ELECTRICITY AND MAGNETISM

BY

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PREFACE

THIS text-book forms one volume of the Intermediate Science Series. It is one of four books intended to meet the requirements of the Intermediate examination in Physics and the Advanced level examination in Physics of the General Certificate of Education. It will also prove useful to students who are reading for University Scholarship examinations. Students taking a course for the Ordinary National Certificate in Applied Physics will find that the standard reached in the book goes somewhat beyond that needed for the Ordinary level examination.

An inspection of the contents page will show the order of treatment that has been adopted. The aim has been to start with the study of current electricity and to defer the consideration of electrostatics and magnetometry—which are often treated first—until later in the book. Chapters I and II are therefore introductory in character; their purpose is to acquaint the reader with certain concepts—such as those of charge, electric and magnetic field strength, and electric potential—which are needed in the development of the theory of current electricity contained in Chapters III to X. The succeeding five chapters (XI to XV) deal with electrostatics, the magnetic properties of materials, magnetometry and thermoelectricity.

Chapter XVI considers the units and dimensions of electrical quantities; it also contains an introduction to the rationalized m.k.s. system of units. At the time of writing, a knowledge of this system is not required by the examining bodies; nevertheless, a book of this standard would be incomplete without some reference to a system which has already been adopted internationally for use by electrical engineers. Moreover, it has such undoubted advantages over the older systems that its use is likely to become increasingly widespread. It should be pointed out that the treatment given in Chapter XVI has been designed to follow the order of development of the older systems given in this text-book. It is not necessarily the best treatment when the rationalized m.k.s. system is to be used *ab initio* in the teaching of electricity.

Finally, Chapters XVII and XVIII give a brief survey of our knowledge of atomic physics and describe some applications of electronic valves and cathode-ray tubes.

Figures are numbered consecutively throughout the book; equations throughout each chapter. Numerical references to equations refer to the chapter in question, unless a page reference is also given.

The writing of this book was undertaken as a result of a suggestion from my chief, MR. F. Y. POYNTON, M.SC., F.INST.P.; I am grateful to him for his encouragement and interest. I must acknowledge my indebtedness to my former colleague, the late P. PARKER, M.SC., for many stimulating discussions during the earlier stages of the preparation of the manuscript. I wish to express my gratitude to my colleague, C. A. PADGHAM, PH.D., for reading and criticizing the manuscript; also to A. WALSH, B.SC., for preparing the material for certain of the diagrams, and to D. WARBURTON for help with the checking of the proofs. Finally, my thanks are due to my wife for the many hours that she has spent in the production of the typescript.

Many of the examples at the ends of the chapters have been taken from papers set by the examining bodies listed below. I am grateful for their permission to reprint the questions.

London University (L.U. Inter. and L.H.S.C.)
Northern Universities Joint Matriculation Board (N.U.J.B.)
Oxford and Cambridge Schools Examination Board (O. & C.)

I wish to thank also Cambridge University Press for their kind permission to reprint questions from Entrance Scholarship examinations at Colleges of Cambridge University (C.S.).

The sources of the questions used in the book are indicated by the letters in brackets.

J. N.

INTERMEDIATE SCIENCE SERIES
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ELECTRICITY AND MAGNETISM

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CHAPTER I

INTRODUCTION TO ELECTROSTATICS

THE scientific study of Electricity and Magnetism is of relatively recent origin. The majority of the experimental facts have been discovered and the modern theories concerning the nature of electricity and matter have been developed during the last two hundred years. Nevertheless, it is probably true to say that the study of this branch of physics has had a greater effect on our everyday life than have the discoveries which have been made in any other branch of science in a comparable period.

We are all so familiar with the many applications of electricity in the fields of electrical power, illumination, transport, communication, television, etc. that it is difficult for us to realize the enormous number of fundamental discoveries which had to be made before these applications became possible. One of the most far-reaching of these was the discovery of the primary cell or battery by VOLTA (1745–1827) which started the study of current electricity. This was followed by the work of OERSTED (1777–1851) and of AMPÈRE (1775–1836) on the magnetic effect of an electric current. Their discoveries showed that electricity and magnetism are closely related to one another; this relation forms the basis of many electrical measuring instruments and of the electric motor. FARADAY (1791–1867) carried out a long series of researches on many aspects of electricity and magnetism; his greatest contribution was probably the discovery of electromagnetic induction, since the large-scale generation of electrical power depends on this phenomenon.

