper ‡ and Lieut. M. L. Sale,§ which were answered in the next number by Willoughby Smith. ‖

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* See lecture by Siemens in Proc. Roy. Inst. of Great Britain, vol. viii, p. 68.

† Jour. of Soc. of Teleg. Engin., ii, p. 31 (1873); Nature, vii, 303; Teleg. Journal, III, (1873), v, 301.

‡ Nature, vii, 340, March 6th, 1873.

§ Ibid.

‖ Nature, vii, 361, March 13th, 1873.

Sale and Draper were soon able to corroborate the statements that had been made by Willoughby Smith.

Sale[*] presented his researches to the Royal Society on the 8th of May, 1873, and in the following November, Draper[†] presented his results to the Royal Irish Academy in the shape of a joint paper by himself and Richard J. Moss.

Draper and Moss gave in their paper an admirable summary of the condition of our knowledge regarding selenium at that time. They confirmed Hittorff's observation that the temperature of minimum resistance of granular selenium was somewhere about 210° C., and that at 217° C. (the fusing point), the resistance suddenly increased. They carried the temperature to a still higher point than Hittorff had done, and found that the resistance again diminished, reaching a second minimum at 250° C.

During the course of their experiments they produced a variety of granular selenium not different in appearance from other specimens but having different electrical properties. In this form the resistance became greater instead of less when the temperature was raised.

They also used thin plates of selenium instead of the cylindrical bars formerly employed, and found great advantage from the increased sensitiveness of the former to light.

Sale found upon exposing selenium to the action of the solar spectrum that the maximum effect was produced just at or outside the extreme edge of the red end of the spectrum at a point nearly coincident with the maximum of the heat rays, thus rendering it uncertain whether the effect was due to light or to radiant heat.

In the winter of 1873–4 the Earl of Rosse[‡] attempted to decide this question by comparing the selenium effects with the indications of the thermopile. He exposed selenium to the action of non-luminous radiations from hot bodies, but could produce no effect; whereas, a thermopile under similar conditions gave abundant indications of a current.

He also cut off the heat rays of low refrangibility from luminous bodies by the interposition of glass and alum between the selenium and the source of light without materially affecting the result; but when the thermopile was employed the greater portion of the heat-effect was cut off.

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[*] Proc. Roy. Soc., xxi, 283; see also Pogg. Ann., cl, 333; Phil. Mag., IV, xlvii, 216; Nature, viii, 134.

[†] Proc. Roy. Irish Acad., II, Nov. 10th, 1873, 1, 529; see also a communication from Richard J. Moss to Nature, Aug. 12th, 1875, xii, 291; being an answer to a letter from J. E. H. Gordon upon the "Anomalous behavior of Selenium," published in that journal on the 8th of July, 1875; see vol. xii, p. 187.

[‡] Phil. Mag., IV, March, 1874, xlvii, 161; see, also, this Journal, III, vii, 512.

Later, Prof. W. G. Adams,* of Kings College, took up the question, and his experiments seemed to prove conclusively that the action was due principally, if not entirely, to those rays of the spectrum which were luminous, and that the ultra-red or the ultra-violet rays had little or no effect.

This conclusion was supported by the marked effect produced by the light of the moon, and by the apparent insensitiveness of selenium to rays passed through a solution of iodine in bisulphide of carbon. He found that the maximum effect was produced by the greenish-yellow rays, and showed that *the intensity of the action depended upon the illuminating power of the light*, being *directly as the square root of that illuminating power.*

Professor Adams and Mr. R. E. Day† continued these researches, and among other interesting and suggestive results, discovered that light produces in selenium an electromotive force without the aid of a battery.

The most sensitive variety of selenium that has yet been produced was obtained in Germany by Dr. Werner Siemens, by continued heating for some hours at a temperature of 210° C., followed by extremely slow cooling.

Dr. C. W. Siemens,‡ in a lecture delivered before the Royal Institution of Great Britain, on the 18th of February, 1876, stated that his brother's modification of selenium was so sensitive to light that its conductivity was *fifteen times as great in sunlight as it was in the dark.*

In Werner Siemens'§ experiments special arrangements were made for reducing the resistance of the selenium.

For this purpose two fine platinum wires were coiled into a double flat spiral and were laid upon a plate of mica, so that they did not come into contact with one another. A drop of melted selenium was then placed upon the platinum wire arrangement and a second sheet of mica was pressed upon the selenium so as to cause it to spread out and fill the spaces between the wires. Each cell was about the size of a silver dime. The cells were then placed in a paraffine bath and annealed.

