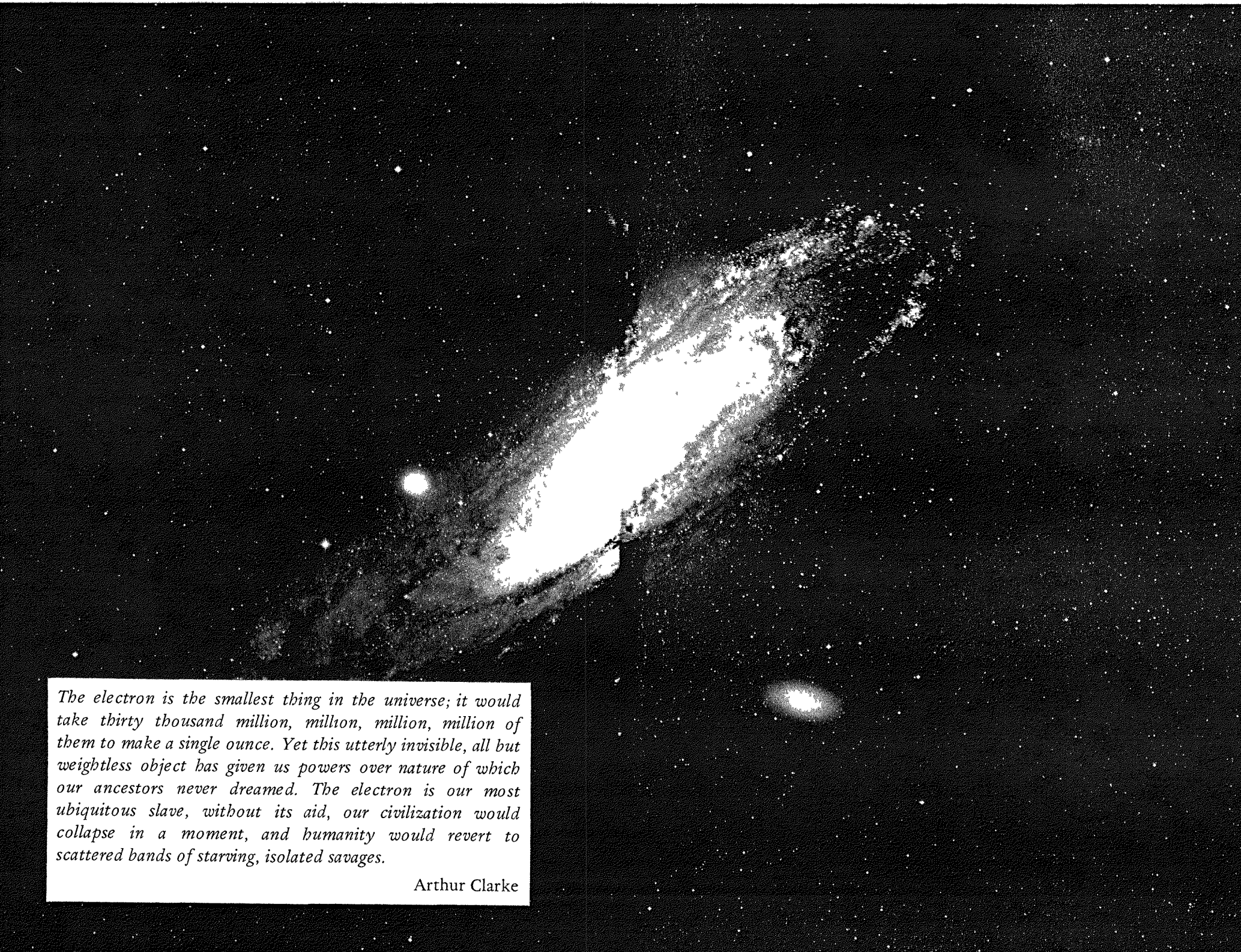
The Electron

by George Thomson



The electron is the smallest thing in the universe; it would take thirty thousand million, million, million, million of them to make a single ounce. Yet this utterly invisible, all but weightless object has given us powers over nature of which our ancestors never dreamed. The electron is our most ubiquitous slave, without its aid, our civilization would collapse in a moment, and humanity would revert to scattered bands of starving, isolated savages.

Arthur Clarke

Nuclear energy is playing a vital role in the life of every man, woman, and child in the United States today. In the years ahead it will affect increasingly all the peoples of the earth. It is essential that all Americans gain an understanding of this vital force if they are to discharge thoughtfully their responsibilities as citizens and if they are to realize fully the myriad benefits that nuclear energy offers them.

The United States Atomic Energy Commission provides this booklet to help you achieve such understanding.

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Sir George Thomson is a physicist who won a Nobel Prize in Physics for his discovery of the diffraction of electrons by crystals. He has lectured at a number of universities and was delegate to the Atomic Energy Committee of the United Nations. He has written several books including *The Atom, The Foreseeable Future,* and *J. J. Thomson: Discoverer of the Electron,* a biography of his father.

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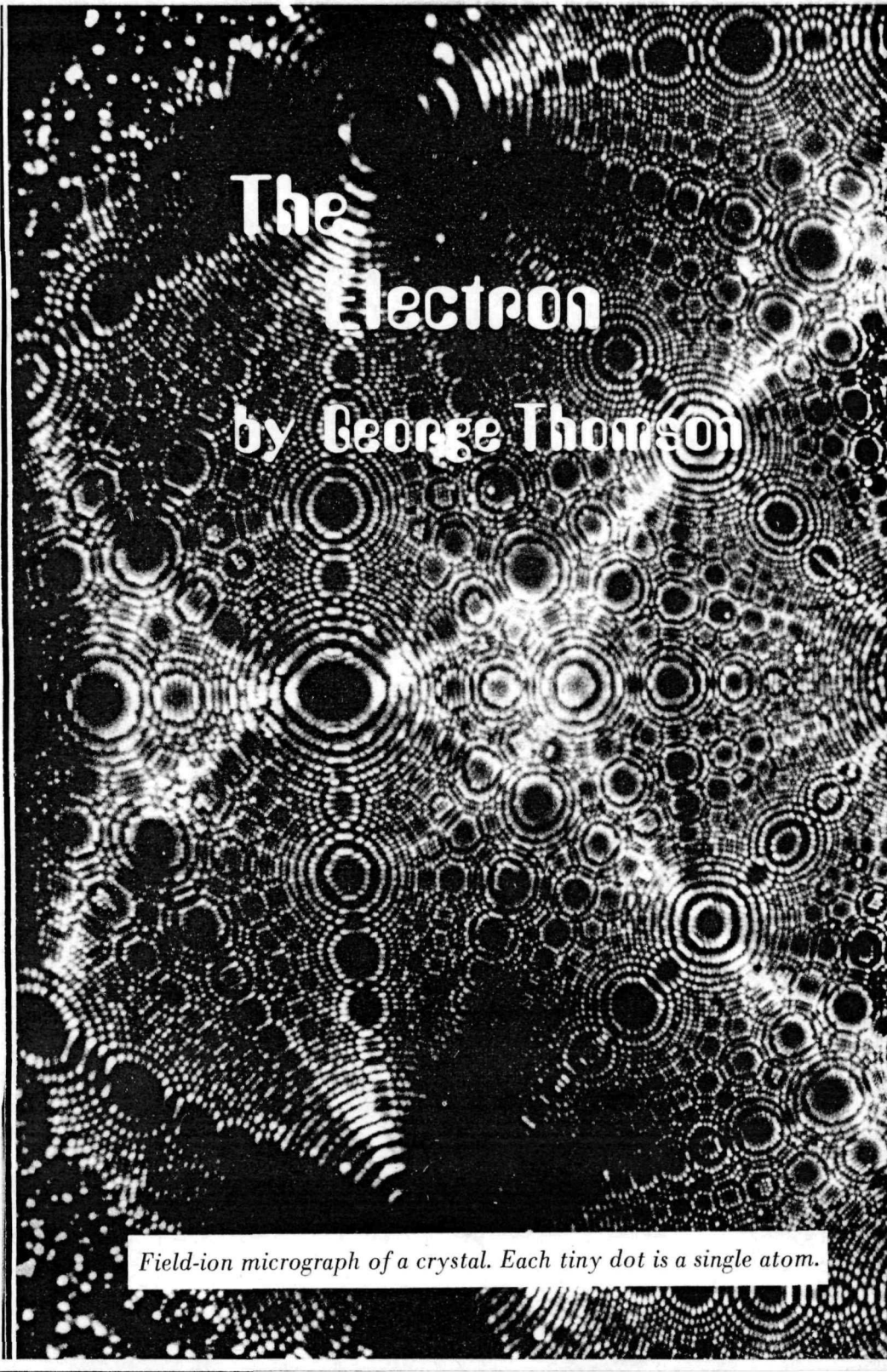

Field-ion micrograph of a crystal. Each tiny dot is a single atom.

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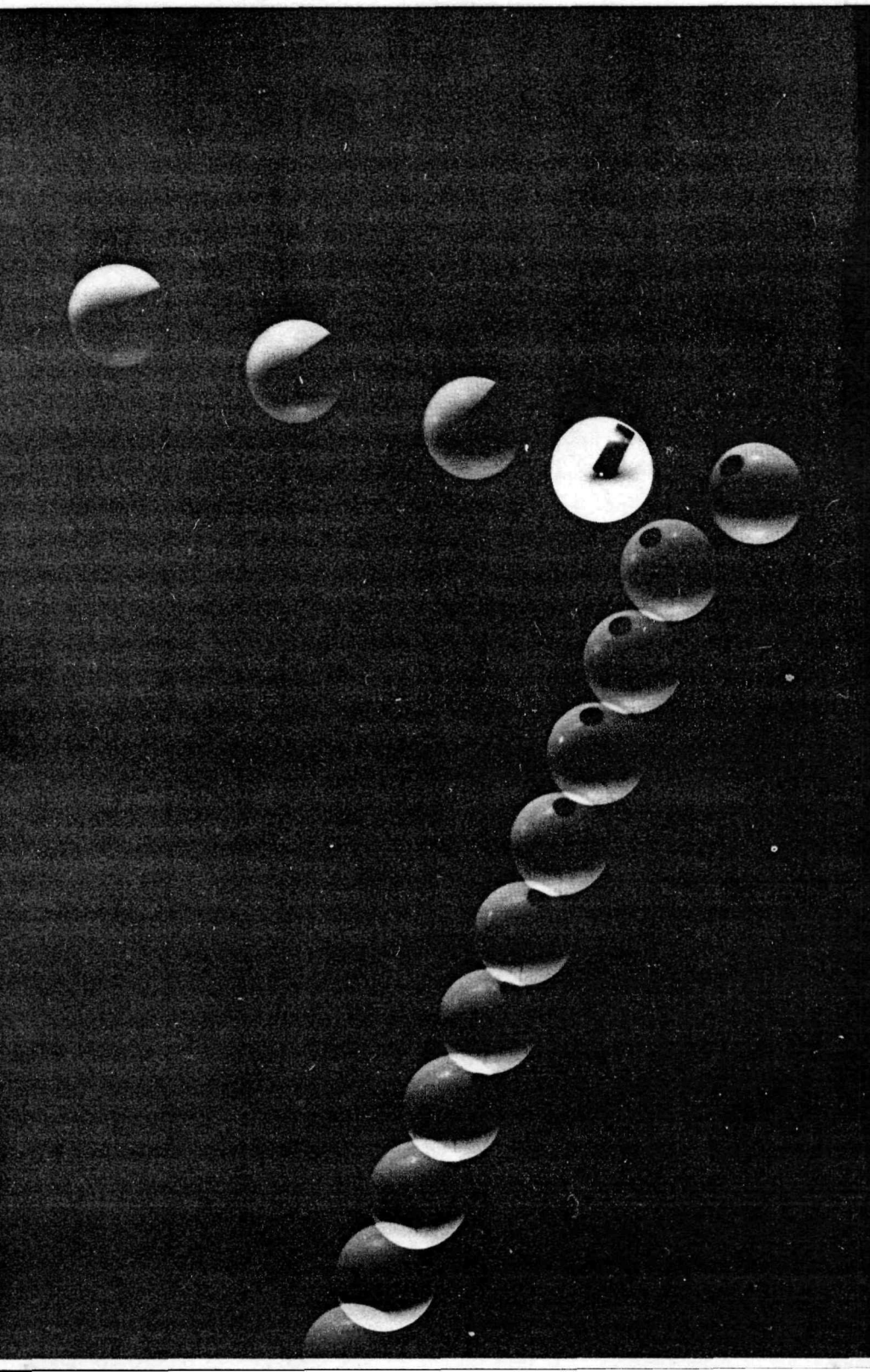


WHAT ARE ELECTRONS?

Nearly everyone has heard of electrons and electronics, and most people probably know someone who earns his living by a profession whose name includes the word in some form. Few people, however, know what electrons are, and not even scientists can answer all the pertinent questions about them.

The electron is one of the building blocks out of which all matter is constructed. In a booklet of this size it is impossible to mention more than a small fraction of the ways in which electrons are used in physics, chemistry, biology, and engineering. All ordinary matter, including that in our bodies and in plants and animals, acts chiefly through the electrons that it contains (except for gravity and nuclear energy). A complete account of electrons would be the story of almost all that is known of matter.

Electrons are light elementary particles; on the average, they account for only about 1/4000 of the mass of ordinary matter that contains them. All electrons have the same mass (or weight) and the same electric charge.

Electrons are very permanent. Most electrons now on earth have been here for as long as there has been an earth. A few have come from the outside, for example, from the sun or in the iron or other elements present in meteorites that have entered our atmosphere. Some have also been produced by radioactive decay.

Electrons are very strongly electrified per unit of mass—much more so than other kinds of matter, and their charge is negative. Furthermore, electrons can never be separated from their charge.

Electrons form part of all normal atoms. But they are not part of the atom's nucleus (or center). The nucleus contains protons and neutrons, two other kinds of elementary

particles. Electrons revolve around and outside the nucleus in a kind of cloud.

Forces between electrons serve as a sort of glue that holds atoms together in chemical compounds. Therefore chemistry—and with it life—is an affair of the electrons in atoms.

Not all electrons are attached to atoms. Metals have "free" electrons that can move easily inside the metal. Free electrons enable metal wire to carry an electric current. What we call the current arises from the motion (or flow) of electrons in the wire.

The electron has a negative charge, but the proton has a positive one. Protons are about 1836 times heavier than electrons. The positive charge on a proton is numerically equal to the negative charge on an electron, and so they balance. Or we can say that the charges cancel each other. Thus, ordinary matter is electrically neutral because it contains as many protons as electrons.

ELECTRICITY BEFORE ELECTRONS

Electrical Charges

Pre-19th century science was concerned with electrical experiments such as those made by rubbing a glass rod with a silk handkerchief. It was observed that both the glass and the silk were then able to attract light objects (like bits of chaff or thin paper). A similar effect was found when a piece of sealing wax was rubbed with fur. Both the glass and the sealing wax were said to have become electrified, as were the silk and the fur.

In addition, scientists found that a glass rod that had been rubbed with silk repelled another similar electrified glass rod, but attracted a piece of sealing wax that had been rubbed with fur. These and other observations led to the conclusion that there were two kinds of electricity or electrical charge. Like charges repel each other whereas unlike (or opposite) charges are drawn together. Based on the suggestions made by Benjamin Franklin in 1747, one kind of charge was called positive and the other negative.