We nowadays take for granted the existence of broadcasting, television, the sound film and long-distance telephony. All these make use of devices, such as radio valves, cathode-ray tubes and photo-electric cells, which depend for their action on the motion of minute negatively-charged particles through a vacuum or through a gas at low pressure. These particles are called electrons; their existence was confirmed by SIR J. J. THOMSON (1856–1940) as recently as 1897. This discovery may be said to be the starting point of the branch of science known as atomic physics, the study of which has revolutionized our ideas about the nature of matter. In addition, it has led to the invention of the electronic devices mentioned above.

It is our purpose in the following pages to describe the phenomena, and build up a consistent theory, of electricity and magnetism. We shall start our discussion with introductory considerations of static electricity and permanent magnetism.

EXPERIMENTAL PHENOMENA

Since the earliest studies of electricity were concerned with the properties of certain bodies after they had been rubbed with other materials, we shall describe first some of these early experiments. This branch of electricity is called electrostatics because it is concerned with the properties of electric charges at rest.

Frictional Electricity

The discovery that amber rubbed with fur acquires the property of attracting light objects is attributed to the Greeks (about 600 B.C.); in fact, the word "electricity" is derived from the Greek name for amber, *ηλεκτρον* (pronounced "electron"). The amber is said to be "electrified"; that is, it possesses a charge of electricity. No attempt appears to have been made to investigate this phenomenon scientifically until about 1600 A.D. In that year WILLIAM GILBERT (1540–1603) reported that many other substances, such as diamond, glass, sulphur, and sealing wax, were capable, when rubbed, of attracting many kinds of light objects. Some seventy years later OTTO VON GUERICKE (1602–86) discovered that if a light body is allowed to touch an electrified body it is repelled from it.

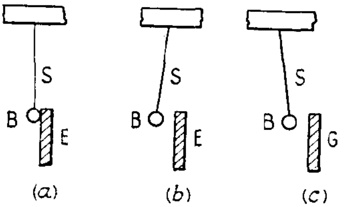


FIG. 1. Experiment to Show the Attraction and Repulsion between Charged Bodies

We can repeat von Guericke's experiment by suspending a small pith ball, or a small piece of cork, *B*, by a silk thread, *S*, and touching it with an ebonite rod, *E*, which has been rubbed with fur (Fig.1(*a*)). After being in contact for a moment, *B* is repelled away from *E* (Fig.1(*b*)). If we carry out the experiment using a glass rod rubbed with silk, we obtain similar results. Since part of the charge on *E* flows to *B* when the two are in contact, it appears that two charged bodies repel each other. However, if we first touch the pith ball with the charged ebonite rod and then bring the glass rod, *G*, near to the pith ball, we find that the pith ball is attracted towards the glass rod (Fig. 1(*c*)).

This attraction between charged bodies was first observed by CHARLES FRANÇOIS DU FAY (1698–1739) in 1734. He suggested that there are two kinds of electricity; vitreous electricity, which is possessed by glass, fur, wool, etc., and resinous electricity, which is possessed by amber, ebonite, silk, etc. He concluded that a charge of electricity of one kind repels a charge of the same kind but attracts a charge of the other kind.

