balls; electrons dashing past a magnet are displaced like a current-carrying wire. (Indeed it is only because of this that we are able to define and measure the charge and mass of an electron). Perhaps this sounds self-evident, hardly worth the verifying, let alone the saying. However, there is no law of nature to the effect that things which seem self-evident are necessarily found to be true. I will tell you of a case where something not self-evident occurred.

Suppose we send a beam of electrons against a crystal. The crystal is an assemblage of atoms regularly arranged. Each atom is a collection of electric particles roaming in vacant space. The sizes of these particles are so small compared with the spaces between them that each atom may be regarded for the present purpose as a narrow empty region where there is an electric field (and also a magnetic field) varying rapidly from point to point. The crystal is an assemblage of these narrow concentrated fields, tens of millions of them to the linear inch. We might say that it is a region of space occupied by a rhythmic pattern of field strengths. This is traversed by the electron-stream, which behaves in a most remarkable way, as Davisson and Germer found. It behaves as though it were attended by a train of waves, and the crystalline pattern seized upon these waves and guided them according to the well-known laws of wave motion, while the corpuscles trailed along after them.

This is a notion difficult to admit, for we are not accustomed to water-waves or sound-waves dragging massive bodies with them, although there is a striking analogy to be found in the phenomena of light. One immediately inquires whether the concept of the waves would serve in the cases of electron-streams traversing large-scale electric and magnetic fields, such as we know so well in the laboratory. So it does; the deflections of electron-streams in such fields as these can be explained by supposing that the fields act directly upon wave-trains, which accompany the corpuscles and steer them. In these cases by themselves the idea of waves would be superfluous, since we can explain the phenomena as well without them. But when electrons pass through crystals the waves are necessary to account for the phenomena, and this obliges us to imagine them always. It is by no means easy to adapt one's thought to the conception of corpuscles guided by waves, nor to the further and highly abstracted refinements which this notion has undergone in the last few years. But I came here with the intention of speaking to you not of the perplexities of theory, but of the clarities of experiment; and I must not continue to impair your memories of these.

THE ELECTRON THEORY OF METALLIC CONDUCTION[1]

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ELECTROMAGNETIC theory may be broadly divided into two parts: the theory of electric and magnetic fields and the theory of the electrical structure of matter, of conductors, insulators, magnetic bodies, charges, currents. Both branches have undergone profound changes since the time of Maxwell. The electromagnetic field has been of interest particularly in cases of very rapid oscillations, the waves of light and x-rays. There, from the photoelectric effect and other similar phenomena, has arisen the idea that in some respects light seems to behave in a corpuscular way, its energy being concentrated in particles of energy or photons. The electromagnetic waves of Maxwell and Hertz have but a statistical connection with the motion of these photons. The discreteness of the photons is shown beautifully by such a device as a Geiger counter, which can be made to register each photon as it comes along. In weak radiation of high frequency, as x-rays or gamma rays, no one after seeing the experiment can doubt the corpuscular nature inherent somewhere in the phenomenon. But the photons get smaller and smaller as the frequency decreases, the energy of a photon being proportional to the frequency, according to Planck's famous equation

$$\text{energy} = h\nu.$$

Thus by the time we reach the frequencies with which practical electricians deal, frequencies which even in these days of short wave radio are only about 10^{11} cycles per second, the photons are so excessively small that any electromagnetic field of reasonable strength contains enormously many photons, so many that their individual effect is entirely lost. We deal with them only statistically, and we may without error replace the discrete photons by the continuous field of Maxwell. For this reason, unless he is dealing with photoelectric cells or some such device, the electrical engineer need hardly come in contact with the theory of photons.

The developments of the other side of electrical theory, the electrical structure of matter, on the other hand, are, and even more promise to be, of great

[1] Address delivered at the Massachusetts Institute of of Technology, March 29, 1933, in connection with the celebration of Professor Elihu Thomson's eightieth birthday.

practical importance. But three examples need be mentioned to make this clear: the development of magnetic theory and magnetic materials, with application to submarine cable construction, the development of the theory of dielectrics, with application to insulating materials, and the development of the theory of electrical conduction and of electrical emission from conductors, with application to vacuum tubes. It can not be claimed that these developments have all been direct results of the theories, but at least they have all had theoretical guidance, and as theory becomes more powerful, as it is doing all the time, it may be expected to serve more and more usefully in suggesting practical advances.

