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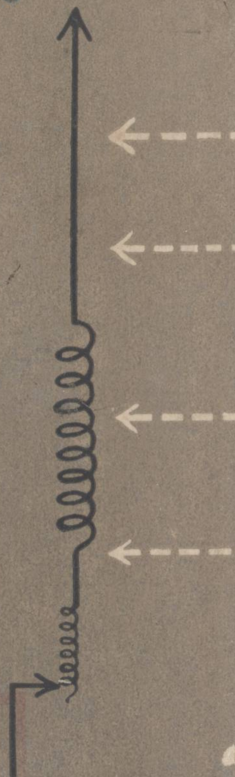
HUTCHINSON'S

Advanced Text Book of

ELECTRICITY and MAGNETISM

VOLUME ONE



ADVANCED TEXT-BOOK
OF
ELECTRICITY & MAGNETISM

VOLUME I.
MAGNETISM AND ELECTROSTATICS

BY
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NOTE TO SECOND EDITION.

Advantage has been taken of the demand for a second edition to amend and extend certain sections, and a quantity of new matter has been added in connection with Magnetic Induction, Ships' Compass Errors, the Dielectric Constant, the Induction Coil, Telegraphy and Telephony, Electromagnetic Waves, Conduction through Gases, Radioactivity and the Electronic Theory. In particular Chapters XXII. and XXV. have been much extended, and Chapters XXIII. and XXIV. have been re-written and considerably enlarged.

The best thanks of the author are due to Mr. C. T. R. Wilson for the kind loan of his remarkable photographs of the tracks of α and β particles, etc., and for permission to reproduce them in the book.

R. W. H.

HAGLEY ROAD, EDGBASTON,
BIRMINGHAM,

PREFACE TO FIRST EDITION.

The aim of this book is to give a clear and comprehensive account of the main principles of the subject based on accurate scientific definitions and embodying the distinctive results of modern research. Both the experimental and the theoretical sides of the work have been fully treated, and great care has been taken to deal adequately with the many difficulties which in the present state of our knowledge must necessarily arise in connection with the theoretical explanations of the various phenomena.

The point of view of the writer is that of a teacher with many years' experience in dealing with senior students of Electricity both on the Engineering and on the pure Physics side. This will explain why, in a book the scope of which is that of the Final Degree Examinations of the Universities, certain of the elementary yet fundamental sections are treated at some length. Even the student who feels that he already has sufficiently grasped these fundamental principles will probably appreciate a revision on scientific lines.

The conception of *potential*, the visualisation of *tubes of force and induction*, the idea of the *electron*, and certain features and anticipations of the "New Physics" are introduced early, and kept in view throughout. Incidentally no apology is needed for the introduction at an early stage in the Magnetism of the ideas of permeability, hysteresis, etc., which are in most text-books relegated to

PUBLISHER'S NOTE

Hutchinson's Advanced Textbook of Electricity & Magnetism hardly needs any introduction. The book remained out of print for sometime and its want was very keenly felt by the students of Indian Universities. To remove this want, we have secured the permission of University Tutorial Press Ltd., to whom our best thanks are due, to reprint and publish in India this classical work of Robert W. Hutchinson.

We have much pleasure in now being able to place this Indian Edition in the hands of teachers and students, and it is hoped that the same will receive the same reception as the British Edition.

This edition has been carefully printed, and exactly similar types and diagrams have been used to keep it in line with the original British production. We trust our attempt will be appreciated by all lovers of learning.

the later chapters; these terms are now in daily use, the student will repeatedly encounter them in his reading, and experience shows that an early elementary treatment is alike possible and desirable, minute details of theory and experiment being postponed to a later stage.

Though the mathematics involved is confessedly elementary, use has been made of the notation and first principles of the Calculus. In the earlier portions of the book such applications usually appear in the form of neater alternative investigations, solutions, and proofs, but the methods are employed generally whenever it appears that a distinct advantage is gained thereby. Students of Physics cannot realise too early that a knowledge of the rudiments of the Differential and Integral Calculus is an essential part of their mental equipment: the necessary knowledge can be acquired by a very slight expenditure of time.