In 1747, BENJAMIN FRANKLIN (1706–90) suggested that there is only one kind of electricity and that a certain amount of electricity is contained in all bodies, even when they are not electrified: that is, when on coming into contact with a pith ball they do not cause it to be repelled. According to Franklin, when two bodies are rubbed together a certain amount of electricity passes from one to the other. One of the bodies then possesses a quantity of electricity in excess of its normal amount when not electrified; the other body possesses an *equal* quantity less than its normal amount. Hence, in charging by friction, the two bodies acquire equal charges but the amount of electricity possessed by one has increased while that possessed by the other has decreased. Franklin suggested that the body possessing a greater amount of electricity should be said to have a positive charge; the other, a negative charge. Since, at that time, it was impossible to observe the details of the charging process, Franklin was forced to make an arbitrary choice as to which bodies were positively charged and which were negatively charged. He adopted the convention that when a glass rod is rubbed with silk the glass becomes positively charged and the silk negatively charged. This implies that electricity flows from the silk to the glass in the charging process. If a pith ball is given a positive charge by bringing it into contact with a glass rod, an ebonite rod rubbed with fur will attract it and the fur will repel it; hence the charge on the ebonite is negative and that on the fur positive.

Du Fay's rule for the force between charges may now be stated in the following way: two positive, or two negative, charges repel each other while a positive charge and a negative charge attract each other. We can determine the sign of an unknown charge by observing the nature of the force which it exerts on a pith ball to which we have given a charge of known sign.

It should be noted that the nature of the rubbing material affects the sign of the charge which appears on a given rod. Thus, ebonite rubbed with fur acquires a negative charge but when rubbed with flannel it acquires a positive charge.

The arbitrary convention adopted by Franklin in defining positive and negative charges has proved to be unfortunate. We now believe that all matter is built up from a limited number of different kinds of chemical elements, such as hydrogen, carbon, and iron. Each element consists of large numbers of small particles called atoms, the atoms of different elements differing from one another, as for example in mass. It was thought for many years that the various types of atom were the smallest particles into which matter could be subdivided but it is now known that the atoms themselves have an inner structure. An atom can be considered to consist of a minute, positively-charged, nucleus (Fig. 2) which is surrounded by a number of negatively-charged particles, called electrons. These electrons rotate in orbits round the nucleus in much the same way as the planets revolve round the sun in the solar system. The charge on the nucleus increases with the atomic weight of the element. The number of electrons in any atom is normally such that the total negative charge carried by them is equal to the positive charge on the nucleus; thus the algebraic sum of the charges on the atom as a whole is zero (Chapter XVII). Consequently, when each atom in any body has associated with it its normal number of electrons, the body is not electrified.

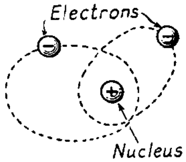


FIG. 2. The Structure of the Atom

During the process of charging by friction, electrons are transferred from one of the bodies to the other. For example, electrons *move from glass to silk* when these materials are rubbed together; hence, the silk becomes negatively charged while the glass, having lost some electrons, becomes positively charged. Thus, the particles which cause the transfer of charge move from the glass to the silk whereas, on Franklin's convention, electricity moves from the silk to the glass. This contradiction need not worry us for the present, and we shall assume that charge moves in the manner implied by Franklin's convention. Later, when we consider the flow of electricity through a gas, we shall have to be more precise.

Conductors and Insulators

In 1729, STEPHEN GRAY (1696–1736) discovered that electric charges will pass through some materials but not through others. Materials of the former type are called conductors; the others are called non-conductors or insulators (we shall see in Chapter XII that they are also called dielectrics). It should be noted that the difference between conductors and insulators is one of degree only; no material is a perfect insulator while conductors vary widely in their ability to allow an electric charge to pass through them. The best conductors are metals; solutions of salts, acids, and bases are the next best; while oils, waxes, ebonite, glass, sulphur, etc. are very poor conductors (Table I, page 100). Certain materials, for example air, are under some conditions good insulators and under others good conductors (Chapter XVII).

We can use a charged pith ball to test whether a material is a conductor or an insulator. If we hold a piece of insulating material in the hand and rub it we find that it either attracts or repels the charged pith ball. We conclude that it has acquired a charge. When we bring different parts of the insulator close to the pith ball, we find that the force experienced by the latter varies considerably; hence, the charge is localized in patches on the insulator. If we repeat the experiment with a conducting material we find that it neither attracts nor repels the pith ball. We conclude that the charge generated by friction has been conducted away, first through the material itself and afterwards through the hand of the experimenter. The above experiment also shows that the human body is a conductor of electricity.