When the electrical battery was discovered, toward the end of the 19th century, there seemed to be another kind of electricity that could flow in a metal wire. In due time, scientists came to realize that the movement of electrical charges in the wire produced an electric current. The laws governing the behavior of electric currents were then discovered by such men as Alessandro Volta, André Ampère, Georg Ohm, and Michael Faraday. But the concept of the electron was to come later.

Conductors and Insulators

Electricity could pass through "conductors", such as copper, but was stopped by "insulators", such as air, sulfur,

and many other dry solids. Most solutions containing water—and damp objects generally—fall somewhere in between; they are better conductors than ordinary air, but not nearly as good as metals.

The study of the passage of electricity through gases, which started in the 18th century and of which Franklin's famous experiment with lightning was an important part, led to a number of significant discoveries in the late 19th century. Some of these results are summarized below.

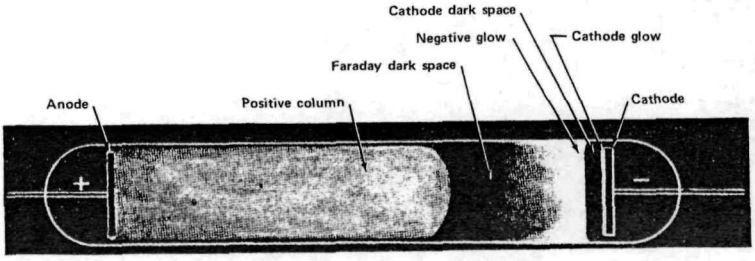
Air is an insulator as long as only moderate voltages are used. But air breaks down as an insulator when exposed to very strong electric fields (a lightning flash is an example of such a breakdown) or when its density is greatly reduced.

A simple experiment may be conducted by pumping most of the air from a glass tube into which two metal wires are sealed. If the wires are then connected to the terminals of a source of electricity yielding a few thousand volts, visible discharges occur when only a fraction of 1% of the atmospheric air remains. But if more of the air is removed it again becomes difficult to conduct any current.

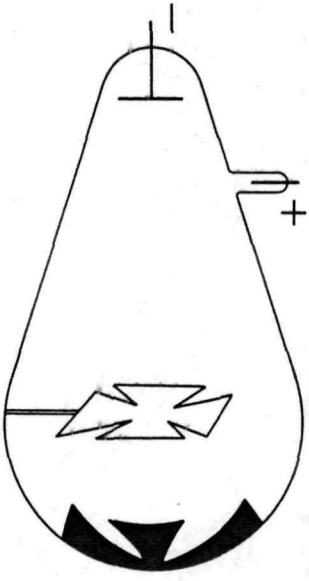
Cathode Rays

The study of the beautiful glows in such tubes led to the successive discoveries of cathode rays, X rays, and electrons. It was found that these three are related. Cathode rays are electrons moving through gas in the cathode-ray tube at speeds of about one-half the speed of light. Cathode rays produce X rays when they strike matter, especially matter composed of heavy elements.

In 1879 Thomas Edison invented the carbon filament lamp that required a fairly good vacuum. The need for better evacuation equipment led to improved vacuum pumps. These made discharge experiments easier and speeded up the study of cathode rays by such physicists as Eugene Goldstein in



A typical discharge at a pressure of about 1 millimeter of mercury. Cathode rays begin to appear as a slightly divergent beam of light coming from a region not far from the cathode at a somewhat lower pressure and the other features grow fuzzy.



Shadows cast by cathode rays. Cathode rays were generally studied by the luminescence (or glow) they cause when they strike the walls of the tube.

Germany, Sir William Crookes in England, and Jean Perrin in France. It was partly, at least, Crookes's work that led the German physicist Wilhelm Roentgen to discover X rays on November 8, 1895.

William Crookes

X Rays

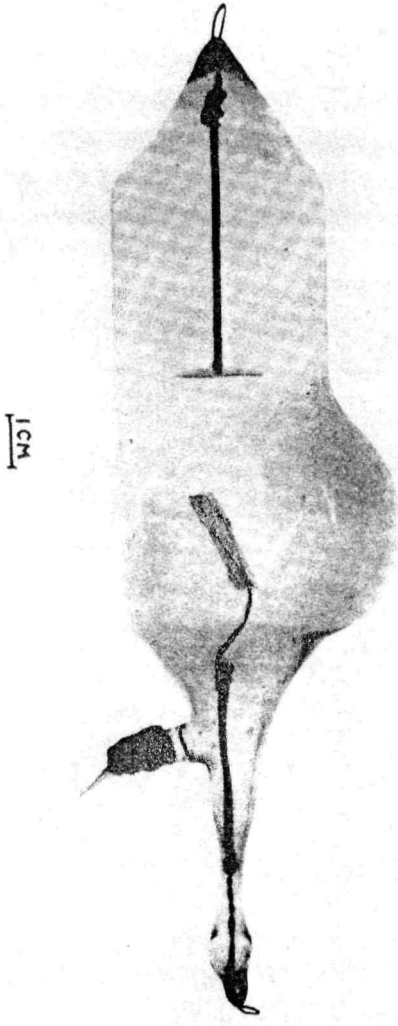
Like Columbus, Roentgen was looking for one thing, but found something else. You might say that he was looking for a dime and found a diamond. Roentgen was using an evacuated discharge tube, like the one used by Crookes, to study the luminescence (emission of light) exhibited by certain solids when struck by the cathode rays. Many solids, including the glass of the discharge tube, behave in this manner.

Instead of putting luminescing substances inside the tube, where the rays could hit them, Roentgen thought he would try putting them on paper outside. He knew that some substances luminesce in ordinary light and do so to a greater degree in the presence of invisible ultraviolet rays. For some unknown reason, he had covered the tube with black cardboard, which was opaque to all rays then known. It was with astonishment that he saw that a sheet of paper coated with barium platinocyanide luminesced when the discharge tube was turned on.

After 6 weeks of experimenting, Roentgen, working alone, established the existence of what he called X rays. (X stood for "unknown".) X rays move in straight lines like light and can penetrate matter to an extent depending roughly on the density of the matter used. X rays are thus able to cast shadows (for example, the dense bones of the hand cast a heavy shadow within the lighter shadow cast by the flesh). No scientific discovery has ever been so quickly received. Within a month or two, X rays were being used for medical purposes in several countries.

Among other things, Roentgen proved that the X rays came from the glass of the tube where the cathode rays hit it. He later showed that the X rays could be strengthened if the cathode rays were made to strike a target of platinum instead of the glass wall. The connection with cathode rays was definite. This discovery made the controversy then raging on the nature of these rays more important.

On the left is Wilhelm Roentgen. Below, two professors at Dartmouth College X-ray the fractured arm of a patient on February 3, 1896. The equipment consists of a battery, a cathode-ray tube (illuminated), and an induction coil and film (under the patient's arm). The professor at left is timing the exposure.



An early X-ray tube.

Roentgen gave the first public exhibition of his mysterious rays in January 1896. At this presentation he took an X-ray photograph (above) of the hand of a 79-year-old colleague.

DISCOVERY OF ELECTRONS

The discovery of electrons has a more complex history than that of X rays and was much less a matter of chance.

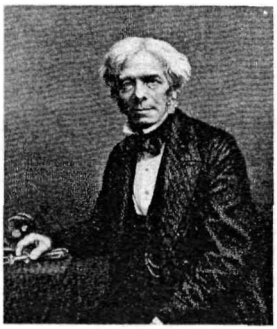
The word "electron" was introduced as a name for the elementary charge of electricity by the Irish physicist G. Johnstone Stoney in 1891. This was several years before the discoveries which convinced physicists that very light, identical particles existed with a charge far greater in proportion to their mass than anything previously suspected.

The Name With Two Meanings

The electron, as then conceived, combined two ideas, both of which had been suggested and rejected (or at least treated with suspicion) years before.

The first of these was the idea that there is a natural unit of electric charge that is the smallest charge that can exist. In other words, all actual charges must be equal to, or multiples of, this unit charge. The second idea goes back to the ancient Greeks, some of whom thought that things are made of a large number of a few very small objects that they named "atoms".

Evidence for the first idea came from Faraday's experiments on electrolysis, which is the general name for what happens when electric currents pass through solutions of various chemicals usually in water. An example of this is electroplating. Faraday's results could be described by saying that the electric current is carried through the solution by atoms (or small groups of atoms), each of which has either the same charge or a small multiple (up to three or four) of this charge. The atoms going one way have positive charges and those moving in the opposite direction have negative charges.



Michael Faraday

Hendrik Lorentz

Pieter Zeeman

Faraday was fully aware of this way of explaining his results, but he shied away from it. The concept of atoms did not fit well with his general approach to electric and magnetic effects. He regarded these effects as spread through space rather than as concentrated in particular charges in a tiny region or at magnetic poles.

His influence and that of James Clerk Maxwell, a Scots mathematical physicist, who shared this view, delayed acceptance of the idea of natural unit charges through most of the 19th century. However, near the end of the century this concept came into favor again. Various theories in its support were advanced but with little experimental backing.

In 1897 the Dutch physicist Hendrik Lorentz suggested a theory that explained the curious effect of a strong magnetic field on the light emitted from a flame containing sodium. The effect had been observed by Lorentz's pupil, Pieter Zeeman. The actual effect is more complicated than Lorentz or Zeeman then supposed, but in its simplest form the theory explained roughly what was observed.

It assumed that the light was due to the motion of a single charged particle (electron) in each sodium atom and that these electrons were influenced by the magnetic field. From Zeeman's experiments, it was possible to estimate the ratio of the charge e to the mass m of the particle. The ratio was much greater than that of any known atom in electrolysis, even that of hydrogen, the lightest atom.

Cathode Rays

The most effective approach to the electron came through a study of cathode rays. Cathode rays had been discovered as early as 1859, but in 1897 their nature was still in sharp dispute. Some physicists thought that they were a kind of wave motion in the "ether". (The concept of the

imaginary ether as the medium in which light is transmitted was fashionable before Einstein developed the theory of relativity.) But others thought that the cathode rays were made up of particles.

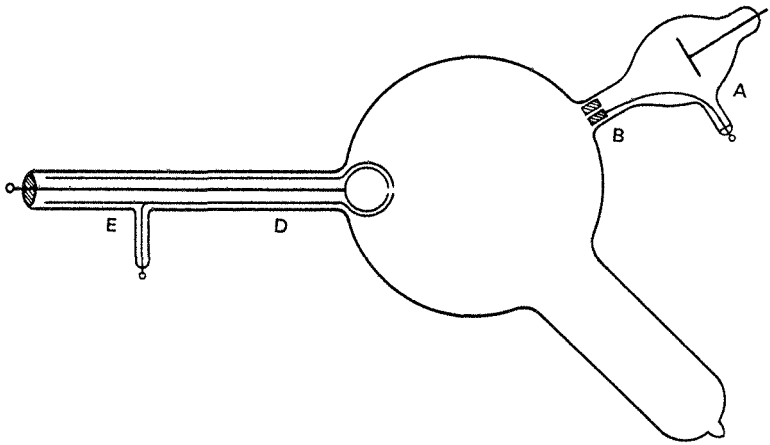
Hertz's Experiment

It had long been known that cathode rays are bent by even a moderate magnetic field, just as a fast-moving, negatively charged particle would be; this evidence favored particles. But the German physicist Heinrich Hertz, the discoverer of radio waves, had concluded erroneously that cathode rays were *not* bent by an electric field as moving charged particles should be.

In Germany, Philipp Lenard, a physicist, following up another discovery of Hertz, had shown that cathode rays could go unchanged through gold foil that was thick enough to contain many layers of gold atoms. In those days it seemed unlikely that a particle could pass through an atom, much less through many of them.

In 1897 the English physicist Joseph John Thomson published the results of experiments that cleared up Hertz's difficulty and demonstrated that particles of cathode rays are fundamental particles of matter. (Thomson was the author's father and was called J.J. by his friends and students.)

Perrin in Paris had just shown that when that part of the wall of the discharge tube where the rays struck was replaced by a metal cup, a negative charge would flow through a wire attached to the cup. This is what one would expect if the rays were charged particles. The evidence obtained by this experiment was not as strong as it seemed at the time. We now know that a secondary radiation phenomenon can carry away a sufficient number of charges to reverse the sign of the



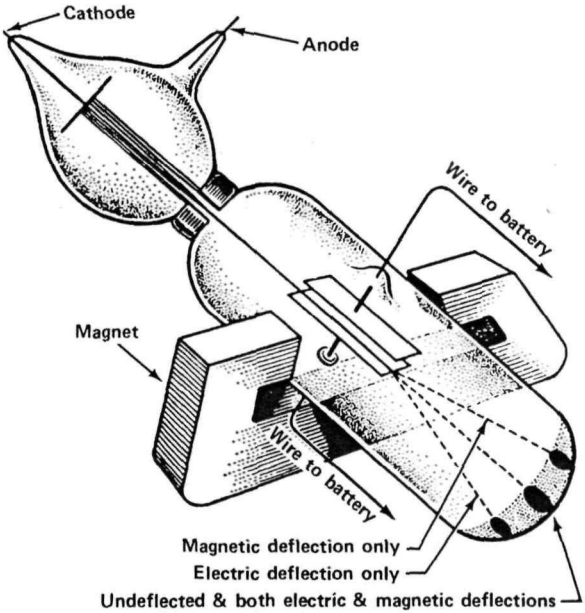
Perrin's experiment as modified by J. J. Thomson. The rays start from the cathode A and pass through a slit in the brass rod B, which fits tightly into the tube; B is connected to ground and serves as an anode. The rays coming through the slit in B are deflected by a magnet and pass through a slit in the grounded tube D. Inside D and insulated from it is the tube E that collects the rays. E is connected to an electrometer that measures the negative charge that was only considerable when the rays were brought by the magnet to the opening of the cylinders.

observed charge.* However, it helped the particle interpretation and Thomson improved on it to discredit some alternative explanations.

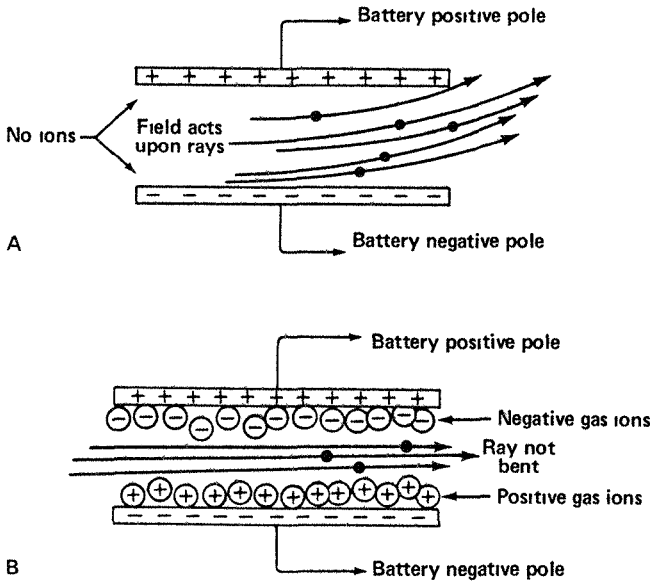
The real trouble was Hertz's experiment, which claimed to show that cathode rays are not deflected by an electric field in a good vacuum. At face value it was conclusive evidence that cathode rays were not particles—at least not

*This probably explains an experiment by Crookes in which he observed a positive charge when cathode rays struck a target.

ordinary particles. But Thomson was able to suggest what had gone wrong in Hertz's experiment. In this, he was helped partly by experiments that he and the New Zealand-born physicist Ernest Rutherford had been doing on conductivity produced by X rays in normal air and partly by one of Goldstein's experiments, as will be seen shortly.



