A history of the invention of and research on the coherer

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The formation of the concepts of electrical resistance and conduction is shown. The history of the invention of and research on the resistor and the coherer is discussed. The role of the coherer in the origin of radio engineering and in the invention of semiconductor devices is shown.

The history of the coherer, a physical device and a radio component, evokes special interest in connection with the upcoming hundredth anniversary of radio. By a UNESCO resolution, this anniversary will be observed in 1995, worldwide. The history of the coherer goes back to the eighteenth century, when the concepts of the basic electrical quantities, such as voltage, current, resistance, and conduction were being formed.

It was discovered in the first third of the eighteenth century that certain substances, which were later, in 1738, named conductors, can transmit an "electrical force" over a distance.[1] For transmission over a significant distance, it turned out to be necessary to insulate the conductors (the term "to insulate" is encountered in Ref. 2 in 1746). Different capabilities for insulation and conducting electricity were noticed for different substances. Thus, in the first third of the eighteenth century, Stephen Gray (1666–1736) determined that, of all silk strings, strings of azure color possess the best insulating properties. William Watson (1715–1787) noticed in 1747 that metals conduct electricity in the best manner, although water is also an excellent conductor.[3]

The term "resistance" (Widerstand in German) is encountered in a book by Johann Heinrich Winkler (1703–1770), published in 1744. This scientist wrote about the possibility of transmitting electricity "even to the ends of the earth," after noting that "here the electric atmosphere must overcome a certain resistance" (Ref. 4, pp. 147–148). There is a clearer physical content in the term "resistance" (résistance in French) in the paper by Louis-Guillaume LeMonnier (1717–1799).[2]

In connection with Watson's experiments on the transmission of electricity over a distance, Benjamin Franklin (1706–1790) became interested in the electrical conductivity of earth. He packed earth into a glass tube that was open at both ends, stuck a wire hook into it from each side, and began to discharge a Leyden jar (a capacitor with glass dielectric) through his body and through a tube with earth of different kinds connected in series with it. In a 1748 letter, Franklin stated that dry earth does not transmit an electric shock. Franklin did not use the term "resistor," although the glass tube with earth and equipped with wire leads fulfilled in these experiments the function of a resistor in exactly the same way as the body of the experimenter fulfilled the function of an ammeter (Ref. 5, pp. 36–37).

Several years earlier, Jean-Antoine Nollet (1700–1770) successfully discharged a Leyden jar through a chain of people in which a glass tube filled with water was included. The water turned out to be a good conductor.[6]

The term "resistor" and a description of the devices which this term absolutely fits is encountered in the letter of March 15, 1759 from the amateur scientist Edward DeLaval (1729–1814) to Benjamin Wilson (1708–1788), a member of the Royal Society of London (an academy of science).[7] It should be noted, however, that DeLaval used the term "resistor" (he wrote "resister," from the Latin resistere, "to resist") to denote not a device, but a substance "exerting resistance to the passage of an electrical fluid."

DeLaval's resistors were glass tubes densely filled with the dry cinder powders of different metals. DeLaval inserted pieces of wire into the ends of the tubes and sealed off their ends with sealing wax. DeLaval hooked one wire lead of the resistor to the conductor of an electric charging machine, and he held the other lead in his hand. By discharging in this manner the charge from the conductor into the earth through a resistor and his own body, DeLaval estimated the resistances of different resistors according to his own sensation "of the passage of the electric fluid" and the spark.

DeLaval drew the conclusion that the resistance is determined not by grinding a metal into powder, but by baking. He wrote: "The finest filings or powders of metals conduct just as well as these substances in undivided state." However, as follows from what is said later, this statement needs to be made more precise.

DeLaval determined that the resistance of a resistor depends on temperature. He found the highest resistance at a temperature which his hand could still stand.

John Canton (1712–1772) and Charles Cavendish (1703–1783), the father of the famous Henry Cavendish (1731–1810), investigated the effect of temperature on the electrical conductivity of glass. Canton probably was the first to show that "moderately heated glass becomes to some degree a conductor of electricity" (Ref. 5, pp. 205–207).

Resin is one of the first known insulators. However, Franz Carl Achard (1753–1821) successfully discharged a Leyden jar through boiling resin (Ref. 8, p. 248).