Throughout the book special attention has been devoted to the various units and systems of units, and their relationships have been indicated, so that students may experience no difficulty in connection with modern research work or general problems necessitating a change from one system to another. The book contains numerous fully worked examples illustrating important principles and applications, and a large number of problems of a similar character to be worked by the student. Over 540 diagrams of a kind best suited to aiding the student to a clear understanding of the principles and methods involved are inserted throughout the book. The more important symbols recommended by the International Electro-technical Commission have been adopted.

The book is based upon the late Dr. R. Wallace Stewart's *Higher Text-Book of Magnetism and Electricity*, the last chapter of which (Chapter XXIV.) was from the pen of

Professor Satterley of Toronto University. Professor Satterley's work has been inserted (with additional matter) in Chapters XXIII. and XXIV. and in Articles 308-310 of the present book. The book has been re-arranged throughout, and almost entirely rewritten and brought up to modern requirements, so that its scope has been considerably increased. In fact, although portions of the older book have been retained where they did not conflict with modern thought, the book is, to all intents and purposes, new.

As already indicated, this work covers the ground of the Final Degree Examinations of the Universities. The author is greatly indebted to the Senate of London University and to the Controller of H.M. Stationery Office for the permission, freely given, to insert the examination questions contained in the book.

The best thanks of the author are due to Mr. H. Garratt, B.Sc., Head of the Physics and Electrical Engineering Department of the Smethwick Technical School, for assistance with the proofs, etc.—assistance all the more appreciated because most willingly rendered despite the present high pressure in the work of the Institute due both to war conditions and actual war work. To Mr. Arthur Adams, F.I.C., F.C.S. (Chemistry Department), Mr. W Jones, Cert. A.M. (Art Department), and Mr. Ayton R. W. Hutchinson (Cadet School, Royal Garrison Artillery) thanks are also due for various services ungrudgingly given in connection with the book. Thanks must finally be tendered to Professor J. A. Fleming (and Messrs. Longmans) for kind permission to reproduce Fig. 488 from *The Manual of Radiotelegraphy and Radiotelephony*.

R. W. H.

TECHNICAL SCHOOL, SMETHWICK,
January 1917.

CONTENTS.

CHAPTER I.

MAGNETISM.—FUNDAMENTAL PHENOMENA.

1. Natural and Artificial Magnets.—The name *magnet* was applied at a very early date to pieces of a mineral found in Magnesia in Asia Minor. These specimens of what is now known as **magnetite** or magnetic iron ore (Fe_3O_4) were found to possess the following properties:—

(*a*) They attracted small pieces of iron or steel. If rolled in iron filings and then lifted out, the filings were found to cling to certain parts, other parts remaining bare. Frequently there were two regions where the filings mainly adhered, and between them was a region showing no attraction (Fig. 1). The regions of greatest attraction are called the *poles*, and the region midway between the poles where there is no attraction the *magnetic equator* or *neutral line*. All specimens do not exhibit definite poles.

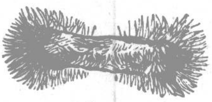

Fig. 1.

(*b*) If such a specimen as is shown in Fig. 1 were suspended so as to be free to turn in a horizontal plane, it came to rest in a definite direction nearly north and south, the one end always pointing towards the north and the other end towards the south. The utilisation of this property in navigation led to magnetite being referred to as *lodestone* (A.S. lœdan = to lead). The pole which points towards the north is called the *north-seeking* or, briefly, the *north pole* of the magnet, and the pole which points towards the south the *south-seeking* or *south pole* of the magnet.

(*c*) If bars of iron or steel were rubbed from end to end with one end of such a specimen as is shown in Fig. 1, or if the bars were even held near the lodestone, they were converted into magnets, and possessed the same properties as the specimen itself.