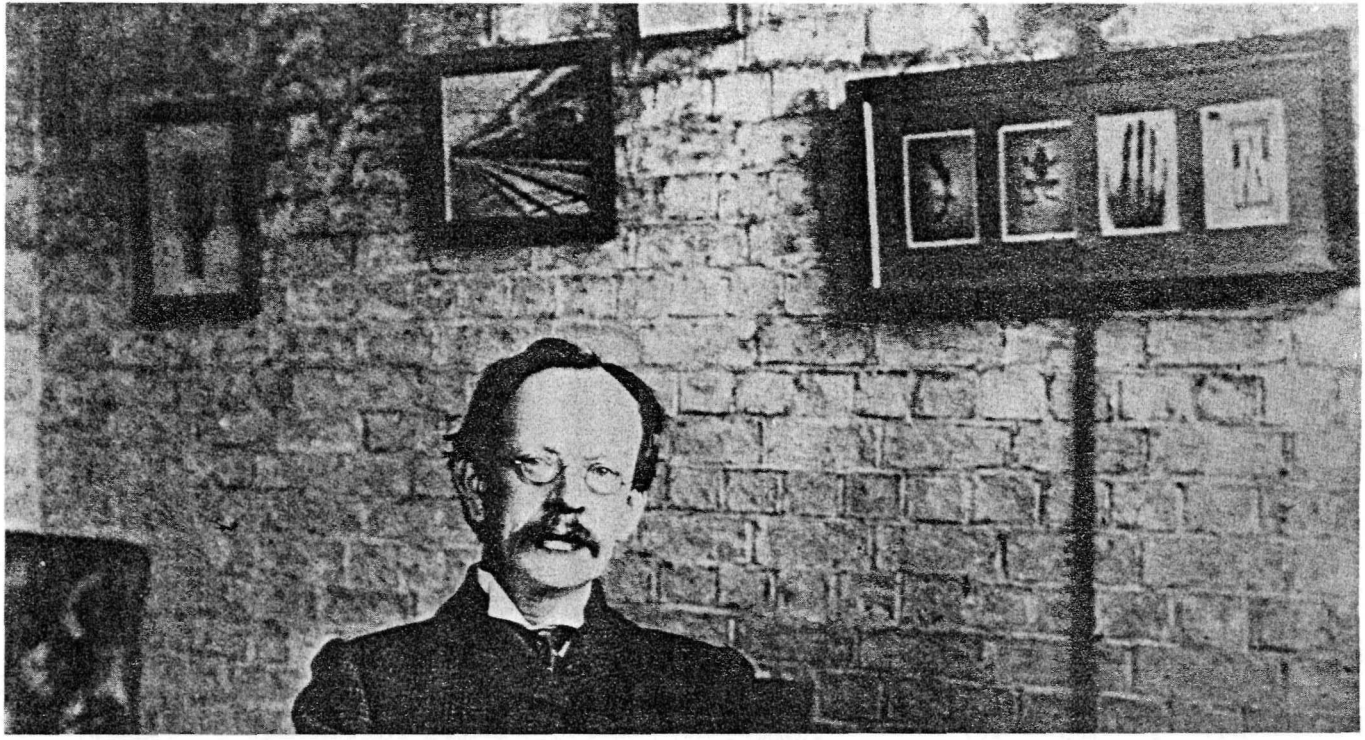
J. J. Thomson's apparatus for measuring e/m of cathode rays. The rays coming from the cathode go through a metal ring in the neck of the glass bottle that is connected to the anode and to ground. They can be deflected by the magnet and also by connecting to a battery the plates between which they pass. These two deflections (by magnetic and electric fields) can be made to balance by adjusting the voltage. The magnetic field can be measured. The ratio of electric to magnetic fields for balance gives the velocity, assuming that the rays consist of charged particles. When the velocity is determined, e/m can be calculated from the deflection by either field alone.



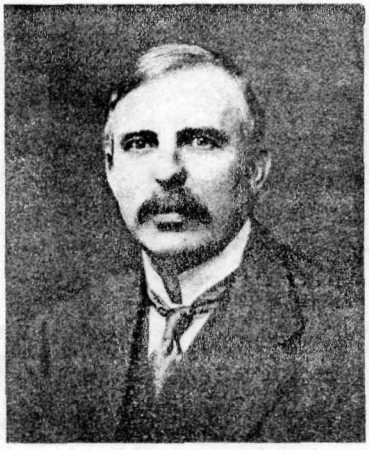
The charges on the two plates connected to the poles of a battery produce a field in A that pushes a positively charged particle down and a negatively charged one up. In B, charged molecules of gas have been pulled against the plates and neutralize the charges on them so that there is no force between the plates.

Thomson repeated Hertz's experiment in a form that not only showed that cathode rays are deflected by an electric field as well as by a magnetic field, but also permitted him to measure the ratio of charge to mass (e/m) for the no-longer-disputable particles of cathode rays. The result was nearly equal to that found a few weeks earlier by Zeeman.

Hertz was an excellent experimenter. How did he make such a mistake? The error occurred because he ignored an effect of the small amount of air or other gas left behind in the tube where the cathode rays were created and deflected. The rays split up some molecules of this residual gas into electrified parts (positive and negative) called "ions". When



J. J. Thomson in his laboratory. On the right are early X-ray pictures.



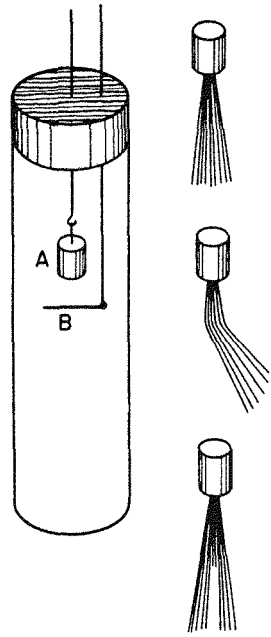
Ernest Rutherford

an electric field was applied between two metal plates to see if the cathode rays were deflected, these electrically charged ions had the effect of almost entirely nullifying the effect of the field. Thus, no deflection was (or could have been) observed.

The strange thing is that Hertz had taken pains to avoid a similar cause of error, which he rightly supposed might occur on the glass walls of the tube, but he did not take the next step. He was at the end of a long series of experiments which confirmed his idea that cathode rays were "phenomena in the ether", and he probably thought it a waste of time to pursue the matter further.

J.J. Thomson's Discovery of the Electron Particle

The vacuum techniques on which Thomson's experiments depended had improved considerably over those used by Hertz. He also had the advantage of having investigated the electrical conductivity of air due to X rays. His experiments with Rutherford were made with air at atmospheric pressure, where the effect in question is magnified and easily observed. Goldstein's experiment, using the apparatus in the figure, was



Goldstein's experiment. On the left is a discharge tube in which two cathodes, A and B, could be connected together; A is a hollow metal cylinder and B is a wire. When B was disconnected, the path of the rays from A was straight (top picture). When A and B were connected, the cathode rays from A were deflected when they were near B (middle or bottom picture). Therefore, the negatively charged cathode rays are repelled by the field of B when it is a cathode.

a stepping stone that paved the way for the successful measurement of e/m.

Thomson was also strongly influenced by Lenard's work, but drew a different conclusion from it. Lenard had proved that absorption of cathode rays by gases and thin solids depends only on the density of the absorbing medium. This was unlike the behavior of light and other ether waves that go through glass but not, for example, slate of about the same density.

To Thomson, Lenard's results implied (1) that absorption of cathode rays was due to their collision with other particles in the kinds of matter Lenard had used, and (2) that all matter contained these cathode-ray particles (which Thomson called corpuscles) in numbers proportional to the density of matter. The corpuscles (or electrons) were thus a universal part of matter, whose existence coincided with his observation that e/m did not depend on the kind of gas used in the discharge or on the kinds of metals used in the cathode.

In 1897, Thomson assumed (and the next year proved experimentally) that, at least on the average, e was equal to the unit charge in electrolysis to the accuracy with which the latter was then known. This last measurement, however, referred not to cathode-ray particles but to the ions formed by X rays.

In 1901 Thomson measured both e/m and e for another class of charged particles, namely those responsible for the photoelectric effect (discovered by Hertz as a by-product of his work on electromagnetic waves). Hertz had found that when certain metals are illuminated by an electric spark, they emit electricity if they are negatively charged, but not if they are positively charged.

Within experimental error, the e/m values for the carriers of photoelectricity were found to be the same as for cathode rays. Thomson also measured e for these carriers by the method he had used for ions produced by X rays and found it the same. Hence he deduced that the photoelectric carriers are identical with cathode-ray particles though their origin is different.

John S. Townsend, working in the Cavendish Laboratory at Cambridge, had shown by an accurate method—without actually measuring either—that the charge on ions produced

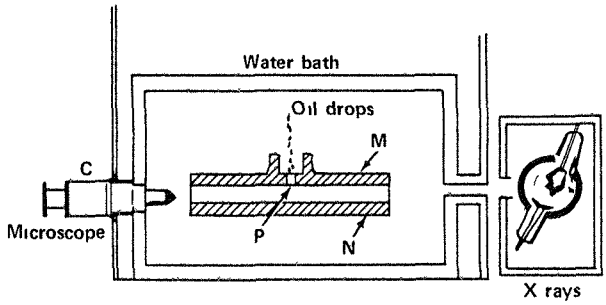
by X rays is the same as the "unit charge" in Faraday's experiments.

Most people were convinced that the above results implied a natural unit of charge. However, the results were all concerned with averages. They did not prove that the charges on all particles were individually the same. Nor did they prove that if some charges were larger than the average (and some were) that the larger charges would be whole-number multiples of the usual value, as the idea of a true natural unit of charge requires. The required proof was given in 1909 by the American physicist Robert A. Millikan using an improved method for measuring e.

Millikan's Unit of Charge

Millikan's celebrated and beautiful experiment proved that changes in the charge of a drop slowly falling through air containing ions produced by X rays always occur by exact multiples of a definite charge, which is the true value of e.

Robert Millikan



Millikan's apparatus for detecting the charge on an electron. Two metal plates, M and N, were separated by three small glass ones (not shown). The drops of oil passed through the hole labeled P. X rays were introduced when required from outside to ionize the air. The apparatus was kept at constant temperature by enclosing it in an airtight vessel and then in a water tank. A controllable difference of potential was applied between M and N, and the oil drops observed through the microscope C.

This was done by balancing the weight of a drop of oil, which evaporates very slowly, against a controllable electric field. This field exerts an upward force on the charge that the drop picks up from ions in the air.

A balance can be maintained for a long time so that the drop hangs in the field of the observing microscope. If it picks up an extra charge from an ion, as happens from time to time, the balance is upset, and the *change* in the electric field needed to restore it is a measure of the *change* in charge. Millikan showed that these changes did occur in multiples of a unit quantity, thus settling this aspect of the electron.

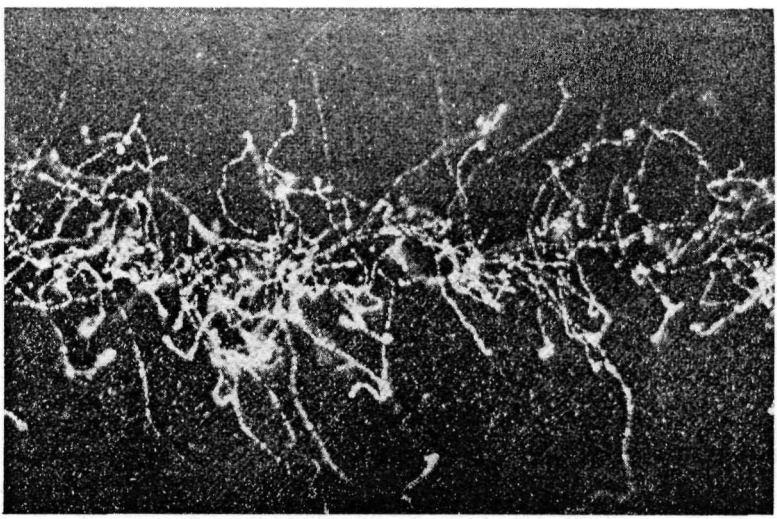
Cloud Chamber Tracks

The "cloud chamber" for rendering visible the tracks of electrically charged particles is largely due to the work of the

Scots physicist Charles T. R. Wilson. When air containing water vapor is suddenly expanded (for example, by uncorking a bottle containing moist air under pressure) a cloud of small droplets will form. If the gas contains particles of dust, the droplets will form first on these. If the air is ionized, expansion will cause the droplets to form on the ions. These droplets can be quickly photographed before they have fallen or reevaporated and the resulting picture shows where the ions were before the expansion.

When Wilson did this for air ionized by X rays, he got pictures like those shown in the figure.

The X rays had been limited by lead blocks and went through the air in a broad path, but the ionization was very chaotic. You can see that the dots which mark the ions lie on twisty tracks. These resemble tracks seen when the gas is ionized by fast electrons. In fact, ionization by X rays is mostly *indirect.* The X rays produce only a few fast



Ionization tracks of electrons produced by X rays.

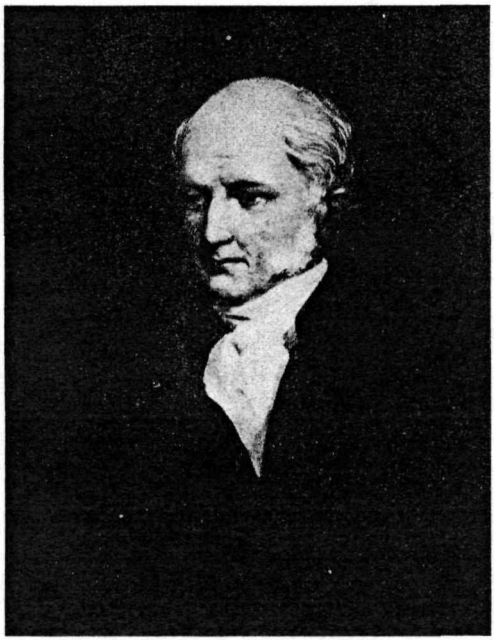
C. T. R. Wilson

electrons; each of these produces many ions by colliding with molecules of air and knocking electrons out of them.

In 1911 Wilson developed a form of cloud chamber with which it was possible to photograph the ionization tracks of individual electrically charged particles. By observing the deflections of these tracks in a magnetic field, the speed and energy of these particles could be determined. Furthermore, scientists were able to use the cloud chamber to study the interactions between particles and even to discover new ones.