Returning to DeLaval's work, one must note that the design of his resistors goes back to Franklin's tubes with earth and wire leads. As far as the material of DeLaval's resistors is concerned, one must mention one investigation by Watson. In a paper published in the Philosopical Transactions of the Royal Society of London for 1748,[9] Watson writes that "the cinders of metals...inhibit to a significant

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degree the rapid propagation of an electrical force," and that white lead, red lead, silver oxide, rusty iron filings, etc. are unsuitable for the electrodes of a Leyden jar. In a footnote to the publiclation of his paper, DeLaval notes that he was not aware of this investigation by Watson when he carried out his own work.

Original research conducted in St. Petersburg also preceded DeLaval's work.

The credit for making the first electric meter in the world in 1745, an electrometer equipped with an angular scale based on a linen thread attached at its upper end to a vertically installed metal rod, belongs to the first Russian electrician, Georg-Wilhelm Richmann (1711–1753), of German nationality, but born in the Russian empire. The angle of deflection of the thread allowed one to estimate the "electric force." The thread was standardized; it was one and a half feet long, and half a grain of lead was attached to its end. Such an electrometer, or "electric indicator," as Richmann called it, made it possible to carry out important experiments.[10]

Richmann began his report at the conference of the St. Petersburg Academy of Sciences on April 30, 1753 with the words: "Lomonosov passed on to me three batches of glass which differ in their degree of grinding, and he expressed the desire that I investigate what will occur if an electricified mass will rest on these powders, thus giving me the occasion to discover important truths" (Ref. 11, p. 232; Ref. 12, p. 283).

It turned out that the electrical properties of glass powders depend significiantly on humidity; the higher the humidity, the greater the electrical conductivity of the powder. The effect of humidity on the electrical properties of a substance were known long ago (for example, see Ref. 5, p. 167), but this question was investigated systematically for the first time only in the paper under disucssion.

This is what the experiment which Richmann performed with each of the powders looked like.

Richmann poured the powder into a metal container. A wire, which hung from the conductor of an electric charging machine to which an electrometer was connected, was immersed in the powder.

Richmann determined that, the higher the humidity, the faster the charge that is measured by the electrometer discharges from the conductor. From the electrometer readings, Richmann reported..." one can learn the state of the atmosphere at different sites and different times" (Ref. 11, p. 323). Thus, we see the first history resistance humidity sensor, or humidity resistor.

Richmann found that "finer powder draws in humidity more strongly than coarser." This indicates the possibility of obtaining humidity sensors of different sensitivities.

Thus, the example of glass demonstrated the possibility of converting insulators into conductors which possess different electrical conductivities. On the other hand, Watson and DeLaval solved the inverse problem by showing that although metals as such are conductors, their oxides exert resistance to the passage of an electric current.

In a book published in 1767, Joseph Priestley (1733–1804) presented a series of electrical conductivities for metals (in increasing order); iron, brass, copper, silver, and gold. Priestley found this order in the following way.

He discharged a battery of Leyden jars, using Franklin's method, through a circuit consisting of two wires of the same dimensions but of different metals joined in series. The parameters of the set-up were chosen such that one of the wires would burn out during the discharge. Franklin and Priestley assumed that this will be the wire with the higher resistance (Ref. 13, pp. 728–729). Of course, the results of such experiments depend on the purity of the metals and on their melting temperatures.

Continuing the research on the electrical properties of materials, a friend and colleague of Franklin in his electrical experiments, Ebenezer Kinnersley (1711–1778), wrote to him in 1770 about the good conducting quality of the charcoal from certain petrified woods: oak, birch, and maple. Kinnersley also reported that he successfully discharged a Leyden jar through his own body and a thick line drawn on paper with a graphite pencil.[14]

In 1772, Giambattista Beccharia (1716–1781) stated: "Metals, although they are considerably more yielding (i.e., conducting) than all other bodies, nevertheless they exert a certain resistance that is proportional to the path length which a spark traverses in them (Ref. 15, p. 179).

The reference quoted above give an equation close to the equation for resistance $R(\rho l/s)$.

A division of conductors into first class conductors (metals) and second class conductors ("moist conductor") arose at the end of the eighteenth century (Ref. 16, pp. 404–411).

On the basis of Franklin's opinions, Franz Ulrich Teordor Epinus (1724–1802; lived in Russia from 1757) thus formulated the difference between conductors and nonconductors: the electric fluid in nonconductors, unlike that in conductors, in moving through the pores of body encounters resistance and cannot flow rapidly through the body (Ref. 17, p. 196). However indistinct such ideas were, the development of science led to the appearance in 1799 of a source of direct current, the voltaic pile.