Siemens devised other arrangements of apparatus for reducing the resistance. In the form known as "Siemens' Grating," the

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* Proc. Roy. Soc., June 17th, 1875, xxiii, 535; see, also, Proc. Roy. Soc., Jan. 6th, 1876, xxiv, 163; Nature, Jan. 20th, 1876, xiii, 238; Nature, Mar. 23d, 1876, xiii, 419: Scient. Amer. Supplement, June 3d, 1876, i, 354.

† Proc. Roy. Soc., June 15th, 1876, xxv, 113.

‡ Proc. Roy. Inst. Gt. Brit., Feb. 18th, 1876, viii, 68; see, also, Nature, xiii, 407; Scient. Amer. Supplement, Apr. 1st, 1876, i, 222; Scient. Amer. Supplement, June 10th, 1876, i, 375.

§ Monatsbericht der Kön. preuss. Akad. der Wissenschaften zu Berlin for 1875, p. 280; Phil. Mag., Nov. 1875, IV, 1, 416; Nature, Dec. 9th, 1875, xiii, 112; Monatsber. Berl. Akad., Feb. 17, 1876; Pogg. Ann., clix, 117; Monatsb. Berl. Akad., June 7, 1877; Pogg. Ann., 1877, ii, 521.

two wires, instead of being coiled together, were arranged in a zig-zag shape, forming a sort of platinum gridiron.

This was treated in the same way as the spiral arrangement. Another form of cell consisted of a sort of lattice-work or basket-work of platinum wires arranged upon a perforated mica plate, the wires interlacing with one another, and with the mica plate so as to make metallic contact only with alternate wires. He also found that iron and copper might be employed, instead of platinum.

Without dwelling further upon the researches of others I may say that all observations concerning the effect of light upon the conductivity of selenium have been made by means of the galvanometer, but it occurred to me that the telephone, from its extreme sensitiveness to electrical influences, might be substituted with advantage. Upon consideration of the subject, however, I saw that the experiments could not be conducted in the ordinary way, for the following reasons: The law of audibility of the telephone is precisely analogous to the law of electric induction. No effect is produced during the passage of a continuous and steady current. It is only at the moment of change from a stronger to a weaker state, or, *vice versa*, that any audible effect is produced; and the amount of effect is exactly proportional to the amount of *variation* in the current.

It was, therefore, evident that the telephone could only respond to the effect produced in selenium at the moment of change from light towards darkness, or, *vice versa*, and that it would be advisable to intermit the light with great rapidity so as to produce a succession of changes in the conductivity of the selenium, corresponding in frequency to musical vibrations within the limits of the sense of hearing. For I had often noticed that currents of electricity, so feeble as hardly to produce any audible effects from a telephone when the circuit was simply opened and closed, caused very perceptible musical sounds when the circuit was rapidly interrupted; and that the higher the pitch of the sound the more audible was the effect. I was much struck by the idea of in this way producing sound by the action of light.

I proposed to pass a bright light through one of the orifices in a perforated screen consisting of a circular disc or wheel with holes near the circumference. Upon rapidly rotating the disc an intermittent beam of light would fall upon the selenium and a musical tone should be produced from the telephone, the pitch of which would depend upon the rapidity of the rotation of the disc.

Upon further consideration it appeared to me that all the audible effects obtained from variations of electricity could also be produced by variations of light, acting upon selenium. I saw that the effect could not only be produced at the extreme distance at which selenium would normally respond to the action of a luminous body, but that this distance could be indefinitely increased by the use of a parallel beam of light, so that we might telephone from one place to another without the necessity of a conducting wire between the transmitter and receiver.

It was evidently necessary in order to reduce this idea to practice, to devise an apparatus to be operated by the voice of a speaker, by which variations could be produced in a parallel beam of light, corresponding to the variations in the air produced by the voice.

I proposed to pass light through a perforated plate containing an immense number of small orifices.

Two similarly perforated plates were to be employed. One was to be fixed and the other to be attached to the center of a diaphragm actuated by the voice; so that the vibration of the diaphragm would cause the movable plate to slide to and fro over the surface of the fixed plate, thus alternately enlarging and contracting the free orifices for the passage of light. In this way the voice of a speaker could control the amount of light passed through the perforated plates without completely obstructing its passage. This apparatus was to be placed in the path of a parallel beam of light, and the undulatory beam emerging from the apparatus could be received at some distant place upon a lens, or other apparatus by means of which it could be condensed upon a sensitive piece of selenium placed in a local circuit, with a telephone and galvanic battery.