Atomic Weight

Early in the 19th century William Prout, an English chemist, suggested that the weights of all atoms were exact



William Prout

multiples of that of hydrogen, the lightest atom. The evidence in favor of this was considerable, but the idea was discarded when accurate measurements showed that some of the chemical atomic weights were definitely not integral in units of hydrogen. We now know that in some cases this is because a chemical element is a mixture of several subspecies of atoms that have different weights; these subspecies are called isotopes. For each single isotope Prout's law is very nearly true; the remaining small differences are due to binding energies within the atom that appear as changes in

mass, in accordance with Einstein's law of mass–energy equivalence, $E = mc^2$.*

In his first paper on the nature of cathode rays, Thomson cited Prout's hypotheses with some approval, but did not press the idea in that form. Although electrons are present in all matter, their weight is too small to count in arguments such as these. In this first paper the evidence Thomson gave for the presence of electrons in all matter was slight for such a fundamental hypothesis. For a few years, the idea was treated with reserve by most physicists, but more evidence rapidly accumulated.

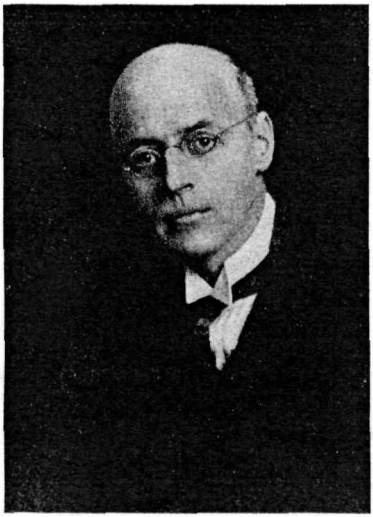
Other Sources of Electrons

First, particles indistinguishable (except in speed) from those forming cathode rays were shown to occur in the photoelectric effect. Furthermore, Thomson showed that the negative particles emitted by some heated metals, in what is called the thermionic effect, had the same e/m as the particles in cathode rays. Both this thermionic emission and the photoelectric effect are difficult to study, because the emission in both cases is greatly affected by the surface state—even one layer of impurity atoms may make a great difference.

However, Owen W. Richardson in England was able to get consistent results for thermal emission from some substances. He devised a theory that explained the effect as the boiling off of an electrified gas contained in the metal, the particles of the gas being the same as those of cathode rays and the photoelectric effect. We may now call these particles *elec-*

*For further information on isotopes, binding energies, atomic masses, etc., see *Inner Space: The Structure of the Atom,* another booklet in this series.

trons and identify them with the electrons Zeeman had found in the sodium flames.



O. W. Richardson

Positive and Negative Charges in the Atom

It was clear from the start that matter cannot be composed entirely of electrons of negative charge. The mutual repulsion of such charges would be so much greater than gravitational attraction or chemical forces that any piece of matter would burst with an energy that would make a hydrogen bomb look like a child's toy! In fact the greatest negative charge that a metal sphere of 1-centimeter radius can have in air at ordinary pressure without sparking adds only 1 electron in about 10^{14} (or 100 trillion) to the number it normally contains. The enormous mutual repulsive forces due to the electrons in the atom must be compensated by the attractive forces due to a positively charged constituent of matter. It was some 15 years before this constituent was proved also to be a particle, which is called a proton.

For a long time, researchers did not know the composition of the non-electronic part of matter, and it is beyond the scope of this booklet to explain this in any detail. We can merely say that Rutherford in 1911 suggested that the main mass of all atoms, and all the positive charge, is concentrated in a very small region at the center, called the nucleus, around which the electrons are grouped.*

The structure of the nucleus is still not fully understood but we know that nuclei are composed of protons and neutrons. In an ordinary atom, the protons are equal in number to the electrons and supply a positive charge, which neutralizes (or balances) the negative charge of the electrons.

We shall come back later to discuss the arrangement of electrons around the nuclei of the various atoms. This subject became the major interest of physicists from about 1913 until 1926 and led to a profound change in the way in which electrons are regarded. But now we turn to the more practical side.

*For further details, see *Inner Space: The Structure of the Atom.*

SOME EARLY APPLICATIONS OF ELECTRONS

When World War I began in 1914 electrons were attracting attention outside university research laboratories. They were moving into business and into war.

A hot metal wire is the most convenient source of electrons in fairly large quantities, making use of the thermionic effect. Emission depends on the kind of metal, but in all cases it increases rapidly as the metal is made hotter. Thus, metals of high melting point are the most effective sources of electrons. Platinum was used for much early work but it is very expensive and melts more readily than tungsten and molybdenum, which are used more often now.

The current from hot tungsten near its melting point is several amperes per square centimeter. Electrons escape from the surface, but unless they are removed as fast as they escape, their negative charge accumulates in the space close to the metal. This charge—by repulsion—prevents more electrons from escaping. The emission is then said to be "space-charge limited", and no longer depends on the temperature of the wire.

If a strong external electric field is applied, all electrons that get through the surface of the metal are removed and the emission is said to be "saturated". At this point the emission becomes more or less independent of the applied field even if this is greatly increased, but at very high electric fields (millions of volts per centimeter) electrons can be drawn out of the wire even if it is cold. This "strong field emission" can be an important cause of electrical breakdown in the presence of very high voltages.

Thermionic emission has an obvious use in rectifying alternating currents, i.e., turning them into direct currents.

Since these electrons are negative, an alternating field between a clean, hot wire and a cold electrode will provide a permanent current only when the field is directed so as to take the negative charge away from the wire. The emission from a dirty wire may consist of positive ions for a time—usually atoms of sodium or potassium, which are on the surface or dissolved in the metal as an impurity.

If gas is present, it will be ionized in the presence of fields greater than about 10 volts, and the ions will allow an undesired reverse current. The earliest diode tubes of John A. Fleming, an English electrical engineer, and other vacuum tubes were rectifiers in which a certain degree of control of the rectified current could be achieved by changing the temperature of the wire.

The triode, a vacuum tube of enormous versatility, was developed in 1906 by the American inventor Lee De Forest. This device was produced by adding a third electrode—a wire mesh or "grid"—between the cathode (the hot wire) and the anode (connected to the positive pole of the power supply).

Even though the filament temperature remained constant and constant voltage was applied to the anode, the current to the latter could be controlled by changing the potential of the grid. If this was made negative, it kept most of the electrons from getting through to the anode. If positive, it let them through. Details varied greatly both in geometrical arrangements and in the presence or absence of gas, which could be ionized. Ions could greatly affect behavior of the tube for various potentials on grid and anode.

Radio

Vacuum tubes made possible the development of radio and later of television broadcasting. Until about 1914 and

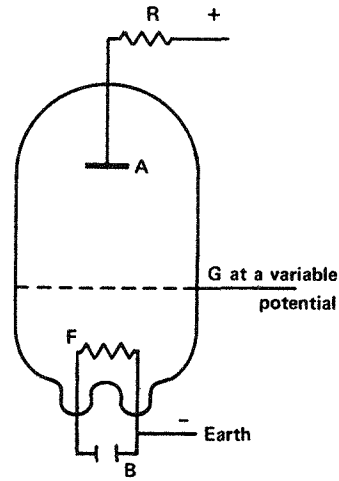


Diagram of triode vacuum tube used as an amplifier. The battery B heats filament F that emits electrons. These are drawn by the power supply to the anode A. A small potential between the grid, G, and the filament, F, can affect the flow of electrons to A and greatly change the anode current; this causes a large change of potential over the resistance R. Variations in the grid potential can thus be amplified.

through most of World War I, radio meant signals in the dot–dash Morse code. To broadcast the human voice one must have a continuous electromagnetic wave with a frequency above approximately 500,000 hertz (cycles per second). This will then be "modulated" by altering either the frequency or the amplitude with the much lower frequencies produced by the human voice or musical instruments, say 100 to 20,000 hertz.

This modulation was most readily achieved by applying the electrical signal from the transmitter of a telephone set to

the grid of a tube controlling the radiation from the transmitting antenna. This can be done in many ways.

One great value of these vacuum tubes is their ability to amplify weak signals, especially in radio receivers. A small change in voltage of the grid can produce a great change in the current to the anode; the power needed for an increase comes from the power supply attached to the anode.

Tubes have been superseded for many purposes by transistors. These still depend on the motion of electrons but the latter now move inside carefully prepared solids that do not have to be kept hot. Thin slices of germanium or silicon are the most commonly used. They are made from very pure materials, except for small quantities of impurities chosen according to the particular action required.

Devices for amplifying electrical currents were nothing new. In a telephone relay a small current through an electromagnet pulls a contact that completes a circuit carrying a heavy current. The many unique features of electronic devices stem from the lightness of electrons: Small forces can rapidly control their movements. Thus, electrodes and transmission tubes can be compact, so that they respond rapidly. For the first time it became possible to deal with events lasting only a millionth of a second.

Coolidge X-Ray Tubes

Another use of electrons from hot filaments came in 1913 when William D. Coolidge of the General Electric Company invented his X-ray tube.

X rays are produced when fast electrons strike a solid target. Roentgen's electrons were cathode rays from the cathode of a discharge in residual air at low pressure. Such X-ray tubes are difficult to control. The pressure of the air or

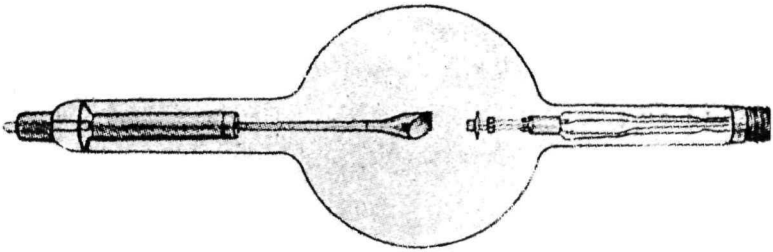
other gas is low and even a small amount of air lost or gained makes a lot of difference.

Coolidge invented an X-ray tube, the operation of which was not sensitive to the amount of residual gas. His cathode was a heated tungsten wire, and the cathode rays were simply the thermionic electrons emitted by it. Most X-ray tubes now work on this principle.

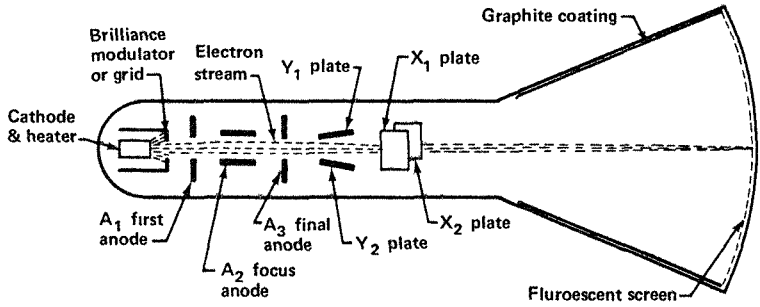
The Photoelectric Effect

Another application of electrons is in the photoelectric effect. A sensitive metal surface (such as potassium) will release electrons instantaneously when illuminated. Unlike photography, no chemical changes are involved. The electrons, though of low energy in the case of visible light, can be accelerated and detected by an amplifier tube or system of tubes. Once they have reached this stage what they can do is limited only by the power available and is independent of the initial stimulus. Hence, the photoelectric effect is used in the many devices that involve recognition of shapes (such as letters or numbers).

The object is scanned by a narrow beam of light, and the reflected light enters a photoelectric cell. The current from this varies according to the lightness or darkness of the point being scanned at the moment.



Coolidge X-ray tube.



Electrostatic cathode-ray oscilloscope. A_1, A_2, and A_3, and the brilliance modulator form the electron gun whose function is to focus a controllable beam of electrons from the hot cathode onto the fluorescent screen.

Cathode-Ray Oscilloscope

One of the most useful instruments in a modern laboratory is the cathode-ray oscilloscope (CRO), a simple modification of Thomson's apparatus for measuring e/m for cathode rays.

A beam of electrons, now usually derived from a hot tungsten wire, is accelerated to a few tens of thousands of volts. The beam strikes a fluorescent screen and produces a small visible spot. Before doing so it can be deflected in two directions, at right angles to each other and to the original direction of the beam. This can be done either by passing the beam between a pair of electrified plates or between the poles of an electromagnet.

One common use of the CRO is to compare two oscillating voltages (or currents), each of which produces a deflection, one horizontal and the other vertical. One voltage is chosen as standard and produces, say, a horizontal deflection of the spot on a vertical fluorescent screen. This voltage may be, and often is, ordinary 60-cycle voltage. If so, the spot oscillates horizontally over a certain range 60 times a

second, and describes a straight line (called the time base) if the second deflecting system is not used.

If the second system is also oscillating at 60 cycles the combined effect will be repeated exactly 60 times a second. Since this is faster than the eye can follow, the observer sees a steady trace on the screen: A slanting straight line if the two oscillations are in phase or in opposite phases, or a circle if the phases differ by a quarter period and the maximum voltages are the same.

The phase difference can readily be found by studying the image on the screen. If a signal generator or other device for producing an oscillation of variable and known frequency is available, the CRO can be used to measure the frequency of an unknown oscillation by adjusting the frequency of the signal generator until the combined pattern is steady.

The CRO is also often used for the study of "transients" (for example, the effect produced in an electrical circuit when a sudden change in voltage, such as may be caused by a spark, occurs at some point in it). For this the time base would be chosen to be comparable with, or faster than, the natural time of oscillation of the circuit. The intensity of the pattern due to a single transient is small, but sensitive photographic techniques can be used to detect it.

The most important value of the CRO in fields like radio or radar stems from the great speed with which a beam of electrons can respond to various electric and magnetic forces acting on it. This is again a consequence of the small mass of electrons. Thus the CRO can deal with oscillations of many millions of cycles per second.

Though it came much later than the events we have been dealing with, this is perhaps the right place to mention how a CRO can be modified as a scanning device to form the basis for a television receiver.

The horizontal deflection is made a nearly uniform motion, with a quick flyback at one edge of the screen. The vertical deflection is constant during the uniform horizontal motion and increases during the flyback by a small amount, which is the same each time. The point of the "pencil" of electrons will cover the screen in an orderly manner, each point being illuminated for a moment. The intensity of the electron beam is varied during this scanning motion to form the light and dark areas of the picture being transmitted.

This involves scanning the picture by a beam of light, which eventually produces electrons in a photoelectric cell in numbers proportional to the brightness of each particular point of the picture. These electrons produce a signal that modulates the intensity of the wave from the transmitting station. At the receiving end the intensity of the wave modifies the intensity of the CRO beam by a voltage applied to the apparatus, which is similar to the grid of an old-fashioned vacuum tube in its effect upon electrons going through it.

ELECTRONS AS WAVES

For about a quarter of a century (1900–1925), physicists had accepted that (1) electrons exist in all normal atoms, and that (2) they are particles which possess a negative electric charge of about 1.6×10^{-19} coulomb* and possess a mass of about 9×10^{-28} gram when at rest or moving slowly in comparison with the speed of light. In accordance with the theory of relativity, the mass of an electron increases as its velocity approaches that of light.