We see, therefore, that if we wish to charge a conductor by rubbing we must first support it by a good insulator, such as a rod of ebonite. We then find that, after rubbing, it attracts or repels a charged pith ball placed in its vicinity. Furthermore, we observe that, unlike the charged insulator, all parts of the conductor exhibit the effect showing that the charge has spread over all the surface.

We have already stated that a transfer of charge consists of a flow of electrons. The above experiments suggest that the fundamental difference between conductors and insulators is that electrons can move about freely in conductors but only with difficulty in insulators.

In experiments on electrostatics we often find that the charge on a conductor disappears within a short time, in spite of the fact that it is supported on a good insulator. It has been discovered that this leakage of charge occurs most rapidly when the atmosphere is humid. It is caused by dampness on the surface of the insulator, since even a thin film of water provides a path for the charge to leak away. We must, therefore, keep the surfaces of insulators as dry as possible. It is also desirable to keep the surfaces clean, since some forms of dirt are comparatively good conductors.

Charging by Induction

Let us take two identical, uncharged conductors, *B* and *C* (Fig. 3), supported on insulated stands, *D* and *E*, and place them in contact. We next bring a negatively-charged body, *A* (for example, an ebonite rod which has been rubbed with fur, or a negatively-charged metal rod held by an insulating handle) near to the conductor, *B*, for a moment and then remove it. If we place a charged pith ball, suspended by a silk thread, near to *B* and *C*, we find that it does not experience a force. We conclude that *B* and *C* are uncharged.

We now repeat the experiment but we separate B and C, as shown, while A is close to B. On bringing B and C in turn close to the pith ball we find that, if the pith ball is negatively charged, it is attracted by B and repelled by C. Thus, B and C carry positive and negative charges, respectively. If we again place B and C in contact, after removing A, we find that they exert no force on the pith ball; hence they are again uncharged.

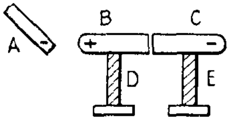


FIG. 3. Induced Charges

We can explain the above observations in terms of the force between charges. When A is near to B, the negatively-charged electrons in B and C are repelled towards C. Thus, C contains an excess of electrons and is negatively charged; B has lost some electrons and is positively charged. If A is removed while B and C are in contact the electrons return to their original positions and the conductors are uncharged. However, if B and C are separated while A is near B, we are left with a positive charge on B and a negative charge on C. On bringing B and C into contact again, in the absence of A, the electrons flow back from C to B and the conductors become uncharged.

The charges which were produced on B and C by bringing A near to B are termed *induced* charges to distinguish them from charges which are produced on an uncharged body by placing a charged body in contact with it.

In the above experiments the algebraic sum of the charges on B and C was zero, both when B and C were in contact and when they were separated. This result is to be expected since no charge could either enter or leave through the insulating supports. It is, however, possible to produce a charge of one sign over the whole of B and C by a process known as *charging by induction*; furthermore, this charge will remain even when A is removed. A negatively-charged rod, A (Fig. 4(*a*)), is brought near to a single, uncharged conductor, BC. The conductor BC is next connected to earth (it is sufficient to touch it momentarily with a finger); electrons are repelled from the conductor to earth by the negative charge on A, leaving a positive charge on BC (Fig. 4(*b*)). On removing the earth connexion the positive charge is left on BC (Fig. 4(*c*)), and when A is removed it spreads over the conductor (Fig. 4(*d*)). It should be noted that the induced charge is of the opposite sign to the inducing charge. When the inducing charge is on an insulator, this is a better method of using it to produce a charge on a conductor than is the contact method, since in the latter it is difficult for the charge to move through the insulator to the conductor. Furthermore, since the original charge is unaltered in amount when the charging is carried out by induction, it can be used repeatedly; whereas, in charging by contact, the original charge is shared with the conductor and is soon used up.