The variations in the light produced by the voice of the speaker should cause corresponding variations in the electrical resistance of the selenium at the distant place, and the telephone in circuit with the selenium should reproduce audibly the tones and articulations of the speaker's voice.

I obtained some selenium for the purpose of trying the apparatus described; but found upon experiment that its resistance was almost infinitely greater than that of any telephone that had been constructed; and I was therefore unable at that time to obtain audible effects in the way desired. I believed, however, that this obstacle could be overcome by devising mechanical arrangements for reducing the resistance of the selenium, and by constructing special telephones for the purpose.

I felt so much confidence in this that in a lecture delivered before the Royal Institution of Great Britain, on the 17th of May, 1878, I announced the possibility of hearing a shadow by means of interrupting the action of light upon selenium. A few days afterwards my ideas upon this subject received a fresh impetus by the announcement made by Mr. Willoughby Smith,* before the Society of Telegraph Engineers, that he had heard the action of a ray of light falling upon a bar of crystalline selenium by listening to a telephone in circuit with it.

It is not unlikely that the publicity given to the speaking telephone during the last few years, may have suggested to many minds, in different parts of the world, somewhat similar ideas to my own; indeed, it has recently come to my knowledge that a writer (J. F. W.,† of Kew) on the 13th of June, 1878, asked the readers of "Nature" through the columns of that periodical, whether any experiments had been made with a telephone in circuit with a selenium galvanic element arranged as in Sabine's selenium battery;‡ and suggested that it was not unlikely that sounds would be produced in a telephone by the action of light of variable intensity upon a selenium element in circuit with it.

In September or October, 1878, Mr. A. C. Brown, of London, submitted to me, confidentially, the details of a most ingenious invention of his, of which we may yet hear more. This invention, although entirely different from my own, involved the use of selenium in circuit with a battery and telephone, and the production of articulate speech by the action of a variable light. I am also aware that Mr. W. D. Sargent, of Philadelphia, has had some ideas of a similar nature, the details of which I do not know. I understood from Mr. Sargent that he proposed submitting selenium to the influence of an oscillating beam of light which should be sent on and off the selenium by the action of the voice. If this is so the effect produced would be only of an intermittent character and a musical tone, not speech, would be heard from the telephone in circuit with the selenium.

Although the idea of producing and reproducing sound by the action of light, as described above, was an entirely original and independent conception of my own, I recognize the fact that the knowledge necessary for its conception has been disseminated throughout the civilized world, and that the idea may therefore have occurred, independently, to many other minds.

I have stated above the few facts that have come under my observation bearing upon the subject.

The fundamental idea, on which rests the possibility of producing speech by the action of light, is the conception of what may be termed an undulatory beam of light in contra-distinction to a merely intermittent one.

By an undulatory beam of light I mean a beam that shines

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* See Journ. of Teleg. Engin., May 23, 1878, vii, 284.

† Nature, xviii, 169.

‡ Nature, xvii, 512, Apr. 25, 1878.

continuously upon the receiver, but the intensity of which upon that receiver is subject to rapid changes corresponding to the changes in the vibratory movement of a particle of air during the transmission of a sound of definite quality through the atmosphere. The curve that would graphically represent the changes of light would be similar in *shape* to that representing the movements of the air. I do not know whether this conception had been clearly realized by J. F. W., of Kew, or by Mr. Sargent, of Philadelphia, but to Mr. A. C. Brown, of London is undoubtedly due the honor of having distinctly and independently formulated the conception and of having devised apparatus, though of a crude nature, for carrying it into execution.

It is greatly due to the genius and perseverance of my friend, Mr. Sumner Tainter, of Watertown, Mass., that the problem of producing and reproducing sound by the agency of light has at last been successfully solved. For many months past we have been devoting ourselves to the solution of this problem and I have great pleasure in presenting to you to-night the results of our labors.

Researches of Sumner Tainter and Alexander Graham Bell.