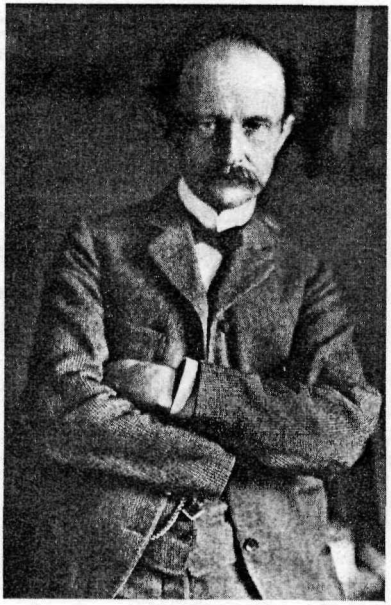
Quantum Theory

At the beginning of the 20th century the German physicist Max Planck introduced his revolutionary "quantum theory". At the time, there was a tendency among scientists to believe that the laws of physics had all been discovered. (This attitude is well illustrated by the following advice that Max Planck received when he was 17 years old from a physics professor: "Physics is a branch of knowledge that is just about complete. The important discoveries, all of them, have been made. It is hardly worth entering physics anymore.")

Planck's ideas were therefore received with incredulity mixed with respect. He had deduced theoretically a formula showing how the light from a hole in a furnace kept at a certain temperature varies in intensity and in color as the temperature is changed.

The formula was not unduly complicated. It introduced only one quantity, h, that was unexpected, and which is now called Planck's constant. The formula was undoubtedly right; it agreed excellently with the experiments while the

*A coulomb is the charge carried past a fixed point by a current of 1 ampere in 1 second of time.



Max Planck

formulas deduced from more orthodox considerations, though they might work tolerably well within a certain range of conditions, were quite wrong in other cases. Planck had suggested that exchanges of energy between matter and radiation occurred in units, rather like the transfers of electric charge in Millikan's experiments, but with this important difference: The unit of energy, now called a "quantum", depends on the frequency of the radiation considered. If the frequency is ν, the transfers are in units of $h\nu$ and only in units of $h\nu$.*

However, this last concept was not as hard to accept as was the idea that radiation is transferred in units at all. The difficulties to which this idea leads cannot be explained in

*The frequency of radiation (or any wave motion) is equal to the velocity of the wave motion (3×10^{10} cm per sec for radiation) divided by the wavelength. Wavelength is defined as the distance between crest and crest (or trough and trough) measured in the direction in which the wave is traveling.

nonmathematical language. They led Planck himself and many of the leading physicists of the time to try to explain the Planck formula without assuming unit (or quantum) transfers of energy, but they all failed.

As time went on the mysterious h turned up in other parts of physics as widely separated as the behavior of diamonds at the temperature of liquid hydrogen and the energy of the electrons produced by light and by X rays. The latter is the most closely connected with the subject of this book.

Light Waves and Diffraction Gratings

Since the early 19th century, scientists have been convinced that light is composed of waves, originally thought to be waves in the imaginary ether, which was mentioned earlier. Later the waves were proved by Maxwell and Hertz to be electromagnetic oscillations. In 1913, experiments made at the suggestion of the German physicist Max von Laue had shown that X rays were similar in nature.

Max von Laue

The wavelengths actually studied varied from many miles down to the size of an atom, and there was no particular reason to suppose that either of these was a natural limit. X rays are in fact just light of short wavelength. The wavelengths of visible light are in the range of 7000–4000 angstrom units (A)*, ultraviolet light about 4000–2000 A, and ordinary X rays from about 10 to 1/10 of this unit, which itself is about the size of a typical atomic radius.

The experiments on X rays, which proved them to be electromagnetic oscillations, consisted in showing that they can be affected by a crystal in a manner similar to that of visible light with a ruled diffraction grating. The regular rows and sheets of atoms, which make up crystals, act like the lines of the grating (see page 51). But the atomic rows are much closer together than any grating can be ruled, and thus they can deal with the much shorter waves that compose the X rays.

Waves Versus Particles

Experiments on the photoelectric effect and on X rays introduced a terrible demon into this beautiful picture of scientific order; the demon was h. Careful measurements of the maximum energies of the electrons produced from various substances in these processes showed that in both cases they increased with the frequency ν of the radiation used, and were equal to $h\nu$ minus an amount that depended on the substance but not on ν. This term was correctly explained as the amount of energy the electron needed to escape from the experimental substance, such as a solid or a gas. So the result is that radiation can give the energy $h\nu$ to an electron *inside* a solid or a gas molecule.

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*An angstrom is 10^{-8} centimeter or one hundred millionth of a centimeter.

This result was startling not so much in what it said but in what it omitted. The intensity of the waves of light or X rays, as the case might be, is *not* mentioned. If ocean waves were to behave in a similar manner, individual stones on the beach would be moved as much by a gentle swell as by a violent wave; the difference being that only a few stones would be moved in the former case and the remainder would be unaffected.

While this seems nonsense for ocean waves, it would not have been nonsense for light if physicists had retained Newton's theory of light as particles. Fast particles are like bullets. Bombardment of a brick wall by bullets will do much the same damage to any single brick that a bullet actually hits. Violent bombardment with bullets of the same speed merely strikes in more places.

Yet the particle theory of light had been abandoned for excellent reasons. The agreement between wave theory and observations on light (for more than a century) and on X rays (for a few years) was apparent from many detailed and beautiful experiments. This agreement was true provided that the experimenter only asked *where the light went* (for example, which parts of a screen were strongly illuminated and which dark) but never asked *what the light did* when it arrived.

The difficulty in understanding the photoelectric effect is encountered in other properties of light, although the cases are often more complicated. Some examples are the blackening of photographic plates and other chemical actions, and the effects of light on the human eye.

Therefore light behaves like a wave and like a particle! To the physicists of the early 1920s, this so-called photoelectric paradox was a devastating experience. It seemed to be contrary not merely to the truth of some cherished laws of physics but to the whole idea of a rational universe! Waves

Louis Victor de Broglie

and particles seemed totally different concepts, yet light and X rays were apparently both.

De Broglie and His Particle Waves

The first indication of a way out came in 1923 from the Ph.D. thesis by Prince Louis Victor de Broglie, a French physicist, who was at the University of Paris. This thesis was a theoretical attempt to resolve the difficulty of Planck's formula by starting from the other end. Instead of trying to show how waves could behave like particles he tried to see if particles could not for some purposes act like waves.

Niels Bohr

De Broglie assumed the existence of particles of light, as indeed Einstein had already done, and tried to deduce waves from them. This was moderately successful. But instead of limiting his considerations to the immediate problems of light or X-ray waves and their possible particles (now called photons), de Broglie extended the idea to *any* particle, in particular to electrons.

This led to some striking conclusions, which helped to explain some assumptions the Danish physicist Niels Bohr had made 10 years before on the states of electrons bound inside atoms. Bohr's theory had had a great success, but there were some difficulties outstanding. The theory postulated the arrangement of the electrons in certain preferred (or permitted) orbital paths around the nucleus like planets around the sun. It was assumed that while traveling in any one of these paths the electrons did not radiate electromagnetic waves, although according to the existing theory of electricity they should have done so. Only if an electron switched from one permitted orbit to another would energy be emitted or absorbed.

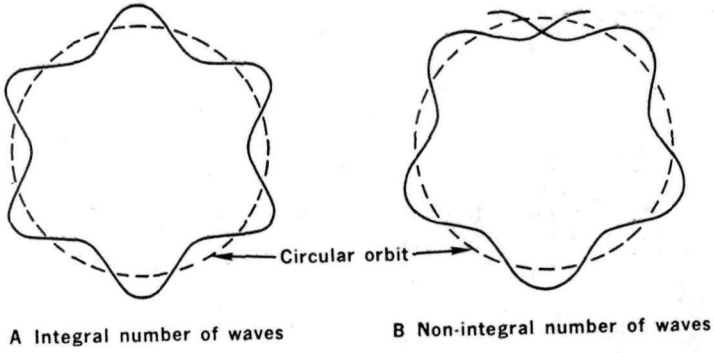
De Broglie pointed out a special property of these permitted orbits. He had suggested that every particle is accompanied by a wave of unspecified nature. The permitted Bohr orbits turned out to be orbits in tune with these hypothetical waves for electrons. Each time the electron in such an orbit completed the cycle, the wave associated with it was back in the phase in which it started.

It is a little like papering a room with patterned wallpaper; you may find by luck that the pattern joins up nicely when you have finished (although more likely it will not). According to de Broglie's view, Bohr's stable orbits did just this! De Broglie's original theory was somewhat sketchy and of limited use. Erwin Schrodinger, an Austrian physicist,

Erwin Schrödinger

put it into more precise mathematical terms and showed that it not only explained many facts in the spectroscopy of atoms, as Bohr's theory had done, but also solved several other problems.

We shall return later to the arrangement of electrons in atoms. Now we will consider some of the consequences of de Broglie's theory for electrons and the insight that the behavior of the latter gives into the great paradox of radiation just described.



Permitted (A) and nonpermitted (B) Bohr orbits of the de Broglie theory.

To explain the 1925–1927 experiments on electron waves, which are described below, we must say something of the essential character of all waves—water, sound, light, or the de Broglie waves of electrons. These features are that (1) they can be transmitted for a long way unchanged except for a gradual decrease in intensity, and that (2) two waves of the same kind can interfere with one another.

One can regard the first of these as part of the definition of a wave. The second is a less obvious property.

Indeed the word "interference", which is commonly used, is something of a misnomer. "Superposition of effects", though a cumbrous phrase, better describes what is meant. Suppose two waves exist at the same time in the same medium, e.g., the waves on the surface of the sea due to two ships passing one another or the waves of sound in the air due to two whistles at some distance apart being blown at the same time. Each will produce a motion of the water or air, as the case may be, as though the other did not exist. But, and this is the essential point, in finding the combined effect, which is what you actually observe, you must remember that the motion of each part of the surface of the sea produced by each wave is sometimes up and sometimes down, and that in a sound wave the air at a particular place is compressed and rarified successively many times a second by each wave.

Now depending on where the two sources of waves are, and how long the waves are, a person watching (or listening if the waves are those of sound) at any particular place may find the separate effects of the two waves *adding* or he may find them *subtracting*. One wave may push the water up when the other pulls it down and *vice versa*, or they may both move it up and then down *together*. If both sets of waves are regular, having the same speed and the same

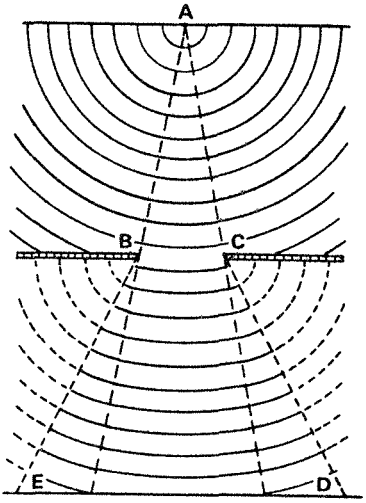
constant wavelength (see page 43), the pattern formed by the places where the waves *add* will be steady and so will the pattern of places where they *subtract*. The former is where the combined waves are strong, the latter where they are weak.

In general the two patterns are superposed to form a composite pattern of varying intensity. Interference is an appropriate name for the places where the waves subtract, less so for those where they add, but common usage applies it to both. Thus one wave can destroy the effect of the other, wave added to wave can produce calm, sound added to sound can produce silence, and light added to light can produce darkness. But in all these cases absence of effect in one place implies in others *greater* effect than one would have expected. The total energy of the waves is not altered by this process, merely concentrated into certain regions at the expense of others.

The addition and subtraction of waves can be readily demonstrated experimentally for water waves in a ripple tank. The effects were first shown for light by the English physicist Thomas Young, from whose London lectures, published in 1807, the figures on pages 52, 53, and 54 are taken. (Besides establishing the wave theory of light, he was also the first to decipher Egyptian hieroglyphics.)

When interference occurs from a large number of equally spaced slits, which form what is called a diffraction grating, the effects become sharper and brighter. Many spectroscopes use these ruled gratings instead of prisms.

Diffraction gratings had long been familiar in optics. A plane of a crystal is formed by a number of equally spaced parallel lines of atoms, each line being made up of atoms that are also equally spaced. (Often, but not always, the spacings of the lines and of the atoms in each line are the same.) A



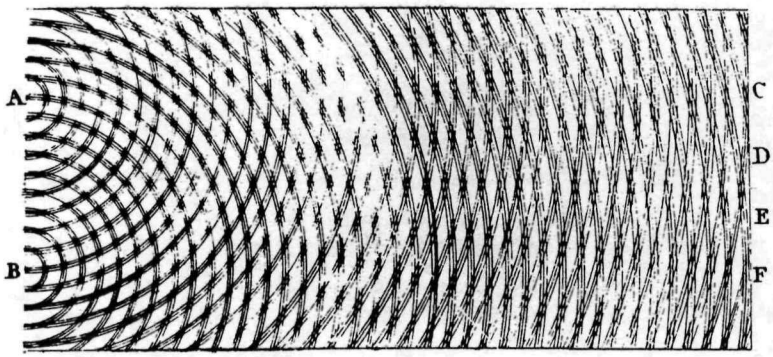
A water wave after going through a small gap, BC, spreads to each side and eventually its crests and troughs become circles centered somewhere between B and C. The spreading is called diffraction.

good model of this is a fine wire mesh or a finely woven piece of muslin.

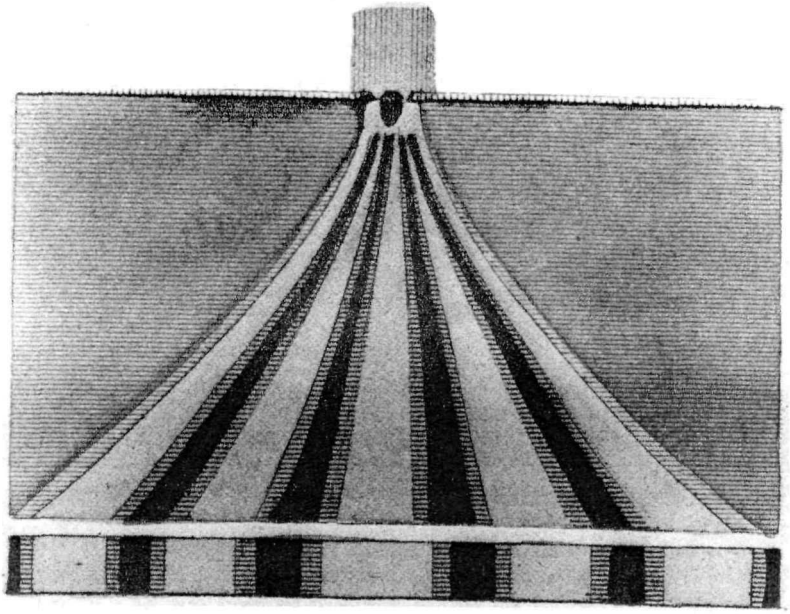
By 1925 the interference effects due to X rays scattered by the atoms of crystals (which by their regular arrangement form a kind of 3-dimensional grating) had been studied in a number of cases including simple metals. These effects were familiar both when the specimen was a single crystal, and in the more usual case when it was a large number of small crystals arranged more or less at random. (See the figure on page 62.)