Magnetite is found in abundance in Scandinavia (*e.g.* Dannemora), Finland, the Urals, the States of New York, New Jersey, and Pennsylvania, and in Canada; it is also widely distributed in smaller amounts, occurring as grains in certain rocks, *e.g.* granite, and its presence leads to the magnetic properties of many basalts, of haematite, etc.

Magnetite is often spoken of as a *natural magnet*, whilst a bar of iron or steel which has been magnetised either by rubbing with the natural magnet, or by more powerful methods to be described later, is called an *artificial magnet.* Nickel, cobalt and manganese, although considerably inferior to iron, can also be magnetised. In the study of magnetism which follows, artificial magnets of iron or steel are always referred to.

2. Poles. Magnetic Attraction and Repulsion. The Earth a Magnet.—Permanent artificial magnets are made of hard steel (Art. 7) and are frequently horse-shoe-shaped or in the form of bars. As in the case of the natural magnet of Fig. 1, if a bar magnet be placed in iron filings, the latter adhere mainly to regions near the ends, and if the bar be suspended (Fig. 2) so as to be free to turn in a horizontal plane, it comes to rest in a definite direction nearly north and south, the one end always pointing northwards and the other southwards. **The strongest parts of the magnet are therefore near the ends, and these are referred to as the "poles," the one which points towards the north being called the "north pole" and the one which points towards the south the "south pole" of the magnet.**

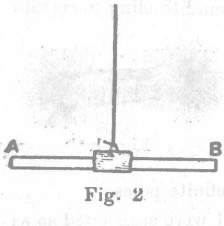

Fig. 2

The filings experiment above, and others, more exact, to be described later, indicate that the bar magnet exhibits magnetism *in varying degree along its surface* from zero at its centre to a maximum in *regions* near the ends, but it may be stated that at some distance from the magnet the action is very nearly the same as if the magnetic effects were due to *two points within the bar and near the ends*; these points may be regarded as the poles, and the straight line joining the poles is called the *magnetic axis*.

The longer the bar in comparison with its thickness, the nearer the poles are to the ends. An indefinitely thin magnet would exhibit no lateral magnetism, and the poles would be at the ends; such a magnet is called a *simple magnet*. The Robison **ball-ended magnet** consists of a magnetised steel rod on the ends of which balls of steel or iron are screwed, and it has been proved that this magnet acts almost like a simple magnet with poles situated at the centres of the balls.

Exp. Suspend a magnet by means of a thread as shown in Fig. 2. Bring the north pole of a second magnet *gradually* near the north pole of the suspended one: *repulsion* ensues. Remove the second magnet, bring the suspended one to rest and then bring the south pole of the second magnet near the north pole of the suspended one: *attraction* ensues. Similarly, bring the north pole of the second near the south pole of the first and the result is *attraction*. Bring the south poles *gradually* together and the result is *repulsion*.

The above establishes the fundamental law in magnetism, viz. **like poles repel and unlike poles attract.**

The setting of a suspended magnet in a definite direction nearly north and south is merely another illustration of the law. The earth itself is a magnet having its magnetic "poles" not so very far removed from its geographical poles. The magnetic pole in the northern hemisphere is called the "north magnetic pole of the earth," but it must be remembered that as it attracts the *north* pole of a magnet the two are unlike poles, i.e. *the north magnetic pole of the earth is like the south pole of a magnet*. Similarly, the magnetic pole in the southern hemisphere is called the "south magnetic pole of the earth"; but it attracts the *south* pole of a magnet, and therefore *the south magnetic pole of the earth is like the north pole of a magnet*.

The vertical plane in which the magnetic axis of a suspended magnet or a compass comes to rest is called the *magnetic meridian of the earth* at that particular place.

The property of magnets (and of the earth) that they possesses poles with different characteristics is called "polarity."

