ELEMENTARY ELECTRO-TECHNICAL SERIES

MAGNETISM

BY

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PREFACE

THIS volume on MAGNETISM, like the others in the *Electro-Technical Series*, is intended to meet the demand which exists on the part of the general public for reliable information respecting such matters in Electricity and Magnetism as can be readily understood by those not especially trained in electro-technics.

Magnetism has always proved an attractive subject to the general reader. The mysterious nature of the force has naturally caused it to possess a deep interest for the inquisitive mind of man. While the mysterious in science, as a rule, is rapidly dispelled, as our knowledge of the science grows, magnetism has proved an exception, so that even to-day much remains to be explained concerning the origin and nature of this strange force.

The authors have discussed at some length various theories of magnetism that have been propounded from time to time, and have adopted, provisionally, for purposes of explanation, that particular modern theory which would seem to them to be the most readily comprehended.

The phenomena both of permanent and electromagnetism are as fully described as the limits of the book will permit. The important laws of the magnetic circuit are carefully presented and are explained in language which it is hoped avoids the vagueness that too frequently attends such descriptions. The phenomena of the earth's magnetism are considered at some length and the peculiarities in the distribution and variation of this magnetism have been developed in a manner which it is hoped will prove attractive to the reader.

The authors have employed throughout the book the magnetic units provisionally adopted by the American Institute of Electrical Engineers.

The authors desire to acknowledge their indebtedness to Prof. Mark W. Harrington, formerly of the U. S. Weather Bureau, for valuable data concerning magnetic observations in the United States; also to Prof. S. P. Thompson for Fig. 81.

Complex mathematical formulæ have carefully been excluded.

The authors present the book in the hope that if may prove of value to the general public.

CONTENTS.

MAGNETISM.

CHAPTER I.

INTRODUCTORY.

THE mysterious invariably possesses a strange fascination for the human mind, which ever desires to peer into the realm of the unknown. Apparent incomprehensibility, in any physical phenomenon, begets a curiosity that urges the mind to attempt to wrest the secret of its cause from nature. It is, therefore, not astonishing that so mysterious a force as magnetism should, at a very early period, have attracted considerable attention. It is uncertain to whom the honor of the discovery of this strange force is due. History differs as to both the year and the nation. According to some, the discovery of the *attractive power* of magnetism, for iron and similar metals, as possessed by a certain ore of iron called the *lodestone*, was made by a shepherd on Mt. Ida, who, it is alleged, discovered this property by the iron end of his shepherd staff being not only attracted to, but also held by a massive lodestone rock.

It is, however, more probable that the attractive power of the lodestone was discovered subsequently to its *directive power;* that is, the ability of a mass of this material, when suspended by a thread, to point in a more or less north and south direction.

But it is doubtful that the world remained as long in ignorance of this strange mineral, and its curious properties, as the alleged first discovery on Mt. Ida would indicate. There would appear to be but little doubt that the Chinese, long before this time, had a knowledge both of the attractive and of the directive power of the lodestone, and that they employed the latter power, not only in directing their vessels over their waters, but also for finding their way across the trackless plains of Tartary.

Even the origin of our word *magnetism*, like the property itself, is involved in doubt. According to some this word was derived from *magnis*, heavy, alluding to the high specific gravity of magnetic iron ore, or the lodestone, in which the property was first observed. According to others, the word magnetism was taken from the place where it is claimed the property was first discovered; namely, Magnesia, Asia Minor. The name formerly given to the lodestone had reference to its ability to point or lead the navigator. This word is frequently misspelled *load*stone, this error being probably due to the erroneous idea that the original significance of the word was that of a stone which could support a weight or load, rather than one possessing a directive leading tendency.

There would appear to be but little doubt as to why the ancients looked with such surprise on the curious properties of the lodestone. This strange substance seemed to them instinct with life; for it was apparently able to determine, while yet at a distance from a body, whether it should attract it or not, a property eminently characteristic of intelligence. Moreover, observing the facility with which the lodestone could impart its mysterious properties to other bodies, such, for example, as hardened steel, by merely stroking them, did it not seem as if it were thus able to endow such bodies with a portion of its own vitality? Even when more intimate knowledge of the properties of the lodestone showed beyond doubt that it possessed no animation, there still remained to be explained that strange facility with which it can apparently reach across intervening space and draw to itself certain bodies.

It happens seldom, in the history of scientific discovery, that the first observed phenomenon, in any particular field of research, possesses on its face a promise of marked practical value. On the contrary, the unexplored realm, as seen through the partly open door of the first recorded observation, generally seems to promise but little of true practical value. Magnetism forms no exception to this general rule. The comparative insignificance of the force developed in the attractive power of the lodestone as it was first known, would scarcely lead even the most sanguine to expect from it valuable results. It is true that the discovery of the directive property of the lodestone gave to the world, in the *mariner's compass*, an instrument of inestimable value; but, apart from this discovery, there seemed to be but little promise of practical work to which to put the unseen fingers of the magnet, as manifested in its ability to reach out across apparently empty space and draw to it the bodies it apparently selected. But modern discovery has shown in this case, as it has in many others, that it is unsafe to assert that any observed physical phenomenon, however apparently insignificant, is devoid of practical value; for, is it not the invisible fingers of the magnet that to-day stretch across land and sea and deliver the telegraphic message? Nor is the power of these unseen fingers limited to the movement of delicate machinery. They prove indeed the giant fingers, that in the electro-magnetic motor, move ponderous machinery of many a mill and factory, or drag loaded street cars, even up mountain slopes.