Experiments of C. J. Davisson and L. H. Germer

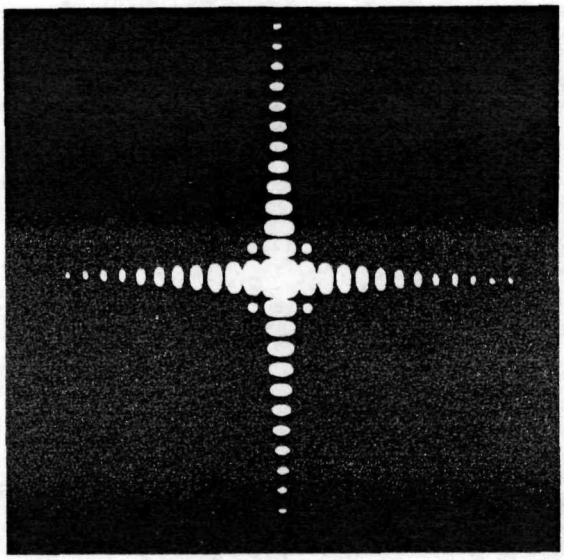
The experiments of Clinton J. Davisson and Lester H. Germer at the Bell Telephone Laboratory and of A. Reid and the author at the University of Aberdeen were attempts to



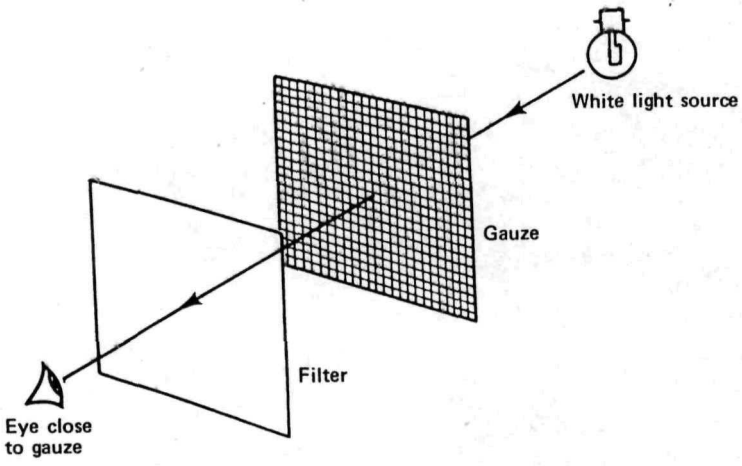
If a wave goes through two small holes fairly close together, each hole has its waves centering on it. These waves overlap and interfere and their effects add or subtract. At points such as D and E where the distance from A is half a wavelength more or less than to B, the waves will be just out of step and subtract. Midway between C and D and between E and F the distances from A and B differ by a whole wavelength and the waves are in step again so that they add. To see this, look along the length of the figure from left to right, your eye near the paper, and far enough from the righthand edge to focus it. You will see well-marked waves in directions halfway between C and D, D and E, and E and F, but towards C, D, E, F themselves there is only a blur and no well-defined lines. The waves are out of phase (out of step) in these directions.



This shows the same effect as the figure on page 53, but is a picture of an experiment with waves of light. The light that comes through the two narrow slits at the top spreads out and the two beams interfere to form regions of light and darkness. The bottom strip represents the appearance on a screen at right angles to the beam. The upper part is seen much foreshortened. The actual distance of the slits from the screen to give bands of the width shown would be about 20,000 times the distance between the slits. With slits 0.05 millimeter apart this makes 10 meters between slits and screen.



The lower drawing shows wire mesh acting as a two-dimensional grating. The filter is colored glass that transmits only light of approximately a single wavelength. The pattern seen by the eye, as shown in the top picture, is not a shadow of the mesh. The finer the mesh of the gauze, the more widely spaced are the spots.



Left to right, George P. Thomson, Louis Victor de Broglie, and C. J. Davisson.

press de Broglie's theory in a new direction. As noted earlier, this theory provided an interpretation of Bohr's somewhat arbitrary assumptions about electron orbits. It had also been developed mathematically in a novel and satisfactory way by Schrödinger. But nothing had been done with the waves that, if de Broglie was right, must accompany an electron moving freely in space. Surely they must *do* something. To a physicist waves require experiments in optics, for example, with diffraction gratings.

One thing was known about electron waves if they existed: The wavelength of de Broglie's theory had to be h divided by the momentum. This applies for *any* particle. It means that for electrons with 150 volts of energy (a reasonable figure for those in radio tubes of the period), the wavelength would be 10^{-8} cm—about the size of an atom. For 100 times the energy, i.e., 15,000 volts (in the region of cathode rays), the wavelength would be 1/10 the above (i.e., 10^{-9} cm).

Davisson had been working for some years with the "scattering" of electrons (in the 100-volt range) from metals, especially nickel and platinum. The results were not at first terribly exciting although it seemed that they might throw light on the arrangement of electrons in the metal atoms.

In April 1925 a famous accident* occurred with the nickel target, and Davisson described it as follows:

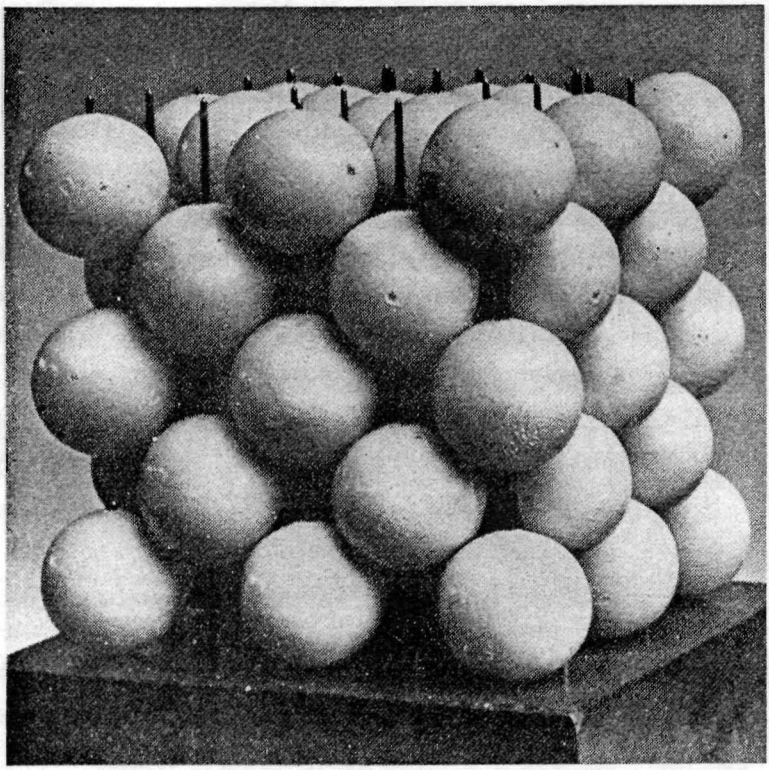
> During the course of his [Germer's] work, a liquid-air bottle exploded at a time when the target was at a high temperature; the experimental tube was broken, and the target heavily oxidized by the in-rushing air. The oxide was eventually reduced and a layer of the target removed by vaporization, but only after prolonged heating at various high temperatures in hydrogen and in vacuum. When the experiments were continued it was found that the distribution-in-angle of the scattered electrons had been completely changed. . . . This marked alteration in the scattering pattern was traced to a recrystallization of the target that occurred during the prolonged heating. Before the accident and in previous experiments we had been bombarding many small crystals, but in the tests subsequent to the accident we were bombarding only a few large ones. The actual number was of the order of ten.

*The physicist P. M. S. Blackett once remarked, "May every young scientist remember . . . and not fail to keep his eyes open for the possibility that an irritating failure of his apparatus to give consistent results may once or twice in a lifetime conceal an important discovery."

While meditating on these strange new results, Davisson attended the meeting of the British Association for the Advancement of Science held in 1926 in Oxford. He showed his results to various physicists there, and there was a good deal of talk of the work of de Broglie and Schrödinger. He records that he studied the latter's papers on his way home. Then he calculated the directions in which beams of electrons should appear if they behaved like waves of light reflected from a diffraction grating, which was made up of the atoms in the top layer of the nickel crystal. He looked for them and failed to find them. He looked again more systematically and he found them!

By April 1927 Davisson and Germer had enough to report and in December published their full paper. Because they knew how the atoms in the top layer of the nickel crystal were arranged, it was a simple calculation to show where the beams ought to be if due to a diffraction grating formed by this top layer. They agreed excellently, although there was no adjustable constant to play with. Actually things were rather more complicated; the electrons do in fact penetrate more than one layer of atoms. Theory shows that, unless the wavelength is chosen just right, the effect of under layers may weaken or destroy beams that would otherwise appear. Such effects were observed, though with a slight modification in the apparent spacing of the two layers.

These experiments were triumphant examples of superb experimental skill. Electrons of only about 150 volts are easily deflected, and a very high vacuum, unequaled at the time, was needed. Further, the exploration of the beams coming from the target at varying angles to the surface of the crystal, and also in different azimuths (directions in space), required complicated motions of parts of the apparatus during the experiment without spoiling the vacuum.

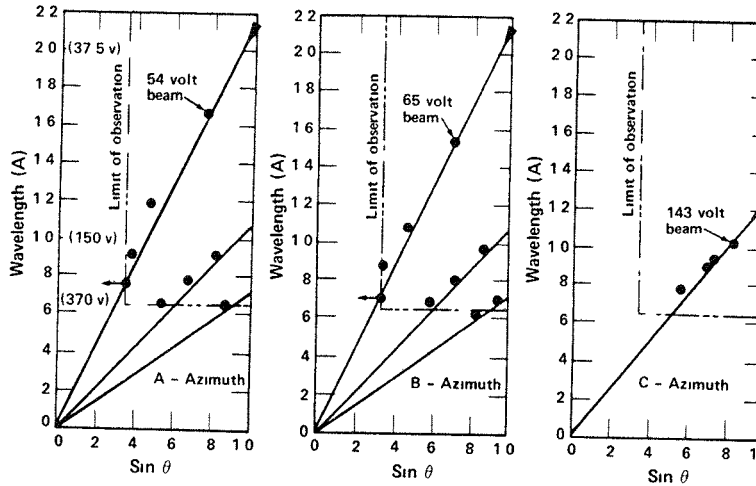


Cubic packing of certain metallic atoms, such as aluminum, nickel, copper, and gold.

The experiments revealed that electrons, admittedly particles, appeared precisely where they would have had they been waves of the length predicted by de Broglie. The particles had wave properties; waves of light, inversely, had already been shown to act like particles.

G. P. Thomson's Experiments

I also attended the meetings at Oxford, although I don't remember meeting Davisson. I had been much interested in



Some of Davisson's results for three directions of measurement (azimuths). Some electrons were received by the container at all settings but far more at certain settings (especially when the container was in one of the symmetrical azimuths A, B, or C). The points on the diagrams show the sine of the angle between the incident and reflected electron beams and the corresponding wavelength of the electron waves. According to de Broglie, the wavelength is equal to Planck's constant divided by the momentum or h/mv. The straight lines are calculated from the spacings known from the X-ray work. The points for electrons lie on them with remarkable agreement.

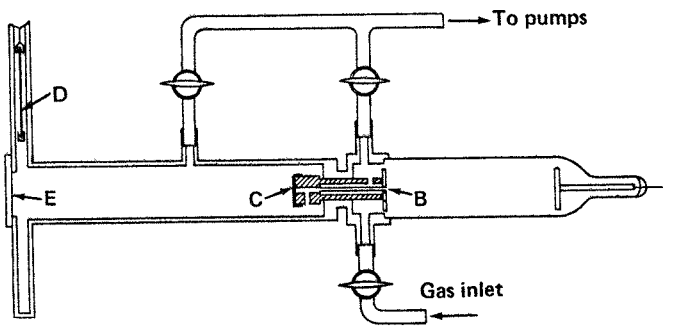
de Broglie's work and was excited by the talk I heard about it. I also decided to repeat an optical experiment with electrons.

The one I chose first was one of Young's, which I had done as a class experiment when a student. Haloes round the sun or moon are due to diffraction by water drops of nearly

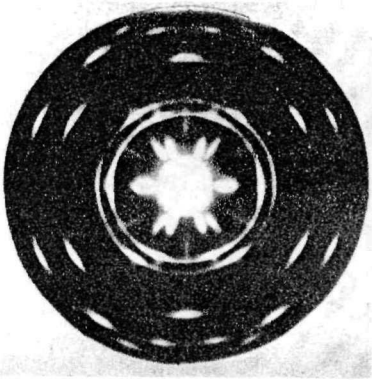
constant size—the size of the halo depending on that of the drop. The same effect can be obtained in a laboratory by means of certain small seeds; and Young showed that it would also work with threads of cotton of the same thickness, and could be used to measure their thickness. Celluloid, an early kind of plastic, was almost certainly composed of long molecules, and in a thin film might be expected to act towards electrons as Young's thread did towards light.

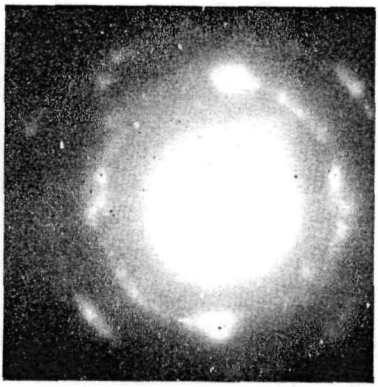
As it happened, one of the research students in Aberdeen, A. Reid, was using an apparatus that could be readily adapted. Using cathode rays of around 20,000-volts energy, Reid got some haloes.

At first they were indistinct, and we hesitated to publish. Gradually we got better ones and published the results a few



Early electron diffraction camera for transmission. Rays from the cathode at the right go through a fine tube at B and pass through the specimen at C. They then strike the fluorescent screen at E where the pattern is observed. By lowering the photographic plate D in front of E a permanent record is obtained.



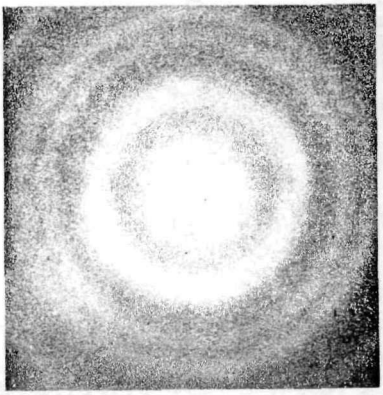


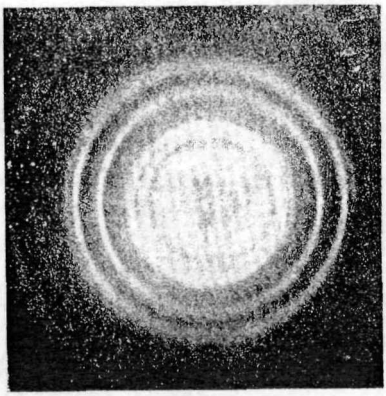
Patterns obtained by X rays (above) and by electron diffraction (opposite page). Both show specimens of aluminum and of gold. In these metals the atoms are arranged in the same way, namely like cannon balls in a pile. The patterns obtained by either X rays or electrons differ for two reasons: The difference in size of the atoms and in the arrangement of crystals in the specimen. If the specimen contains many tiny

months after Davisson's first paper. The sizes of the haloes varied with the energy of the rays (as they should) and were about the right size for a long organic molecule, but the structure of celluloid was not then precisely known. However, the structure of ordinary metals was well known from work on X rays, so it seemed obvious to us to use them.

There was only one serious difficulty: Electrons of the voltages available have little penetrating power and are scattered strongly, especially by heavy atoms. Using commercial gold and aluminum leaf, we got only blurred images. It was necessary to thin them down.