The fact that a suspended magnet or compass does not, in general, point geographically north was noted by Adsiger in 1269, and again by Columbus in 1492, the latter also observing that the deviation from the true north was different at different places.

In 1576 Norman discovered that if a magnet were suitably suspended—"freely suspended at its centre of gravity" as it is often worded—it came to rest in the magnetic meridian but with its north pole "dipping" in London, the angle between the horizontal and the magnetic axis of the magnet being (then) 71° 50′. In general, in the northern hemisphere the north pole of the above magnet dips downwards, and in the southern hemisphere the south pole dips downwards, the dip angle being different at different places; in the vicinity of the equator the magnet lies horizontally in the magnetic meridian; at the north magnetic pole it sets vertically, the north pole being downwards; at the south magnetic pole it sets vertically, the south pole being downwards (Fig. 3) The line drawn through places where the above magnet lies horizontally *i.e.* where the dip is zero gives the earth's *magnetic equator*. Further details of the earth's magnetism appear in subsequent pages. Needless to say, Fig. 3 is diagrammatic only; it is inserted to assist the student to grasp the general idea.

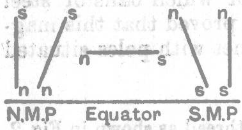

Fig. 3.

3. Magnetic Induction. Magnetic Induction by the Earth. Magnetic Difference between Iron and Steel.

Exp. Let the magnet *NS* (Fig. 4) be fixed vertically in a clamp, and let a short piece of steel be brought near the lower end; it is attracted by the magnet, and clings to it as shown at (*a*). Let another short piece of steel be now brought near the lower end of the piece clinging to the magnet; this second piece is also attracted, and, if the magnet be strong enough, it will remain hanging to the first piece as shown at (*b*). If the first piece be now gently detached from the magnet, it will be found that the lower piece still clings to it, and, if the two pieces of steel be tested, each will be found to be a magnet with poles as shown at (*c*). It will be noticed that these poles are arranged relative to one another and to the magnet *NS*, so that dissimilar poles are in contact, and therefore exert mutual attraction.

If this experiment be modified, as indicated in Fig. 5, by arranging the magnet and the pieces of steel on a table so that they are not allowed to come into contact with one another, it will be found that the result is exactly the same as before, only that the magnetisation produced in the pieces of steel is somewhat more feeble

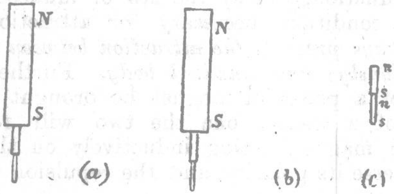

Fig. 4.

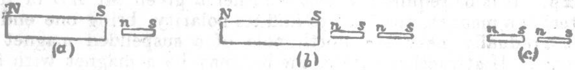

Fig. 5.

than in the first case. On removing the magnet *NS*, each piece of steel will be found to possess all the properties of a magnet as shown at (*c*).

The phenomena indicated in the above experiments, viz. the making of a piece of unmagnetised steel into a magnet by the influence of another magnet, with or without actual contact, are referred to as "magnetic induction," and the steel is said to be *magnetised by induction*. The "law of induced polarity" is readily derived from the experiments. Thus in Fig. 5 (*a*) the end of the steel opposite the south pole of the inducing magnet is found to be a north pole. If

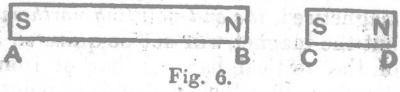

Fig. 6.

the experiment be repeated, and a piece of unmagnetised steel *CD* (Fig. 6) be placed near the north pole of the inducing magnet *AB*, the end *C* of the steel opposite the north pole is found to be a south pole. Hence *when a bar is magnetised by induction, the end of it nearest the inducing pole acquires polarity opposite to that of the inducing pole.*

The experiments also indicate why a magnet attracts an unmagnetised piece of iron or steel. When brought near, the iron or steel is no longer unmagnetised, but is magnetised by induction, and by the law of induced polarity we have the conditions necessary for attraction. Thus *induction always precedes the attraction between a magnet and a (previously) unmagnetised body.* Further, if the north pole of a powerful magnet be brought near the north pole of a weaker one the two will repel, but the powerful magnet, acting inductively on the weaker one, may reverse its polarity, and the repulsion change to attraction.