Conditions arose which allowed the discovery of the laws of electricity and magnetism. After generalizing these laws, James Clerk Maxwell (1831–1879) created the theory of the electromagnetic field, from which followed the existence of electromagnetic waves. Heinrich Rudolf Hertz (1857–1894) experimentally confirmed Maxwell's prediction in 1888, as a result of which the prerequisites appeared for the creation of radio engineering. A resonator spark gap served as the detector in the experiments of Hertz, by means of which Hertz observed with difficulty miniature sparks while conducting his famous experiments in a dark basement. A different electromagnetic wave detector was required for practical purposes.

The "Branly tube," which Sir Oliver Joseph Lodge (1851–1940) called the coherer and which goes back to DeLaval's resistors in its design, played the role of such a detector. Research carried out after DeLaval directly preceded the appearance of the "Branly tube;" this could have suggested the ieda for it to Eduard Branly (1844–1940).

In a paper published in 1835, the Swedish physicist P. S. Munk af Rosenschöld (1804–1860) reported his experiments with powders of mercury sulfide, of ground tin or charcoal, etc. in a glass tube equipped with wire leads. This scientist also experimented with solidified masses like those of alloys of sulfur with coal powder, etc. (Ref. 18, pp. 347–349).[19] Just like Franklin, Munk discharged a Leyden jar through powder (or a solidified mass). When the Leyden jar was charged to a sufficiently high voltage, the resistance of the powder (mass) after discharge was greatly reduced and remained low. If we poured the powder out of the tube after the experiment, then upon a repeated filling with this same powder, its resistance again turned out to be high, etc. Upon shaking the tube, the resistance of the powder, which became low after the discharge, increased greatly. Just like his predecessors Franklin and DeLaval, Munk himself "served as the ammeter." Thus, by using a procedure available even in the eighteenth century, Munk took a step on the path to creating the coherer. Besides, Munk's experiments anticipated the invention of the variable resistor.

Similar results were also obtained by other researchers, who were already using the electric meters and power supplies that were modern for them. In 1866 the Varley brothers (England) patented a device to shield telegraph equipment from lightning, which contained two copper electrodes separated by a thin layer of charcoal powder mixed with the powder of an insulating material. At low voltage the powder exerted high resistance to the passage of current, but low resistance at high voltage (Ref. 20, p. 11; Ref. 21, pp. 58–59).

In 1884 the Italian physicist T. Calsecchi-Onesti (1853-1922) investigated the resistances of metal filings in ebonite and glass tubes (Ref. 18, pp. 350–352).[21] The resistances of the filings were considerably reduced by the action of currents from the opening of a circuit containing inductance and a tube with filings.

David Edward Hughes (1831-1900) might have become the inventor of a charcoal coherer and even the discoverer of electromagnetic waves, but this did not come to him.

Hughes was born in England. He was taken to the United States of America at age seven. He was the author of important inventions in the field of electric communication. He returned to England in 1867.

In 1879, nine years before the experiments of Hertz, Hughes noticed that, during the operation of an induction coil (of the Ruhmkorff version) in the vicinity of a circuit containing a telephone and a charcoal microphone, the resistance of the microphone changes; here sounds are audible in the telephone. Hughes correctly hypothesized that one may explain this by the action of electromagnetic waves on the charcoal powder, but the colleagues whom he invited to a demonstration of the experiments convinced him that the observed effect is caused simply by electromagnetic induction. Publication of this episode from the history of science appeared only in 1899 (Ref. 20, p. 10; Ref. 21, pp. 43–44). The words of John Bernal (1901–1971) are recalled: "The difficulty in science is often not so much how to make the discovery but to known that one has made it" (Ref. 23, p. 438).

The recognized invention of the coherer, a device whose resistance is changed greatly by the action of electromagnetic radiation, belongs to Branly, a professor of physics at the Catholic University of Paris. Branly discovered in 1890 that the resistance of a polished layer of finely ground copper (sometimes with tin added to improve cohesion) that has been coated onto a glass or ebonite plate is grealty reduced (from many megohms to several ohms) by the action of nearby electrical discharges (Ref. 18, pp. 353–355).[22] The connection of the powder to an external circuit was accomplished by means of copper plates that are clamped by screw clamps. Branly also successfully conducted similar experiments with filings of iron, aluminum, antimony, cadmium, zinc, bismuth, etc., that were sometimes mixed with insulating liquids, in glass or ebonite tubes. The discharges were produced by means of an electric charging machine (with or without a capacitor), a Ruhmkorff coil, etc. Branly wrote in an 1890 paper: "By using a Wheatstone bridge, I could establish the effect at a distance greater than 20 m, and moreover, the spark apparatus operated in a hall separated by three large rooms from the galvanometer with the bridge, so that noise from the sparks could not be heard" (Ref. 18, p. 353). The resistance sometimes remained low for more than a day, but upon shaking, the resistance was restored to its earlier high value.