This is a difficult process, and I owe the success of the early experiments to the skill of the late C. G. Fraser, chief mechanic of the laboratory. Using caustic potash for the aluminum and aqua regia for the gold, and working under a





crystals arranged at random, the pattern will be one of concentric circles with radii in the proportion of certain square roots. If there are only a few crystals in the specimen the rings are replaced by spots that depend on what crystals happen to be present, but every spot should lie on one of the permitted circles.

microscope, he was able to thin pieces of foil, stopping just before they completely disappeared. His resulting specimens must have been about 100 atoms thick. With these I got patterns made by electrons that had passed through the specimen and had struck a photographic plate 32.5 cm behind the specimen.

These patterns were identical, except in size, with those already obtained with X rays by earlier workers using much thicker specimens. The patterns shown in the figure are complicated but reproduce those obtained with X rays in great detail. Further, the size varied with the voltage as it should in accordance with de Broglie's law of wavelength, and varied as expected with the distance from specimen to plate. In fact the whole pattern came out as predicted without any adjustment.

The conclusions as to the wavelike behavior of electrons were valid. The only objection anyone raised was a suggestion that the patterns were somehow produced by X rays. Apart from the absence of X rays, this objection was disproved by showing that the whole pattern could be shifted undistorted by a magnetic field, as electrons should be and as X rays of course should not.

This method is technically much easier than that of Davisson. Because the cathode rays are less affected by gas than the slow electrons he used, it is not necessary to be so fussy about the vacuum. The technique has been used extensively to study the structure of surface layers, which are too thin to be easily detectable by X rays, and also of surface films.

George P. Thomson

Particles and Waves

Thus the photoelectric paradox was "explained" by showing that it is not unique to electromagnetic radiation (in radio waves, heat waves, light waves, or X rays), but applies also to electrons and, as was soon recognized, to any kind of particle.

In fact, what was wrong was that we had held too narrow a view of a particle. Each particle is associated with a wave whose wavelength is h/momentum. Because h is a very small quantity, the wave is usually too short to be detected as such. It had been known both in theory and practice that waves, whose lengths are very small compared with the dimensions of the experiment, act like particles. Thus very short sound waves, i.e., very high notes, are cut off sharply by a moderate obstacle, which casts a sharp shadow, while lower pitched notes go past with little loss.

Every wave can be associated with a particle, and every particle with a wave. In some cases the particle aspect predominates, in others the wave aspect does. Among electromagnetic waves it would be very difficult to detect the individual particles (photons) from a station broadcasting on 300 meters. On the other hand, it is not easy to detect wave properties in the X rays of very short wavelength from a target struck by electrons of many millions of volts of energy.

Complementarity and the Uncertainty Principle

It was Niels Bohr who first clearly stated an idea that he called "complementarity", and showed how it overcomes the apparent impossibility of something being both wave and particle. It is *not* a logical contradiction. The meaning of the statement "cathode rays are particles" is that experiments meant to detect particles will find particles. On the other

hand "cathode rays are waves" means that experiments meant to find waves will find waves.

Now what kind of experiments are needed in the two cases? If you try to devise them you will find that experiments to detect and measure *waves* need cathode rays in the apparatus over relatively large intervals of time and space while those to detect *particles* (for example, to count them) must be fast acting and confine the particles to a limited region.

If we wish to prove that light or electrons are waves, a space must be used which will contain many waves. For example, in the experiment with gold foil described above the patterns get fuzzy if the crystals are so small that they are only a few atoms thick. If the area of the crystal or of the cross-section of the beam is restricted too much, the sharp patterns that prove that the electrons are behaving like waves would not be seen. The characteristic of a particle is that it is only in one place at one time. If the electron is allowed to be anywhere in a fair-sized crystal during the experiment, it could not be called a particle and it would not be surprising if it behaved like a wave.

Conversely, fast electrons in a Wilson chamber leave ions along their tracks, which need only be as wide as the gas molecules they ionize. Here the electrons behave like particles with no obvious wave properties. They move in continuous paths. Further, the collisions they make that produce the ions around which the water droplets form show particle-like behavior. Thus the energy required to ionize the molecules of the gas comes from the motion of the electron, which is slowed down by the ionizing collision. If a collision, as sometimes happens, deflects the electron strongly in one direction, the molecule, or part of it, is shot off in the opposite direction by the recoil. Newton's law of action and reaction thus remains true.

A somewhat different way of looking at complementarity is due to the German mathematical-physicist Werner Heisenberg. He proved by detailed arguments that it is not possible to know the position *and* momentum of a particle at the same time. To determine the position one could theoretically use radiations of short wavelength and then observe the particle in a microscope (although no such powerful tool exists). However, if this were done, the radiations would disturb the momentum. Conversely, a diffraction grating could be used to measure the electron's wavelength and then the momentum could be calculated.

But when an electron is diffracted its direction is changed and its position is no longer known. In other words the means of observing particles of atomic dimensions would disturb the motions of the particles. An example of this is the Heisenberg Uncertainty Principle.

A cathode ray is both a wave and a particle, and it can be shown to behave as either, but the experiment that proves it a wave cannot show it as a particle and vice versa. When we wish to know the position of an electron it is observed as a particle, but when the momentum is desired it is studied as a wave.

Bohr's theory of complementarity is often likened to a coin. Both sides of a coin exist equally—one impossible without the other. But if you look at one the other eludes you.

The electron and photon are not unique as particles with observable waves. Waves have been detected that are associated with protons and neutrons and even with helium atoms and, by indirect inference, with other "particles". It is generally agreed that this is part of the behavior of all particles and even of groups of particles, but the difficulties of detection increase rapidly with increasing mass.

ELECTRONS IN ATOMS AND SOLIDS

Most of this booklet has been devoted to free electrons, which show clearly the nature of electrons and which have contributed much to the understanding of the hidden depths of nature. But the vast majority of electrons in the universe are attached to individual atoms, and most of the rest are held in metals.

In 1911, Rutherford had suggested that each atom has a central nucleus with an integral charge of Z times the charge of an electron. The nucleus was positively charged, and so capable of neutralizing the negative charges of the electrons. The atomic number Z ranges from 1 for hydrogen to 92 for uranium among naturally occurring atoms; unstable atoms have been created with Z up to 105. Atoms with the same atomic number are isotopes of the same chemical element and have identical chemical properties, but not all have the same mass (see page 30).

Electronic Arrangement

The following problems were encountered in the search for the key to electronic arrangement: (1) How are the Z electrons arranged? (2) Are they at rest or in motion? (3) If the latter, how do they keep going forever with no obvious supply of energy? (4) Are they ever detached? (5) How do they account for the existence of chemical molecules, or don't they?

The answer to the first question is equivocal: they are not always in the same place, but their movement cannot be observed because of the Heisenberg Uncertainty Principle. It is possible to say, however, that some regions of an atom—those nearer the nucleus—are more densely populated by electrons than other regions.

Each electron has a particular wave form associated with it; two electrons usually "occupy" one wave, as will be explained in the next section. Each wave is identified by a group of three integers called "quantum numbers". These determine the regions in which the waves operate and their symmetry. The chance of an electron being found in a certain small region is proportional to the volume of the region and to the square of the average amplitude of the wave there. It is a general property of waves that the energy associated with them is proportional to the square of the amplitude, i.e., the maximum displacement from rest. For water waves this is the maximum distance of a particle above or below the undisturbed surface.

The quantum numbers are analogous to the number of segments in which a violin string vibrates when excited to a particular harmony, but the waves round the nucleus are in three dimensions.

According to a principle introduced by Bohr, an electron in an atom can only radiate energy by changing from one permitted (or quantized) state to another. Since no unoccupied quantized state of lower energy is available in a normal atom, the electrons continue forever in the states they occupy unless they obtain, in some manner, sufficient energy to permit them to escape.

Electrons in waves (or quantized states) near the nucleus usually require more energy to free them from it than those farther away, just as it takes more energy to bring up a stone from a deep hole than from a shallow one. Such electrons are often said to be in "deep levels". Electrons can be removed from an atom, which is then ionized, by collisions with other electrons of sufficient speed or by the photoelectric effect. In the latter case a quantum of radiation, for which $h\nu$ *exceeds* the energy required to remove the electron from the atom, is

absorbed. The balance of energy appears as kinetic energy of the freed electron.

Pauli's Exclusion Principle

The reason the electrons do not disappear into the nucleus (except in certain rare cases), but continue the unending dance of their waves, is that they have no means of getting rid of the energy they would gain if they approached the nucleus more closely. You may ask, "Why not radiate the energy?" (In fact a single atom, such as sodium, does just this when its outermost electron is excited by any means beyond its normal range of positions.) The answer is given in a very important rule discovered in 1925 and called Pauli's Exclusion Principle in honor of the Austrian physicist Wolfgang Pauli who proposed it.

This asserts that only *two* electrons can occupy a state (i.e., a set of waves) defined by one set of three quantum numbers. The electrons in the innermost levels thus exclude those farther out and prevent them from getting closer to the nucleus, as the attraction between the positive nucleus and the negative electron would otherwise make them do.

Why does Pauli's principle allow *two* electrons to each set of three quantum numbers? The reason is that even in its particle aspect the electron is not merely a point charge; it is also a tiny magnet because it behaves as if it were spinning like a top. The magnetic forces between two electrons are extremely small compared with the electric forces, and for most purposes can be ignored except in the case of "all-or-nothing" principles such as Pauli's. The magnetism affects the whole character of the waves. In consequence of this, any electronic wave can exist in two distinguishable forms corresponding to the two directions of all magnetic moments of the electron; in particle terms, these represent the electron spinning in opposite directions.

Outermost Electrons

Outside the levels normally occupied by electrons are empty levels defining waves of longer wavelength, corresponding to weaker binding energies. An outer electron may be driven to one of these levels, either by absorbing a photon of the right energy, by collision with a fast electron from outside, or even (if the extra energy required is not too large) by the collisions of atoms that occur in random heat motions. This can happen for example with sodium, which has one electron loosely attached, and is readily excited to a higher (normally empty) level. When the electron returns to its normal level and wave state, the typical yellow light of sodium is emitted.

The outer electrons account for the forces that hold atoms together in chemical compounds. The inert gases—helium, argon, etc.—which until recently were thought to form no compounds, are inert because even their outer electrons are tightly bound and difficult to displace.* The chemical action of one atom on another, which is governed by the interaction of the outer electrons of each, is a very difficult problem. It can be stated mathematically by the methods of the quantum mechanics, but can rarely be solved exactly. However, even rough approximations can give useful results that can be confirmed experimentally.

There are two main types of chemical compounds. In the first, one or more electrons are actually transferred from one atom (usually a metal) to others. Common salt is a case in point. Here the sodium loses its one lightly bound electron, which is absorbed into the wave pattern of the chlorine atom. Since one atom is missing an electron and the other has one too many, the positive charge of the first attracts the negative

*See *The Chemistry of the Noble Gases*, another booklet in this series.

charge of the second, and the atoms stick together. Substances that dissolve in water and then conduct electricity are of this class.

The second type of combination is more complex; it consists in the sharing of certain outer electrons between two adjacent atoms. This happens, for example, in the molecule of hydrogen where the two electrons form a pattern with the two protons (hydrogen nuclei). The German physicists W. Heitler and F. London in 1927 worked this out mathematically and so they may be said to have united chemistry with physics.

The modern science of theoretical chemistry has shown that similar ideas can be applied to a number of compounds.

Free Electrons in Metals

In most substances, each electron is associated with a particular atom or it may be shared between two adjacent atoms, as mentioned above. In metals, however, some of the outer electrons appear not to be attached to any particular atom but are shared by all the atoms. These electrons are sometimes referred to as "free" electrons although they are not completely free. In terms of the wave character of electrons, we may say that the free electrons have stationary waves that vibrate in the "box" formed by the piece of metal, much as the waves of the other electrons do in "boxes" formed by the attractions of the positive nuclei of the individual metal atoms. As a rough approximation, one can neglect the atoms in a piece of metal except for the fact that the positive charges of their nuclei neutralize the negative charges of the electrons and hold the piece together.

The presence of the free electrons explains why metals are good conductors of electricity. If an electric field is applied to a metal wire, by connecting the ends to the poles

of a battery, the free electron waves moving in one direction are helped whereas those going in the other direction are hindered. There is thus a net flow of current in the direction of the applied field. In nonmetals, there are usually no free electrons available so they do not conduct electricity well.

The so-called free electrons are thought to be the electrons that are released from metals by the photoelectric and thermionic effects. The mechanisms of these effects are quite complicated, so that we can give only a simplified explanation of them. In the photoelectric effect, a light photon provides a free electron with sufficient energy to permit it to escape from the electrical attraction of the positively charged atomic nuclei in the metal. In thermionic emission, the free electrons acquire the necessary energy in a different way. As the temperature of the metal is raised, the speed (and kinetic energy) of the free electrons increases. Some electrons are thus able to escape from the surface of the metal in much the same way as molecules escape from a heated liquid by evaporation.

Wolfgang Pauli lecturing in Copenhagen in April 1929.

Since light and electrons are both particles with wave properties (or "wavicles" as the English physicist Sir Arthur Eddington used to call them), it is reasonable to hope that electrons might replace light in microscopes. There was a need to improve the limit of useful magnification in microscopes, which was set by the wavelengths of light waves. In fact, light cannot distinguish (or resolve) detail finer than about a third of a wavelength, about 1500 A for ordinary light and 1000 A for ultraviolet. These wavelengths correspond to useful magnifications of about 1500 and 2000, respectively. More magnification simply blurs the image.

Now the wavelength of 15,000-volt electrons is 10^{-9} cm, about 30,000 times shorter than ultraviolet. So there is a lot to be gained.

Electrons can be deflected both by electric and magnetic fields; lenses can be made from either type of field to focus them. In fact, coils of wire forming magnetic lenses were used to concentrate the beam of a cathode-ray oscillograph before the wave nature of electrons was understood, but no attempt was made to "see" things.

Very soon after the proof of the wave character of electrons, attempts were made to design an electron microscope. Progress has been rapid. Electron microscopes are widely used both in industry and in many scientific research fields, especially in biology and in the study of metals. One disadvantage is that the specimen has to be in a vacuum.

Magnetic lenses are now used almost exclusively. The action of a typical magnetic lens is shown in the figure. The construction of an electron microscope is remarkably like that of an ordinary optical microscope, and the path of the rays is very similar. Electrons from a hot wire are accelerated through a small hole by a voltage of perhaps 50,000 to

100,000 volts and concentrated on the specimen by a lens, which corresponds to the condenser of an optical microscope.