It generally happens that even a superficial study of a new and strange force at once strips it of all its apparent mystery, but this has proved far from true with the strange force of magnetism. Though much has been discovered concerning its nature, though we have already investigated many of its laws, and caused magnetic force to serve mankind in many and varied directions, yet we seem, even to-day, almost as far as ever from understanding its exact nature and are still confronted with terra incognita at every step.

It is a curious fact that the strange force of magnetism is indissoluably connected with the equally strange force of electricity. Although, as is now well known, an electric discharge or current cannot occur without the production of magnetic phenomena, yet, for many centuries, the sciences of magnetism and electricity were kept apart, the two being regarded as presenting entirely separate groups of phenomena. This unnatural divorce of two sciences, wedded by nature, effectually prevented any marked advance being made in either.

It would appear that the phenomena of magnetism were observed at a much earlier date than were those of electricity. At least, this would be so on the assumption that the first recorded electrical observation was that of Thales, 600 B. C.; for Thales was anticipated, many centuries, by the Chinese discovery of the directive properties of the lodestone. But though magnetism had thus very much the start of electricity, yet it by no means maintained its lead. Progress in electricity was very rapid during the 18th century. During the last century, however, the happy discovery, by Oersted, of the relation between electricity and magnetism, broke down the barriers between the two sciences, and, since that time, both have progressed, side by side, with unexampled rapidity. The reason for this great rapidity in joint progress during recent times has been owing to the numerous practical applications which have been found for both these forces, first in telegraphy; then in electric lighting; and now in the electrical transmission of power.

CHAPTER II.

MAGNETIC PHENOMENA.

THE earliest experiments that were made with magnets, sufficed to convince the observers that there were two places in every magnet where it manifested its peculiar properties in the most marked manner. These places are called *poles.* The pole which points approximately toward the geographical north, when the magnet is freely suspended, is called the *north pole* of the magnet, and the other pole is called the *south pole.* The portion of the magnet that lies between these two poles apparently possesses but little magnetic influence. At this time, therefore, a magnet was regarded as consisting practically of a pair of poles, separated by a mass of intervening material. As we shall see, in the modern theory of magnetism, this view has entirely passed away. All portions of a magnet are now considered as possessing equal, although not apparently equal, influence, in the production of the magnetic phenomena.

Early in the study of magnetic phenomena, it became evident that it was not sufficient to confine one's attention entirely to the magnet itself; that something existed in the surrounding medium, outside the magnet, which formed an integral part of the magnet. In this region external to the magnet, extend, as it were, the invisible fingers of the magnet, and in it, almost all the observed magnetic phenomena occur. Further experimental investigations soon indicated that the magnetic influence extends externally, not merely from one pole to the other, but also returns through the substance of the magnet, thus completing what may be called a *magnetic circuit.*

The whole body of a magnet may, therefore, be considered as a means or device whereby the magnetic influence may pass out from the magnet at its north pole, and, after having traversed the external space, re-enter the magnet at its south pole, completing the circuit through the mass of the magnet. Moreover, it has been ascertained that no magnetic phenomena can be developed without producing a complete magnetic circuit.

By a circuit, in the sense in which the word is employed above, is meant a completely closed path, motion in a circuit necessarily consisting of motion in completely closed curves or chains. In this sense, motion in a magnetic circuit is not unlike the motion of a belt around a pair of pulleys, or the motion of a street-car cable through the conduits in the streets. In neither of these instances can the effect of the moving belt or the cable be produced, unless its circuit is completed. In the same way no magnetic effect can be produced unless the force acts in closed paths or circuits.

Bearing in mind the fact that, in the study of magnetic phenomena, the attention must extend to the entire magnetic circuit, we will now consider some of the commoner phenomena of magnetism. One of the most important of such phenomena is the directive tendency of the *magnetic needle.* A magnetic needle consists of a slender bar of hardened steel, which has been so magnetized as to bring its poles at its ends, and so suspended, near its middle point, as to be free to move in a horizontal plane. Such a magnetic needle is shown in Fig. 1, where