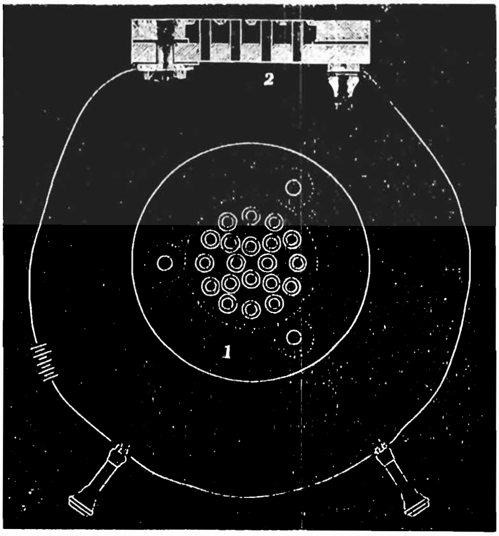
The first point to which we devoted our attention was the reduction of the resistance of crystalline selenium within manageable limits. The resistance of selenium cells, employed by former experimenters, was measured in millions of ohms, and we do not know of any record of a selenium cell measuring less than 250,000 ohms in the dark.

We have succeeded in producing sensitive selenium cells measuring only 300 ohms in the dark and 150 ohms in the light. All former experimenters seemed to have used platinum for the conducting part of their selenium cells, excepting Werner Siemens, who found that iron and copper might be employed. We have discovered that brass, although chemically acted upon by selenium, forms an excellent and convenient material; indeed, we are inclined to believe that the chemical action between the brass and selenium has contributed to the low resistance of our cells by forming an intimate bond of union between the selenium and brass.

We have observed that melted selenium behaves to other substances as water to a greasy surface, and we are inclined to think that when selenium is used in connection with metals not chemically acted upon by it, the points of contact between the selenium and the metal offer a considerable amount of resistance to the passage of a galvanic current, and thus serve to increase the apparent resistance of the selenium.

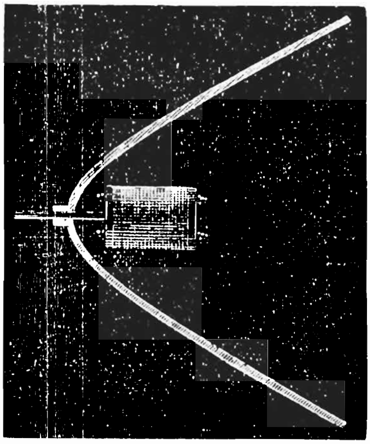
By using brass we have been enabled to construct a large number of cells of different forms. Time will only admit of my showing you two typical forms. One of these is shown in plan in fig. 1, and in section in fig. 2.

1, 2.



This cell consists of two brass plates insulated from one another by a sheet of mica. The upper plate has numerous perforations and brass pins attached to the lower plate, pass through these orifices so that their ends without touching the upper plate are flush with its surface.

3.



The annular spaces between the pins and the plate are filled with selenium. The whole arrangement forms part of a galvanic circuit, and it will be observed that the current can only pass from the plate to the pins through the selenium rings.

It will also be seen that owing to the conical shape of the perforations the points of closest approximation between the pins and the plate are on the upper surface. As the effect produced by light upon selenium is chiefly a surface action, this arrangement is found to be of great advantage.

The second typical cell is cylindrical in form, for the purpose of being used with a concave reflector instead of with a lens (see fig. 3.)

This cell is composed of a large number of metallic discs separated by discs of mica slightly smaller in diameter. The spaces between the brass discs over the mica are filled with selenium, and the alternate brass discs are metallically connected. The arrangement practically consists of a large number of annular selenium cells united in mutiple arc.

The mode of applying the selenium is as follows:

The cell is heated, and when hot enough a stick of selenium is rubbed over the surface.

In order to acquire conductivity and sensitiveness the selenium must next undergo a process of annealing.

The method we first adopted was the following:

The selenium cell was placed with a thermometer in the interior of the cylindrical annealing chamber shown in fig. 4.

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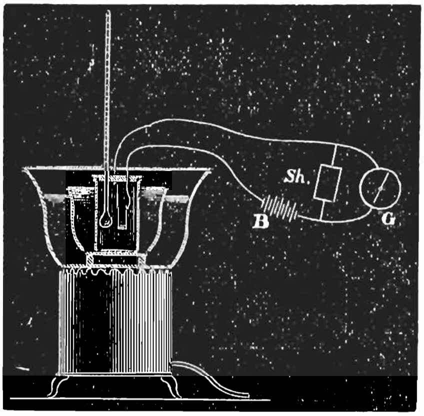


B=battery; Sh=shunt; G=galvanometer.