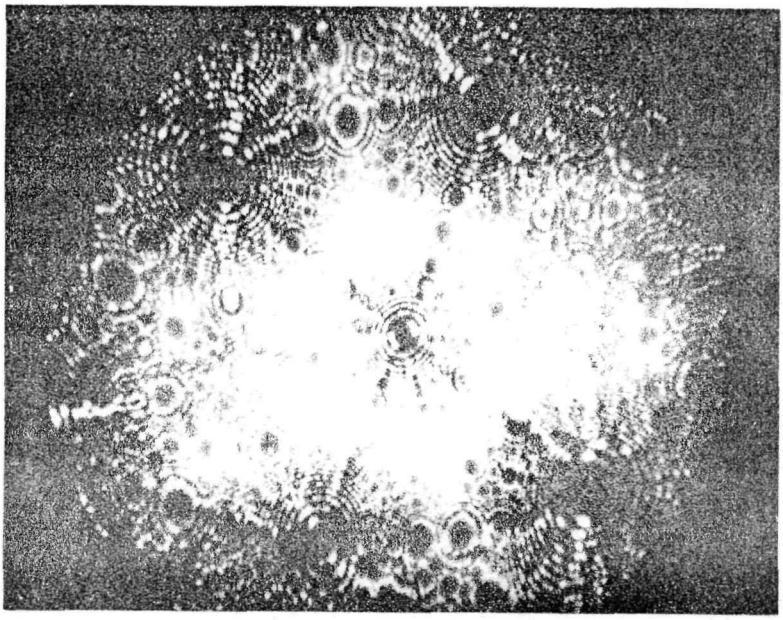
The electrons scattered from the specimen go through a short-focus lens, like the optical objective, which may magnify about 100 times, and then through a projection lens, which focuses this first image on a fluorescent screen. In most modern microscopes both the condenser lens and the projection lens are double.

The first of the projection lenses forms an image with a magnification of about 20, which can be varied. Then the electrons are focussed by another projection lens onto the screen. The resulting image may have a magnification of up to 100,000 (or more) compared with the specimen.

The actual limits of the electron microscope come not from the wavelength of the electrons, which can be made very small indeed, but from the imperfections of the lenses, especially spherical aberration. This occurs with glass lenses and ordinary light. It simply means that rays of light, all parallel to the axis of a lens, do not go through the focus (as they should) when they come out. For a single lens, the marginal rays cross the axis closer to the lens than the central ray. The designers of optical instruments have developed ways of minimizing the blurring effect of spherical and other aberrations. Though the mathematics of electron lenses is different, the general behavior is the same as for glass lenses.

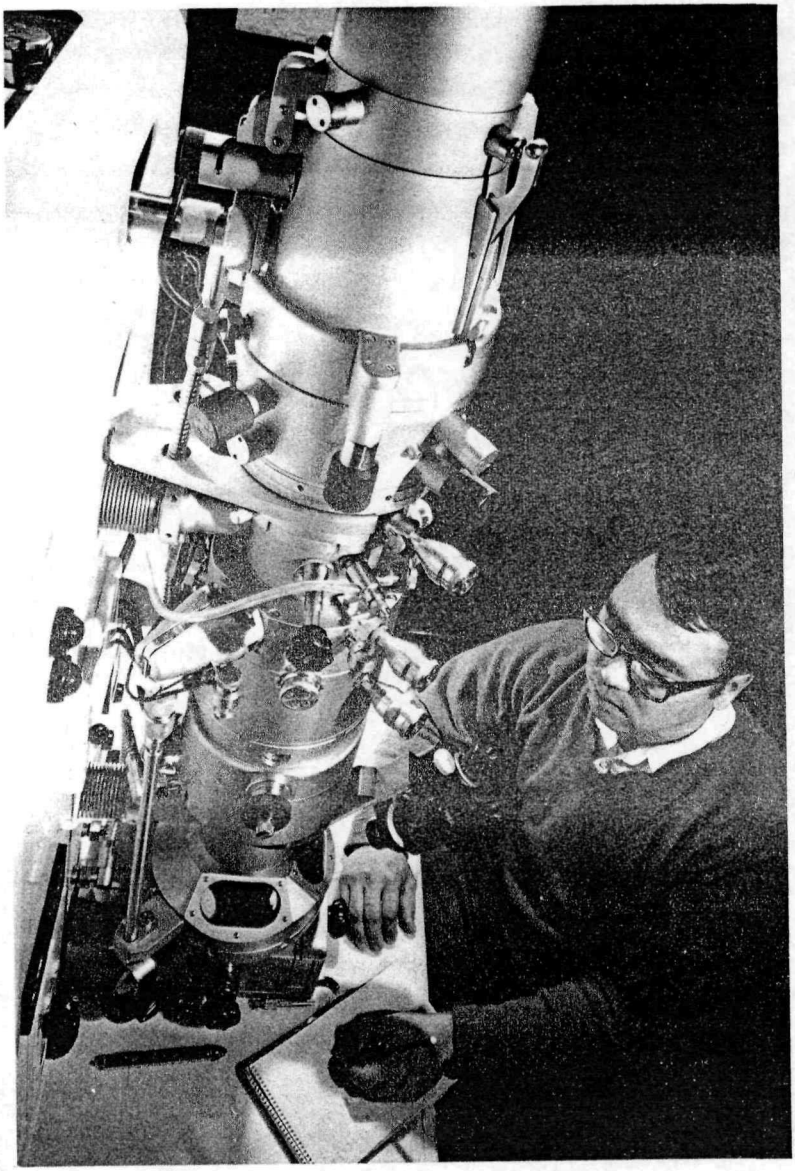
The simplest way of reducing spherical aberration is to use a very narrow beam of rays making only a small angle with the axis. Unfortunately this spoils the resolving power, which is only as good as a third of the wavelength if a beam of very wide angle is used. No one so far has been able to get over this difficulty.

A compromise angle of about ½° is chosen so that the fuzziness due to aberration is about equal to that due to the wave effect. In consequence, a resolving power of 5 A is about the best one can achieve in normal practice. Atoms in solids are about 2 or 3 A apart and cannot actually be seen separately with this kind of microscope. The figure shows the best done so far.



Field emission microscope photograph obtained using sharp tungsten point as specimen and helium atoms as recorders. These are ionized on the sharpest projections on the point and then repelled by the electric field to the fluorescent screen. The smallest bright spots correspond to individual tungsten atoms.

There is another type of instrument, called the field emission microscope, in which a sharp point emits electrons under a very strong electric field in a high vacuum. There are



A modern electron microscope.

no lenses. The electrons move in straight lines spreading from the point until they reach a fluorescent screen, which is the inside of a sphere with its center at the point. If some of the atoms of the point emit electrons more easily than the rest, they will show up as bright spots. Unfortunately only a few metals will serve as points, and it is not yet possible to examine many interesting specimens.

In a modified form of the field emission microscope, the direction of the electric field is reversed. Instead of electrons being drawn *out of* the metal point, they are drawn *into it* from helium atoms in the surrounding low-pressure gas. The helium ions that remain are then repelled by the electric field and they form a pattern on a fluorescent screen, as shown in the photograph.

J. J. Thomson and Ernest Rutherford in the 1930s.

EPILOGUE: THE ELECTRONIC REVOLUTION*
by Arthur Clarke

We started to use the electron fifty years before we discovered it. The first practical application of electricity (which is nothing more than the ordered movement of electrons) began with the introduction of the telegraph in the 1840's. With really astonishing speed, a copper cobweb of wires and cables spread across the face of the world, and the abolition of distance had begun. For over a century we have taken the instantaneous transfer of news completely for granted; it is very hard to believe that when Lincoln was born, communications were little faster than in the days of Julius Caesar.

Although the beginning of "electronics" is usually dated around the 1920's, this represents a myopic view of technology. With the hindsight of historical perspective, we can now see that the telegraph and the telephone are the first two landmarks of the electronic age. After Alexander Graham Bell had sent his voice from one room to another in 1876, society could never be the same again. For the telephone was the first electronic device to enter the home and to affect directly the lives of ordinary men and women, giving them the almost godlike power of projecting their personalities and thoughts from point to point with the speed of lightning.

Until the closing years of the nineteenth century, men used and handled electricity without knowing what it was, but in the 1890's they began to investigate its fundamental nature, by observing what happened when an electric current was passed through gases at very low pressures. One of the

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first, and most dramatic, results of this work was the invention of the X-ray tube, which may be regarded as the ancestor of all the millions of vacuum tubes which followed it. A cynic might also argue that it is the only electronic device wholly beneficial to mankind—though when it was invented many terrified spinsters, misunderstanding its powers, denounced poor Rontgen as a violator of privacy.

There is an important lesson to be learned from the X-ray tube. If a scientist of the late Victorian era had been asked "In what way could money best be spent to further the progress of medicine?" he would never by any stretch of the imagination have replied: "By encouraging research on the conduction of electricity through rarefied gases." Yet that is what would have been the right answer, for until the discovery of X rays doctors and surgeons were like blind men, groping in the dark. One can never predict the outcome of fundamental scientific research, or guess what remote and unexpected fields of knowledge it will illuminate.

X rays were discovered in 1895—the electron itself just two years later. It was then realized that an electric current consists of myriads of these submicroscopic particles, each carrying a minute negative charge. When a current flows through a solid conductor such as a piece of copper wire, we may imagine the electrons creeping like grains of sand through the interstices between the (relatively) boulder-sized copper atoms. Any individual electron does not move very far, or very fast, but it jostles its neighbor and so the impulse travels down the line at speeds of thousands of miles a second. Thus when we switch on a light, or send a Morse dash across a transatlantic cable, the response at the other end is virtually instantaneous.

But electrons can also travel *without* wires to guide them, when they shoot across the empty space of a vacuum tube like a hail of machine-gun bullets. Under these conditions, no

longer entangled in solid matter, they are very sensitive to the pull and tug of electric fields, and as a result can be used to amplify faint signals. You demonstrate the principle involved every time you hold a hose-pipe in your hand; the slightest movement of your wrist produces a much greater effect at the far end of the jet. Something rather similar happens to the beam of electrons crossing the space in a vacuum tube; they can thus multiply a millionfold the feeble impulses picked up by a radio antenna, or paint a fluorescent picture on the end of a television screen.

Until 1948, electronics was almost synonymous with the vacuum tube. The entire development of radio, talkies, radar, television, long-distance telephony, up to that date depended upon little glass bottles containing intricate structures of wire and mica. By the late 1940's the vacuum tube had shrunk from an object as large as (and sometimes almost as luminous as) an electric light bulb, to a cylinder not much bigger than a man's thumb. Then three scientists at the Bell Telephone Laboratories invented the transistor and we moved from the Paleoelectronic to the Neoelectronic Age.

Though the transistor is so small—its heart is a piece of crystal about the size of a rice grain—it does everything that a radio tube can do. However, it requires only a fraction of the power and space, and is potentially much more reliable. Indeed, it is hard to see how a properly designed transistor can ever wear out; think of little Vanguard I, still beeping away up there in space, and liable to continue indefinitely until some exasperated astronaut scoops it up with a butterfly net.

The transistor is of such overwhelming importance because it (and its still smaller successors) makes practical hundreds of electronic devices which were previously too bulky, too expensive or too unreliable for everyday use. The pocket radio is a notorious example; whether we like it or

not, it points the way inevitably to a day when person-to-person communication is universal. Then everyone in the world will have his individual telephone number, perhaps given to him at birth and serving all the other needs of an increasingly complex society (driving license, social security, credit card, permit to have additional children, etc.). You may not know where on Earth your friend Joe Smith may be at any particular moment; but you will be able to dial him instantly—if only you can remember whether his number is 8296765043 or 8296756043.

Obviously, there are both advantages and disadvantages in such a "personalized" communication system; the solitude which we all need at some time in our lives will join the vanished silences of the pre-jet age. Against this, there is no other way in which a really well-informed *and* fast-reacting democratic society can be achieved on the original Greek plan—with direct participation of every citizen in the affairs of the state. The organization of such a society, with feedback in both directions from the humblest citizen to the President of the World, is a fascinating exercise in political planning. As usual, it is an exercise that will not be completed by the time we need the answers.

A really efficient and universal communications system, giving high-quality reception on all bands between all points on the Earth, can be achieved only with the aid of satellites. As they come into general use, providing enormous information-handling capacity on a global basis, today's patterns of business, education, entertainment, international affairs will change out of all recognition. Men will be able to meet face to face (individually, or in groups) without ever leaving their homes, by means of closed circuit television. As a result of this, the enormous amount of commuting and traveling that now takes place from home to office, from ministry to United Nations, from university to conference

hall will steadily decrease. There are administrators, scientists and businessmen today who spend about a third of their working lives either traveling or preparing to travel. Much of this is stimulating, but most of it is unnecessary and exhausting.

The improvement of communications will also render obsolete the city's historic role as a meeting place for minds and a center of social intercourse. This is just as well anyway, since within another generation most of our cities will be strangled to death by their own traffic.

But though electronics will ultimately separate men from their jobs, so that (thanks to remote manipulation devices) not even a brain surgeon need be within five thousand miles of his patient, it must also be recognized that few of today's jobs will survive long into the electronic age. It is now a cliché that we are entering the Second Industrial Revolution, which involves the mechanization not of energy, but of thought. Like all clichés this is so true that we seldom stop to analyze what it means.

It means nothing less than this: There are no routine, non-creative activities of the human mind which cannot be carried out by suitably designed machines. The development of computers to supervise industrial processes, commercial transactions and even military operations has demonstrated this beyond doubt. Yet today's computers are morons compared to those that they themselves are now helping to design.

I would not care to predict how many of today's professions will survive a hundred years from now. What happened to the buggywhip makers, the crossing sweepers, the scriveners, the stonebreakers of yesteryear? (I mention the last because I can just remember them, hammering away at piles of rock in the country lanes of my childhood.) Most

of our present occupations will follow these into oblivion, as the transistor inherits the earth.

For as computers become smaller, cheaper and more reliable they will move into every field of human activity. Today they are in the office; tomorrow they will be in the home. Indeed, some very simple-minded computers already do our household chores; the device that programs a washing machine to perform a certain sequence of operations is a specialized mechanical brain. Less specialized ones would be able to carry out almost all the routine operations in a suitably designed house.

Because we have so many more pressing problems on our hands, only the science-fiction writers—those trail-blazers of the future—have given much thought to the social life of the later electronic age. How will our descendants be educated for leisure, when the working week is only a few hours? We have already seen, on a worldwide scale, the cancerous growths resulting from idleness and lack of usable skills. At every street corner in a great city you will find lounging groups of leather-jacketed, general-purpose bioelectric computers of a performance it will take us centuries and trillions of dollars to match. What is their future —and ours?

More than half a century ago H. G. Wells described, in *The Time Machine,* a world of decadent pleasure lovers, bereft of goals and ambitions, sustained by subterranean machines. He set his fantasy eight hundred thousand years in the future, but we may reach a similar state of affairs within a dozen generations. No one who contemplates the rising curve of technology from the Pilgrim fathers to the Apollo Project dare deny that this is not merely possible, but probable.

For most of history, men have been producers; in a very few centuries, they will have to switch to the role of

consumers, devoting their energies 100 per cent to absorbing the astronomical output of the automated mines, farms and factories.

Does this *really* matter, since only a tiny fraction of the human race has ever contributed to artistic creation, scientific discovery or philosophical thought, which in the long run are the only significant activities of mankind? Archimedes and Aristotle, one cannot help thinking, would still have left their marks on history even if they had lived in a society based on robots instead of human slaves. In any culture, they would be consumers of goods, but producers of thought.

We should not take too much comfort from this. The electronic computers of today are like the subhuman primates of ten million years ago, who could have given any visiting Martians only the faintest hints of their potentialities, which included the above mentioned Archimedes and Aristotle. Evolution is swifter now; electronic intelligence is only decades, not millions of years, ahead.

And *that*—not transistor radios, automatic homes, global TV—is the ultimate goal of the Electronic Revolution. Whether we like it or not, we are on a road where there is no turning back; and waiting at its end are our successors.

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