In conducting successful experiments with a "Branly tube," Lodge understood at one its value as "a device for detecting electrical oscillations" (Ref. 18, p. 358). Lodge wrote in a paper published in 1894: "This device, which I call a coherer, is amazingly sensitive as a detector of Hertzian waves" (Ref. 18, p. 435).[24] Lodge coined the term "coherer" from the Latin cohaerere (to stick together), keeping in mind the sticking of the filings to each other under the action of electromagnetic waves. Branly did not use the term "coherer," which received extensive circulation, because he disagreed with the conductance mechanism which Lodge suggested. Branly called his device a radio conductor. The fact that the device becomes a conductor by the action of electromagnetic radiation is emphasized by this term. The controversial physical mechanism, which has not been completely determined even now, did not delay the practical use of the coherer (often man "is more capable than he knows").

The coherer turned out to be the last necessary component which enabled one to achieve the idea of a wireless telegraph, which was advocated repeatedly after the experiments of Hertz. Lodge came very close to achieving this idea, but just like Branly, he did not claim to be the first to invent the radio. Lodge noted the greater merits of A. S. Popov in this field (Ref. 20, p. 262), and Branly clearly gave precedence to the Russian scientist (Ref. 20, p. 187).

The coherer, the action of which is, generally speaking, based on an incomplete electrical contact between the filings, also prompted the idea for the storm indicator. Thus, the effect in one electroplating workshop of a thunderstorm on a contact that, as it turned out, was of poor quality, was reported in an 1894 note (Ref. 18, p. 358). It said in the note: "This brought to mind the possibility of using an ingenious device (a coherer-L.K.) to investigate the waves that are propagated during a thunderstorm."

The coherers for the first receivers of A. S. Popov and G. Marconi were built differently. Striving to get high sensitivity and stability for the coherer, Popov stayed with a horizontally situated glass tube of 1 cm diameter and 6 cm to 8 cm long with thin platinum electrodes glued to the inner walls almost for the entire length of the tube, and with leads out from both ends of it. The gap between the lengthwise edges of the electrodes was about 2 mm. The tube was almost half filled with iron powder, which rested on the electrodes. The tube was closed by stoppers at its ends (Ref. 18, p. 453).

Marconi used a glass tube with piston-like silver electrodes tightly inserted into it and separated from each other by approximately half a millimeter. This gap, situated in the center of the tube perpendicular to its axis, was filled with a mixture of silver and nickel filings with a small amount of mercury. The tube was pumped out to a vacuum of 4 mm Hg and sealed up.

The trivets—small plates on which the filings of different metals were annealed, and the small sieves for sifting the filings are preserved in the A. S. Popov Central Musem of Communications in St. Petersburg. These small plates and sieves were part of the equipment of commercial radio stations of the Popov–Ducreté system (at the start of the 1900s).[18] Besides, there are coherers from the Marconi firm in factory furnished packing in the museum. They are somewhat different from the Marconi coherer just described. Thus, the filings in the pumped out glass tube contain 96% nickel and 4% silver with a trace of mercury. The coherers are attached to an ivory support, with which they also were installed in the receiver (Ref. 21, p. 66).

The first receivers of Popov and Marconi contained automatic shakers which were activated by the received transmission and thereby accomplished decohering, i.e., they prepared the coherer to receive the next transmission. In Lodge's experiments carried out before Popov and Marconi there were no automatic shakers for a coherer. Self-decohering coherers appeared later on. By the way, the carbon microphone in Huges' experiments described above was such a coherer.

The coherer was used approximately until 1906 before finally giving way to different detectors.

Eduard Branly, the creator of the coherer, had practically no interest in the commercial use of his invention, but as a physicist pursuing fundamental research, devoted himself to studying the mechanism of conductivity of powdered materials.[26]

FIG. 1. E. BRANLY (1844–1940)
(from an 1896 photograph kindly sent to the author by the granddaughter of this scientist, Madame Turnon-Branly through Prof. Gabillard[26]).

Let us consider the hypotheses concerning the operation of the coherer which were suggested in the last decade of the nineteenth century. Lodge probably suggested the first hypothesis. He supposed that, under the action of the voltages that are induced by electromagnetic waves, microscopic sparks arise between the filings, as a result of which the filings are welded together and stick together along parallel chains. Popov supported this hypothesis (Ref. 20, p. 60).