This was inserted in a pot of linseed oil, and the latter stood upon glass supports within another similar pot containing linseed oil. The whole arrangement was then placed over a gas stove and heated to a temperature of about 214° C., which was found to be the temperature of maximum conductivity for the selenium used.

This temperature was retained for about twenty-four hours, and the pots, with their contents, were then packed in a box so arranged as to retard radiation of heat.

The selenium took from forty to sixty hours to cool down to the temperature of the air.

A powerful battery current was passed through the selenium during the whole process of heating and cooling, in accordance with our theory that the current exerted a powerful influence in causing a set of the selenium molecules, and in retaining them in position until fixed by crystallization.

A shunted galvanometer was introduced into the circuit for the purpose of observing the changes of conductivity. We subsequently found this tedious process to be unnecessary, as during the course of our experiments we discovered a method of preparing sensitive selenium in a very few minutes.

We now simply heat the selenium over a gas stove and observe its appearance. When the selenium attains a certain temperature, the beautiful reflecting surface becomes dimmed. A cloudiness extends over it, somewhat like the film of moisture produced by breathing upon a mirror.

This appearance gradually increases and the whole surface is soon seen to be in the metallic, granular, or crystalline condition. The cell may then be taken off the stove and cooled in any suitable way. When the heating process is carried too far, the crystalline selenium is seen to melt.

Our best results have been obtained by heating the selenium until it crystallizes as stated above, and by continuing the heating until signs of melting appear, when the gas is immediately put out.

The portions that had melted instantly re-crystallize, and the selenium is found upon cooling to be a conductor, and to be sensitive to light. The whole operation occupies only a few minutes. This method has not only the advantage of being expeditious, but it proves that many of the accepted theories on this subject are fallacious.

Early experimenters considered that the selenium must be "cooled from a fused condition with extreme slowness." Later authors agree in believing that the retention of a high temperature—short of the fusing point—and slow cooling—are essential, and the belief is also prevalent that crystallization takes place only during the cooling process.

Our new method shows that fusion is unnecessary, that conductivity and sensitiveness can be produced without long heating and slow cooling; and that crystallization takes place during the heating process. We had found that on removing the source of heat, immediately on the appearance of the cloudiness above referred to, distinct and separate crystals can be observed under the microcsope, which appear like leaden snow flakes on a ground of ruby red.

Upon removing the heat when crystallization is further advanced, we perceive under the microscope masses of these crystals arranged like basaltic columns, standing detached from one another—and at a still higher temperature the distinct columns are no longer traceable, but the whole mass resembles metallic pudding-stone with here and there a separate snow flake, like a fossil on the surface. Selenium crystals formed during slow cooling after fusion, present an entirely different appearance, showing distinct facets.

I must now endeavor to explain the means by which a beam of light can be controlled by the voice of a speaker.

Photophonic Transmitters.

We have devised upwards of fifty forms of apparatus for varying a beam of light in the manner required, but only a few typical varieties need be described.

(1st.) The source of light may be controlled, or (2nd) a steady beam may be modified at any point in its path.

In illustration of the first method we have devised several forms of apparatus founded upon Kœnig's manometric capsule, operating to cause variations in the pressure of gas supplied to a burner, so that the light can be vibrated by the voice.

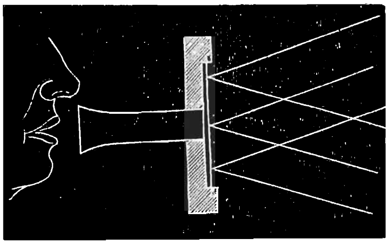
In illustration of the second method I have already shown one form of apparatus by which the light is obstructed in a greater or less degree, in its passage through perforated plates. But the beam may be controlled in many other ways. For instance, it may be polarized, and then affected by electrical or magnetical influences in the manner discovered by Faraday and Dr. Kerr.

Let a polarized beam of light be passed through a solution of bisulphide of carbon contained in a vessel inside a helix of insulated wire, through which is passed an undulatory current of electricity from a microphone or telephonic transmitter operated by the voice of a speaker.

The passage of the polarized beam should be normally partially obstructed by a Nicols prism, and the varying rotation of the plane of polarization would allow more or less of the light to pass through the prism, thus causing an undulatory beam of light capable of producing speech.