The whole theory of the electrical nature of matter, of course, goes back to the discovery that matter is made of electrons and nuclei. It was really an enormous gain, in clearness of thinking as well as in more practical ways, when it became possible to think of particles of electric charge, instead of states of strain in the ether and such ideas. And physicists lost no time in developing electron theories of matter. Lorentz, doing most of his work shortly before and after 1900, was a leader in this, as were Drude and others. The essence of Lorentz's theory was extremely simple. An electric current consists of the flow of electrons. Since conductors carry current, then, they must contain electrons, free to move from point to point. Experiments on electrons in a vacuum show that they obey the ordinary laws of mechanics, their acceleration being proportional to the force acting on them. Then if there is a difference of potential between two points in a metal, and consequently a force acting on the electrons, they would accelerate, speeding up without limit, if there were not some other force to balance the field. Lorentz made the natural assumption that this other force was of the nature of a viscous resistance, resulting from collisions between the electrons and the atoms. If molecules of a gas, representing the electrons, were moving through a region filled with fixed atoms, the collisions would exert a resistance proportional to the velocity of drift of the electrons, whose magnitude is easily calculated. The motion of the electrons is then very much like the falling of raindrops under gravity. Starting from rest, they are at first rapidly accelerated, but soon they come to a constant speed of fall, in which the gravitational force just balances the viscous force of resistance of the air. This latter force is proportional to the velocity, for small speeds. Hence the external force is proportional to the speed of drift. Similarly in the metal there is proportionality between the electric field and the drift velocity or electric current, and this is the origin of Ohm's law. Lorentz was able by arguments similar to those used in kinetic theory in discussing viscosity, to find the conductivity in terms of the mean free time of electrons between collisions and other simple properties of the system. Thus, let the mean free time be T. Since the acceleration measures the increase of velocity per unit time, the velocity of each electron will increase by an amount aT in the direction of acceleration during its free time. The mean additional velocity imparted by the field will be half this, or $aT/2$. But by Newton's law the force, which is eE, if e is the charge on the electron, E the applied electric field, will equal the mass times the acceleration. Hence $a = eE/m$, the mean velocity of drift is $\frac{eT}{2m}E$, and the electric current density, which is the number of electrons per unit volume times the charge of an electron times the mean velocity, is $\frac{Ne^2}{m}\cdot\frac{T}{2}E$. The factor multiplying E is just the conductivity. Lorentz's actual derivation differs from this simple one only in taking account of the variation in free time from one electron to another, the fact that they move in all different directions with different speeds, and such refinements.

In explaining conductivity, Lorentz's theory was perfectly successful, though without independent methods of finding the quantities N and T it could not lead to any new predictions. But there was one rather fatal difficulty with it. Lorentz assumed the electrons to be just like the molecules of a perfect gas, and in particular to have the same temperature, energy and specific heat as a perfect gas. Yet experimentally the specific heat of metals was found to be such that the electrons could have practically no specific heat. That is to say, the experiments indicate that the energy of the electrons does not vary appreciably with temperature, since the specific heat is the increase of energy per degree rise of temperature. This was entirely at variance with Lorentz's theory. It was also in apparent disagreement with the next important experimental and theoretical advance in the theory of metals after Lorentz, namely, the discovery of thermionic emission and its explanation by Richardson.