Exp. If it be required to test whether a given bar *AB* of iron or steel is a magnet, and if so to find its polarity, bring one end *A* of it gradually near the north pole of a suspended magnet or compass. If attraction ensues, the bar may be a magnet with the end *A* a south pole, or it may be unmagnetised originally and only magnetised inductively at the time, the north pole of the suspended magnet inducing a south pole at *A*. To settle the question, bring *A* near the south pole of the suspended magnet; if repulsion ensues the bar is a magnet, the end *A* being the south pole, but if attraction again takes place the bar is originally unmagnetised, being only magnetised by induction. Repeat with the end *B* and verify. Clearly *repulsion is the only sure test for polarity.*

A vertical bar of iron (or steel) in the northern hemisphere will be found to be magnetised by the earth's inductive action, *the bottom end being a north pole and the top end a south pole.* A horizontal bar of iron laid parallel to the direction in which a suspended magnet or a compass needle comes to rest will also be found to be magnetised, *the end pointing northwards being a north pole,* but the magnet will not be quite so strong as in the case of the vertical bar. A bar of iron held parallel to the direction in which a compass points, but inclined at an angle of about 67° to the horizontal, its lower end towards the north, will be even more strongly magnetised than the vertical bar, *the lower end pointing northwards being a north pole.*

All this is in agreement with the "law of induced polarity." The north magnetic pole of the earth is similar to the south pole of a magnet: it induces a *north* pole in the end of the iron towards it, viz. the lower end of the vertical bar, and the ends pointing northwards of the other bars. In the southern hemisphere the vertical bar, for example, would for a like reason be magnetised by the earth's inductive action, *with the bottom end a south pole and the top end a north pole.*

Exp. Repeat the first experiment (Fig. 4), using pieces of soft iron of equal weight to the pieces of steel. Whilst only about two pieces of steel could be hung on the magnet, perhaps eight or nine pieces of soft iron can be attached one under another. This shows that the iron magnets are stronger, *i.e.* that *soft iron is more readily magnetised than hard steel.*

Detach the upper piece of iron from the magnet. Whilst the pieces of steel still hung together and showed polarity, the pieces of soft iron fall away from each other, and when tested show no signs of magnetism. This shows that *soft iron loses its magnetisation much more readily than hard steel.*

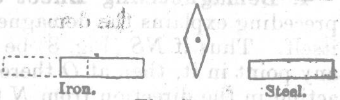

Fig. 7.

The first fact may also be shown thus :—Place equal pieces of iron and steel at equal distances from a compass needle, as shown in Fig. 7. The compass acts inductively on each bar, so that each tends to attract it, *but the compass is deflected towards the iron,* showing that this is the stronger. The iron must be moved to a greater distance (dotted lines) in order that the two attractions may counteract each other.

The power of retaining magnetisation when the inducing influence is removed is called "retentivity" and the magnetisation retained is called "permanent" or "residual" magnetism. The retentivity of steel is greater, therefore, than that of soft iron, and is increased by the presence of 5 to 8 per cent. of *tungsten* or about 4 per cent. of *molybdenum* (Arts. 7, 12). It may be mentioned that soft iron may indicate more residual magnetism than steel *if carefully protected from the least disturbing influence,* but very little disturbing effect will wipe out the magnetisation; in saying the retentivity of steel is the greater, reference is made to the more stable condition. Material which retains a good portion of its magnetisation *despite disturbing influence* is also said to have a large