The beam of polarized light, instead of being passed through a liquid could be reflected from the polished pole of an electro-magnet in circuit with a telephonic transmitter.

5.



Another method of affecting a beam of light is to pass it through a lens of variable focus* formed of two sheets of thin glass or mica containing between them a transparent liquid or gas. The vibrations of the voice are communicated to the gas or liquid, thus causing a vibratory change in the convexity of the glass surfaces and a corresponding change in the intensity of the light received upon the sensitive selenium. We have found that the simplest form of apparatus for producing the effect consists of *a plane mirror*

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* I observe that a lens of similar construction has been invented in France by Dr. Cusco, and is described in a recent paper in "La Nature." See, also, Scien. Amer., Aug. 28, 1880, xliii, 131. Mr. Tainter and I have used such a lens in our experiments for months past.

of flexible material, such as silvered *mica or microscope-glass, against the back of which the speaker's voice is directed*, as shown in the diagram (fig. 5).

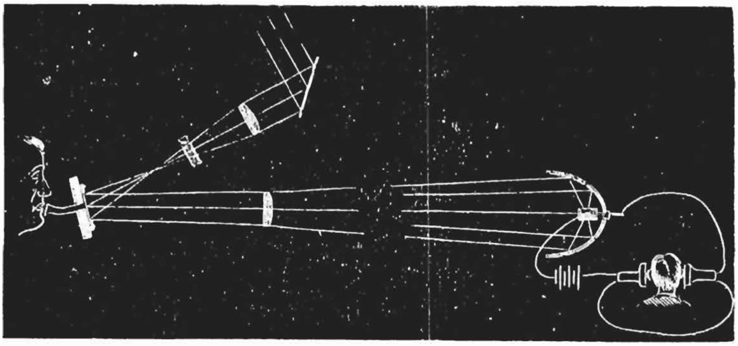
Light reflected from such a mirror is thrown into vibrations corresponding to those of the diaphragm itself. In its normal condition a parallel beam of light falling upon the diaphragm mirror would be reflected parallel. Under the action of the voice the mirror becomes alternately convex and concave, and thus alternately scatters and condenses the light.

When crystalline selenium is exposed to the undulatory beam reflected from such an apparatus, the telephone connected with the selenium audibly reproduces the articulation of the person speaking to the mirror.

In arranging the apparatus for the purpose of reproducing sound at a distance, any powerful source of light may be used, but we have experimented chiefly with sun-light.

For this purpose, a large beam is concentrated by means of a lens upon the diaphragm mirror and after reflection is again rendered parallel by means of another lens. The beam is received at a distant station upon a parabolic reflector, in the focus of which is placed a sensitive selenium cell, connected in a local circuit with a battery and telephone. We have found it advisable to protect the mirror by placing it out of the focal point, and by passing the beam through an alum cell, as shown in fig. 6.

6.



A large number of trials of this apparatus have been made with the transmitting and receiving instruments so far apart that sounds could not be heard directly through the air. In illustration I shall describe one of the most recent of these experiments.

Mr. Tainter operated the transmitting instrument, which was placed on the top of the Franklin School House in Washington, and the sensitive receiver was arranged in one of the windows of my laboratory, 1325 L Street, at a distance of 213 meters.

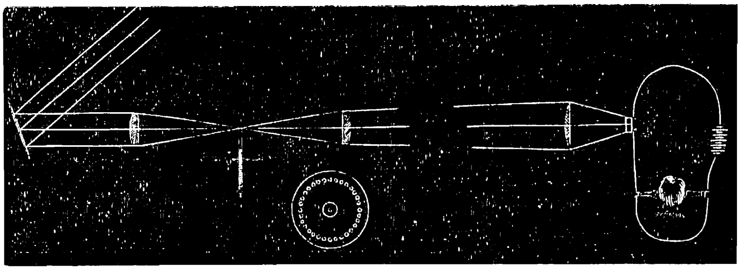
Upon placing the telephone to my ear, I heard distinctly from the illuminated receiver the words:—"Mr. Bell, if you hear what I say, come to the window and wave your hat."

In laboratory experiments the transmitting and receiving instruments are necessarily within ear-shot of one another, and we have therefore been accustomed to prolong the electric circuit connected with the selenium receiver, so as to place the telephones in another room.

By such experiments we have found that articulate speech can be reproduced by the oxyhydrogen light, and even by the light of a kerosene lamp. The loudest effects obtained from light are produced by rapidly interrupting the beam.