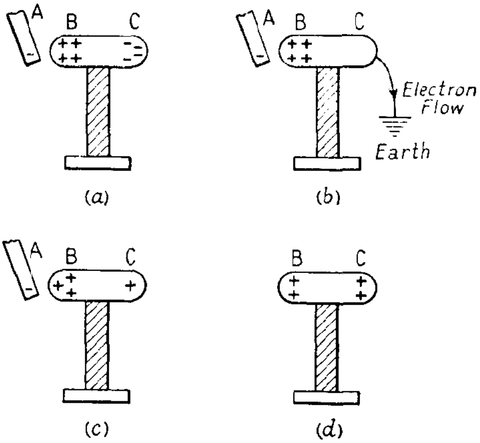


FIG. 4. Charging by Induction

The Electrophorus

The electrophorus is a convenient device with which to carry out the process of charging by induction. A slab of sulphur, ebonite or polystyrene, *S*, is held in a metal container, *M* (Fig. 5); on rubbing with fur it acquires a negative charge. A metal disc, *D*, held by an insulating handle, *H*, is placed on *S*, earthed momentarily, and removed. It is found to have acquired a positive charge; this is due to charging by induction. When *D* is placed on *S* contact is made at only a few points due to irregularities of the surface; hence, since *S* is a good insulator, the flow of charge from *S* to *D* is negligible. Thus, *D* acquires a charge of the opposite sign to that on *S*; also, the amount of charge on *S* remains substantially constant and the above process can be repeated many times after one rubbing of the slab S.

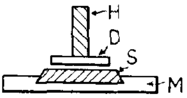
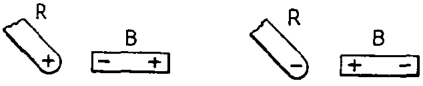


FIG. 5. The Electrophorus

The Attraction of Light Particles

We are now in a position to explain the fact that a charged rod attracts light, uncharged bodies. When a charged rod, *R* (Fig. 6), is brought near to an uncharged body, *B*, for example a pith ball or a piece of paper, the electrons in *B* are either attracted or repelled according to the sign of the charge on *R*. For example, in Fig. 6(*a*) the electrons are attracted towards the end of *B* nearest *R*. There is now an attractive force between the charge on *R* and the negative charge on *B*, and a repulsive force between *R* and the equal positive charge on the far end of the body. Since the positive charge is further away from *R* than is the negative charge, the attractive force will prevail. The effect is observed even if the light body is a good insulator since, although the electrons cannot move about freely, they are still displaced slightly from their normal positions so that the ends of the body acquire the charges shown in Fig. 6.



(*a*) (*b*)

FIG. 6. The Attraction of Light Particles

The Gold-leaf Electroscope

The gold-leaf electroscope has been used for detecting charges since the eighteenth century. It consists of a box, *B* (Fig. 7), the front of which contains a glass window. Two strips of gold or aluminium foil, *FF*, are suspended from a metal rod, *M*, which passes through a plug of insulating material, *I*. If the box is not made of metal, its sides are lined with tin foil, *TT*; this is connected to earth, the conventional symbol for which is shown in the figure. The purpose of the tin foil will be discussed later (page 32). When the leaves are uncharged they hang vertically downwards. A charge can be given to the electroscope by bringing a charged body into contact with the metal disc, *D*; or, by the process of charging by induction. When a charge is given to the disc, some of it flows to the leaves and they repel each other as shown in the figure. The amount of divergence is a measure of the magnitude of the charge on the electroscope. It is useful to place an engraved scale behind the leaves so that the divergence can be read off accurately.