It was discovered by Edison that metals heated to red heat or beyond emitted electrons, the number increasing very rapidly with the temperature. Richardson provided an explanation of this. He supposed that electrons, like molecules evaporating from a liquid, were pulled back into the metal by a surface force if they tried to escape. As a result, only the fastest electrons could escape, those whose energy was greater than a certain minimum, the energy lost in passing through the surface, or heat of evaporation, since even after escaping the electron must have some energy left. Now the number of electrons with energy greater than a given value φ increases very rapidly as the temperature increases, according to a formula containing the factor $e^{-\phi/kT}$, where k is Boltzmann's constant, T the temperature, and this factor is the leading term in the experimental equation giving the thermionic current as function of temperature. This equation is deduced on the basis of electrons sharing in the temperature energy, as the molecules of a gas or liquid would, from which we get our analogy of evaporation. And thus its success in predicting the results of experiment seemed to provide a verification of just that feature of Lorentz's theory which was shown by the experiment of the specific heat to be untenable. For some time the theory of metals was in a very difficult and contradictory state, on account of these facts.

The difficulty was solved by means of the wave mechanics, through the work of many physicists, including Pauli and Sommerfeld. The deduction from the specific heat is shown to be essentially correct: the energy of the free electrons is practically independent of temperature, the electrons possessing even at the absolute zero of temperature a rather large amount of kinetic energy, of the order of magnitude of fifteen volts. The principle leading to this result is the same principle, developed by Pauli, which leads to the structure of the atoms, and the periodic table of the elements. An atom contains electrons in a number of shells, some of low energy near the nucleus, some of the higher energy farther out toward the periphery of the atom. We should naturally suppose that at the absolute zero of temperature all electrons would fall into the shell of lowest energy, to liberate all the energy available. They do not do this, however, and this is explained by Pauli's exclusion principle, which limits the number of allowable electrons in each shell, excluding further electrons from entering the shell. The result is that even at the absolute zero the electrons of the atom contain much kinetic energy. The exclusion principle similarly prevents the electrons of the metal from losing all their energy at the absolute zero. Further, a result of the distribution of velocities is that the electron speeds are practically independent of temperature, as the electrons in an atom are practically independent of temperature. Thus the low specific heat of electrons is explained.

The low specific heat, and at the same time the possibility of thermionic emission, are most easily shown to be compatible by using Fermi's distribution of velocities, which is found to be correct rather than Boltzmann's, which is at the basis of the ordinary statistics. The ordinary formula, on which, for instance, Richardson's equation is based, states that the chance of finding an electron with energy E is proportional to $\sqrt{E}\, e^{-E/kT}$. But Fermi's formula is $\frac{\sqrt{E}}{e^{(E-E_0)/kT}+1}$, reducing to the other if the term $+1$ in the denominator is neglected. For any low temperature, the exponential is practically zero if E is less than E_0, infinite if E is greater than E_0, so that the formula gives $\sqrt{E}$ for E less than E_0, zero for E greater than E_0. This is a distribution independent of temperature, explaining the lack of specific heat. The few fastest electrons, however, which could escape, are those for which $E-E_0$ is so great that the exponential is large compared with 1, the formula reducing to Boltzmann's for these fast electrons, so that Richardson's derivation of the thermionic equation can be used practically without change. Some changes are encountered, however, when we try to apply the theory to such things as emission from coated filaments.

The theory as we have sketched it removes the great difficulty with the previous treatment. But in its present development it goes far beyond this. For the first time, it is now proving possible to connect the theory of metallic conduction with the atomic structure of the metal. We are beginning to get some idea of how the electrons actually move between the atoms, what sort of collisions they make, how their behavior is connected with the particular sort of metal we are considering. This theory is far from usable at the present time, but it is rapidly developing, along with similar theories of magnetism and of other electrical properties. It can not be doubted that in a very few years the theory of metallic conduction will be so well worked out that we can describe the mechanism with a great deal of certainty and apply the results in practical ways. The theory is bound to become of more and more use in electrical engineering, and electrical engineers, taking their guidance as in the past from the fundamental discoveries and advances of physics, will not be slow to take advantage of it.

OBITUARY

FREDERIC POOLE GORHAM

FREDERIC POOLE GORHAM, pioneer in bacteriology, nationally-known authority in sanitation and public health, faithful civic servant for many years and great teacher, died suddenly of a heart attack on June 4 in his sixty-third year.

For forty years Professor Gorham served his Alma Mater as teacher, administrator and director of re-