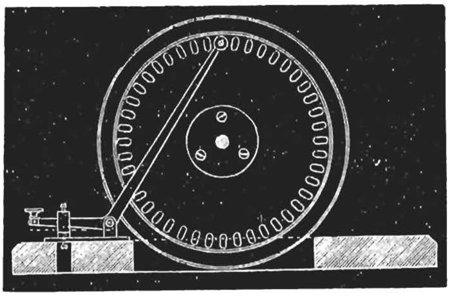
A suitable apparatus for doing this is a perforated disc which can be rapidly rotated. The great advantage of this form of apparatus for experimental work is the noiselessness of its operation, admitting of the close approach of the receiver without interfering with the audibility of the effect heard from the latter—for it will be understood that musical tones are emitted from the receiver when no sound has been made at the transmitter. A silent motion thus produces a sound. In this way musical tones have been heard even from the light of a candle.

7.



When distant effects are sought the apparatus can be arranged as shown in fig. 7.

8.



By placing an opaque screen near the rotating disk the beam can be entirely cut off by a slight motion of the hand, and musical signals, like the dots and dashes of the Morse telegraph code, can thus be produced at the distant receiving station. Such a screen operated by a key like a Morse telegraph key is shown in fig. 8, and has been operated very successfully.

Experiments to ascertain the nature of the rays that affect selenium.

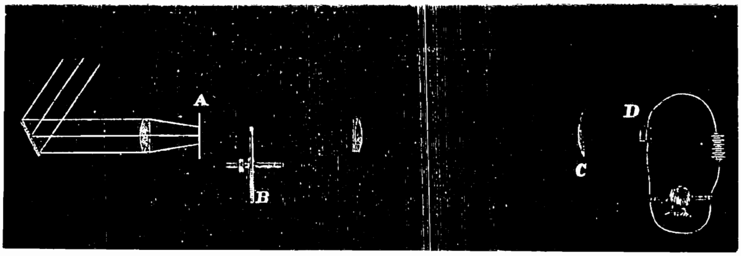
We have made experiments with the object of ascertaining the nature of the rays that affect selenium. For this purpose we have placed in the path of an intermittent beam various absorbing substances.

Prof. Cross has been kind enough to give his assistance in conducting these experiments.

When a solution of alum, or bisulphide of carbon, is employed, the loudness of the sound produced by the intermittent beam is very slightly diminished, but a solution of iodine in bisulphide of carbon cuts off most, but not all, of the audible effect. Even an apparently opaque sheet of hard rubber does not entirely do this.

This observation, which was first made in Washington, D. C., by Mr. Tainter and myself, is so curious and suggestive that I give in full the arrangement for studying the effect.

9.



When a sheet of hard rubber, A, was held as shown in the diagram (fig. 9) the rotation of the disc or wheel B interrupted what was then an invisible beam, which passed over a space of several meters before it reached the lens C, which finally concentrated it upon the selenium cell, D.

A faint but perfectly perceptible musical tone was heard from the telephone connected with the selenium that could be interrupted at will by placing the hand in the path of the invisible beam.

It would be premature without further experiments to speculate too much concerning the nature of these invisible rays; but it is difficult to believe that they can be heat rays, as the effect is produced through two sheets of hard rubber having between them a saturated solution of alum.

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 sounds in this way "the Photophone," because an ordinary beam of light contains the rays which are operative.

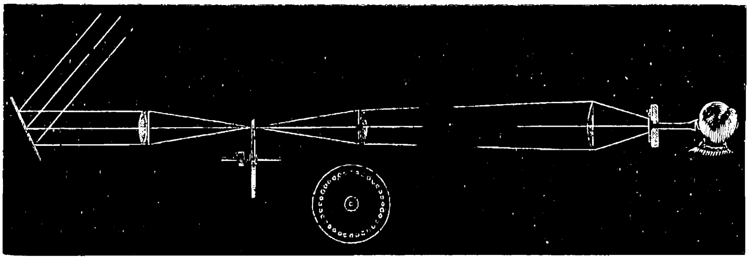
Non-Electric Photophonic Receivers.

It is a well known fact that the molecular disturbance, produced in a mass of iron by the magnetizing influence of an intermittent electrical current, can be observed as sound by placing the ear in close contact with the iron, and it occurred to us that the molecular disturbance produced in crystalline selenium by the action of an intermittent beam of light should be audible in a similar manner without the aid of a telephone or battery. Many experiments were made to verify this theory, but at first without definite results.