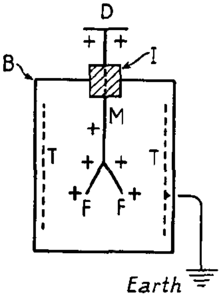
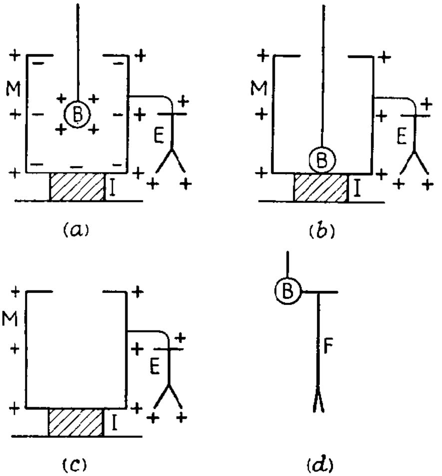


FIG. 7. The Gold-leaf Electroscope

When more charge of the same sign is given to the electroscope, by either of the above processes, the divergence increases. If the electroscope is given a series of small charges of the opposite sign, the divergence of the leaves decreases to zero in steps and then increases again as the original charge is gradually cancelled and replaced by a charge of the opposite sign. Thus, the electroscope can be used to determine the sign of an unknown charge; we must, of course, be able to place on the electroscope a comparison charge of known sign.

Faraday's Ice-pail Experiment

In 1843, MICHAEL FARADAY (1791–1867) published an account of his experiments on electrostatic induction carried out using an ice-pail and a gold-leaf electroscope; the ice-pail served merely as a convenient form of hollow conductor.



(a) (b) (c) (d)

FIG. 8. Faraday's Ice-pail Experiment

For these experiments a hollow conductor, M, is supported on an insulator, I, and connected to a gold-leaf electroscope, E (Fig. 8(a)). A metal ball, B, suspended by a long silk thread is charged, say, positively and the ice-pail and electroscope discharged by earthing them momentarily. B is then brought near to M and as it approaches the opening the leaves start to diverge; this divergence reaches a maximum value when B is well inside M (Fig. 8(a)). It then remains unaltered whatever the position of B, provided that it remains well inside M. It appears that the positive charge on B has attracted electrons in M so that its inner surface is negatively charged while its outer surface and the electroscope are positively charged. (The sign of the charge on E can be confirmed by disconnecting it from M and using the method described above.) When B is allowed to touch the inside of M no alteration in the divergence of the leaves is observed (Fig. 8(*b*)). If B is now removed from M the divergence remains unchanged (Fig. 8(*c*)); moreover, B can be shown to be uncharged by bringing it into contact with a second electroscope, F (Fig. 8(*d*)).

The above observations suggest that when B is inside M the negative charge on the inner surface of M is equal to the positive charge on B, irrespective of the position of B. Since the net charge on M and E must still be zero, the positive charge on the outside of M and on E must be equal in magnitude to the negative charge on M and, hence, to the positive charge on B. When B touches M, the positive and negative charges on B and on the inside of M, respectively, cancel each other, while the charge on the outside of M is unaltered. Thus, B becomes uncharged and the divergence of the leaves is not affected by its removal.

The above experiment shows that the charge induced on the outside of M and on E is independent of the position of B provided it is not too near the opening, and that it is equal in magnitude to the charge on B. Furthermore, the whole of the charge on B can be transferred to M and E by allowing B to touch the inside of M. It should be noted that, if B is made to touch the outside of M instead of the inside, the divergence of the leaves is smaller; hence, we conclude that only part of the charge on B passes to M and E, the remainder being carried away on B. Thus, Faraday's ice-pail experiment gives us a method of comparing charges; for, if the charged bodies are lowered into M successively, the relative sizes of the charges can be expressed in terms of the divergence of the leaves. In particular, if the divergences are the same, the charges will be equal.

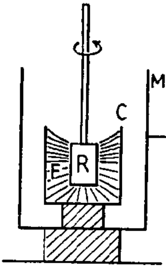


FIG. 9. Experiment to Show that Equal and Opposite Charges are Produced by Friction

We can use Faraday's ice-pail to establish experimentally a result which we have already stated: namely, that equal and opposite charges are produced by friction. In Fig. 9, M and E are the ice-pail and electroscope respectively. A container, C, lined with fur, F, is placed inside M but is insulated from it. An ebonite cylinder, R, on an insulating handle is lowered into C and rotated rapidly. No divergence of the leaves is observed showing that, if any charging is taking place, the charge on the ebonite is equal and opposite to that on the fur. On removing R the leaves diverge; if C is removed without touching M and