The German researcher Fromme hypothesized that the grains of the filings are surrounded by a solid dielectric in the form of oxides, which the sparks puncture. A number of researchers actually observed sparks between filings in 1898 and 1899. Fromme's hypothesis is undoubtedly valid for those cases when a coherer is situated several meters from a powerful transmitter, but under ordinary conditions of remote reception, sparks were not observed between the filings of a coherer.

A different kind of hypothesis started from the electrostatic effect which must lead to motion of the filings that are joining into chains. Actually, in 1897 if not before, experimenters caused cohesion of filings by applying a sufficiently high voltage to a coherer, upon which a sudden "cohering" occurred. This enabled one to hypothesize that, as a consequence of electrostatic induction, the filings become dipoles, attract each other and stick together, forming conducting chains. Since this effect is independent of the polarity of the voltage applied, it must also occur for the alternating voltage that is induced by an electromagnetic wave. This hypothesis is supported by the fact that one can draw threads from 1 small heap of filings situated on a metal plate using a metal point if one supplied a voltage between the point and the plate, and if here one produces an electrical discharge nearby.

One more hypothesis assumed the welding together of filings as a consequence of a temperature increase under the action of induction currents; it was suggested here that the filings touch at sharp points, where the current density must be very high. Actually, researchers observed traces of melting on filings. Also, in this case, the spark sources were probably situated very close to the coherer. It is perfectly obvious that the filings will be melted at large induction currents, but this does not explain remote reception.

Let us now consider Branly's attitude. From the very start he objected against interpretations which involved either sparks which punctured a dielectric, or the motions of filings which collect into chains. Branly assumed that such phenomena are observed near a powerful discharge but have no relation to remote radio reception.

According to Branly, the essence of the problem lies in the properties of the dielectric separating the filings. When its thickness is sufficiently small then, under the action of radio waves, it can become a conductor. Branly did not explain why. It appears he thought that this hypothesis is connected with a fundamental property of matter which still remained to be discovered. Such an attitude was enitrely justified in 1890.

The French scientist held to this hypothesis up to the end of his life, increasing the number of experiments which had to lead to its confirmation. In order to demonstrate the absence of filings motion, he immersed them in solid dielectrics: wax, paraffin, resin, shellac, sulfur, ozocerite, etc. He mixed filings with insulating powder and tightly compressed the mixture. Rods obtained by this method, which could be as hard as marble, display the same property as tubes with filings, "In just what manner do conducting particles pass through a solid insulator so as to set up an alignment in a row?" Branly asked at an International Congress of Physics in 1900.

In order to demonstrate the absence of motion for filings even more clearly, he replaced them...with polished steel spheres with diameters up to 5 mm in a glass tube of approximately the same inner diameter. Later on, in order to eliminate rotation, he placed in the glass tube metal disks of approximately the same diameter as the tube's inner diameter. Branly continued, "But what kind of change of the arrangement can we cause in a column of heavy steel spheres or of wide iron or aluminum disks? And nevertheless, these columns are radio conductors."

After modifying his original device so grealty, Branly became aware of a new fact: "In the case of columns of spheres and disks, the nature of the metal, which did not appear for tubes with fine filings, begins to play a role; here the metals are divided into two groups. One cannot make radio conductors from metals of the first group (zinc, copper, silver, and brass). Good radio conductors are obtained from metals of the second group (iron, aluminum, bismuth, lead, tin, etc.), i.e., from metals which are spontaneously covered with a thin oxide layer: the resistance of a column of them is reduced by the action of a spark and returns to its original value after a shock."

But then of what does the role of this insulating layer consist? And why is it necessary here, but not in metal filings? Branly put forward two hypotheses:

The insulating layer which separates the conducting particles, becomes conducting under the temporary action of high frequency currents; and "The conductor particles do not necessarily have to touch each other in order to conduct an electric current. In this case, the insulation serves mainly to maintain a definite gap between the particles."

Thus, Branly predicted the tunneling effect 33 years before the founding of quantum mechanics.

To determine the role of insulation which separates two metals in contact, Branly arrived at the idea of a radio conductor with one single contact of the type of a steel point on an iron or steel sheet. Branly built a detector based on this principle, which was used later on for some time in radio engineering.[26]

One can say that the history of radio engineering was from the very start the history of the development of semiconductors.[27]

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