The anomalous behavior of the hard rubber screen alluded to above suggested the thought of listening to it also.

This experiment was tried with extraordinary success. I held the sheet in close contact with my ear while a beam of intermittent light was focussed upon it by means of a lens. A distinct musical note was immediately heard. We found the effect intensified by arranging the sheet of hard rubber as a diaphragm, and listening through a hearing tube, as shown in fig. 10.

10.



We then tried crystalline selenium in the form of a thin disc and obtained a similar but less intense effect.

The other substances, which I enumerated at the commencement of my address, were now successively tried in the form of thin discs, and sounds were obtained from all but carbon and thin glass.*

In our experiments, one interesting and suggestive feature was the different intensities of the sounds produced from different substances under similar conditions. We found hard rubber to produce a louder sound than any other substance we tried, excepting antimony and zinc; and paper and mica to produce the weakest sounds.

On the whole, we feel warranted in announcing as our conclusions that *sounds can be produced by the action of a variable light from substances of all kinds when in the form of thin dia-*

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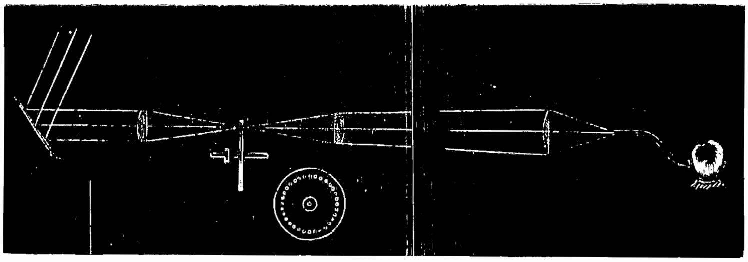
* We have since obtained perfectly distinct tones from carbon and thin glass.

phragms. The reason why thin diaphragms of the various materials are more effective than masses of the same substances, appears to be that the molecular disturbance produced by light is chiefly a surface action, and that the vibration has to be transmitted through the mass of the substance in order to affect the ear.

On this account we have endeavored to lead to the ear air that is directly in contact with the illuminated surface, by throwing the beam of light upon the interior of a tube; and very promising results have been obtained. Fig. 11 shows the arrangement we have tried. We have heard from interrupted sunlight very perceptible musical tones through tubes of ordinary vulcanized rubber, of brass, and of wood. These were all the materials at hand in tubular form, and we have had no opportunity since of extending the observations to other substances.*

11.



I am extremely glad that I have the opportunity of making the first publication of these researches before a scientific society, for it is from scientific men that my work of the last six years has received its earliest and kindest recognition. I gratefully remember the encouragement which I received from the late Professor Henry, at a time when the speaking telephone existed only in theory. Indeed, it is greatly due to the stimulus of his appreciation that the telephone became an accomplished fact.

I cannot state too highly also the advantage I derived in preliminary experiments on sound vibrations in this building from Professor Cross, and near here from my valued friend Dr. Clarence J. Blake. When the public were incredulous of the possibility of electrical speech, the American Academy of Arts and Sciences, the Philosophical Society of Washington, and the Essex Institute of Salem, recognized the reality of the results and honored me by their congratulations. The public interest, I think, was first awakened by the judgment of the

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* A musical tone can be heard by throwing the intermittent beam of light into the ear itself. This experiment was at first unsuccessful on account of the position in which the ear was held.

very eminent scientific men before whom the telephone was exhibited in Philadelphia, and by the address of Sir William Thomson before the British Association for the Advancement of Science. At a later period, when even practical telegraphers considered the telephone as a mere toy, several scientific gentlemen, Professor John Pierce, Professor Eli W. Blake, Dr. Channing, Mr. Clark and Mr. Jones, of Providence, R. I., devoted themselves to a series of experiments for the purpose of assisting me in making the telephone of practical utility; and they communicated to me, from time to time, the results of their experiment with a kindness and generosity I can never forget. It is not only pleasant to remember these things and to speak of them, but it is a duty to repeat them, as they give a practical refutation to the often repeated stories of the blindness of scientific men to unaccredited novelties, and of their jealousy of unknown inventors who dare to enter the charmed circle of science.

I trust that the scientific favor which was so readily accorded to the Telephone may be extended by you to this new claimant—"*The Photophone.*"