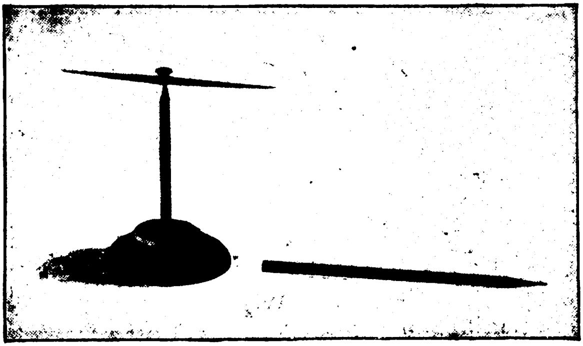

FIG. 1.—PIVOTED MAGNETIC NEEDLE AT REST IN NORTH AND SOUTH DIRECTION, THE PENCIL POINTING IN THE DIRECTION OF THE NEEDLE.

a magnetized needle, suspended as described, is pointing in a north and south direction. In the Northern Hemisphere, a magnetic needle will come to rest with one of its poles pointing approximately to the earth's north geographical pole. This end of the needle is called its *north magnetic pole* and the opposite end, its *south magnetic pole.*

FIG. 2.—REPULSION BETWEEN LIKE POLES OF MAGNETIC NEEDLE.

Suppose now, a second magnetic needle be placed sufficiently distant from the other, so as to be unaffected by its influence; then both needles will come to rest with their north poles pointing approximately north. If one of the needles be now lifted from its support, and, while prevented from moving, as by resting it on a cork, the north pole be brought nearer to the north pole of the other needle, repulsion will occur, as shown in Fig. 2, where the amount of the repulsion is indicated by the pencil, which points in the direction assumed by the suspended needle prior to its repulsion. Similarly, if the south pole of one needle be approached to the south pole of the suspended needle, repulsion will also occur. But if the north pole of one be brought near the south pole of the other, or vice versa, attraction will occur. These effects may be summed up in the following law of magnetic attractions and repulsions; namely,

(1) *Like magnetic poles repel.*
(2) *Unlike magnetic poles attract.*

Let us now inquire as to the cause of the attractive tendency of the magnetic needle. Why is it that in almost any part of the Northern Hemisphere the needle will come to rest with its north pole pointing approximately to the earth's geographical north? The reason may be

FIG. 3.—ATTRACTION BETWEEN ONE POLE OF A PIVOTED NEEDLE, AND THE POLE OF THE APPROACHED BAR MAGNET.

found by the following simple experiment: Suppose, while the magnetic needle is at rest, a magnetized bar be brought, as shown in Fig. 3, with its south pole into the neighborhood of the needle's north pole, then, on account of the attraction of the opposite pole of the bar, the north pole of the needle, instead of pointing as indicated by the pencil, to the north pole of the earth, will point to the approached pole of the bar magnet. The cause of the directive tendency of the magnetic needle is to be found in a similar action. As will be shown in a subsequent chapter, the earth acts as a huge magnet, with its magnetic poles situated in the neighborhood of its geographical poles. All magnetic needles in the Northern Hemisphere will, therefore, point approximately to this magnetic pole and, consequently, to the earth's geographical north pole. But since opposite poles attract each other, it is evident that, if we regard the pole of the magnetic needle which points to the north, as its north magnetic pole, then the magnetic polarity of the earth's Northern Hemisphere must be south.

The above fact has given rise to no little misunderstanding concerning the proper designation of the poles of a magnetic needle. According to some, that pole of the needle which points to the geographical north of the earth is called the *north-seeking pole.* Others have named it the *marked pole.* Some have endeavored to distinguish the poles by different colors, such as the *blue pole* and the *red pole.* The French originally endeavored to overcome this difficulty by calling that the south pole or end of the needle, which pointed approximately to the earth's north. It is now, however, generally agreed to call the end of the needle which points toward the geographical north, the north pole of the needle, in accordance with which the earth's Northern Hemisphere must, of course, be assumed to possess south magnetic polarity.

The laws of magnetic attraction and repulsion may, therefore, be applied to determine an unknown polarity in a magnetized bar. Suppose, for example, that one end of the magnetized bar shown in Fig. 3, be approached to a suspended magnetic needle; then the polarity of the presented end of the bar will be the same as that of the repelled pole of the needle, or opposite to that of the attracted pole.

The simplest form of magnet consists of a straight bar or rod of steel, so magnetized that the poles lie at or near the extremities of the bar. Heavy bar magnets may be made either of a single piece of steel or of a number of thinner bars, placed parallel to one another as shown in Fig. 4, where 12 separate bars *d*, *d*, *d*, are connected at their extremities to soft iron *pole-pieces* *N* and *S*. Such magnets are called *compound magnets*. They are constructed in this

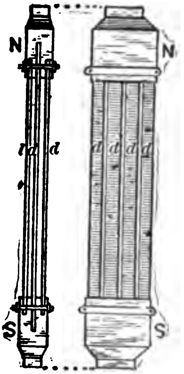

Fig. 4.—Compound Permanent Bar Magnet.

shape for the sake of obtaining a more nearly perfect temper, or degree of hardness, in the material of the thinner bars, than can be secured in a single larger mass.

Fig. 5.—Horse-shoe Permanent Magnet.

The magnetic circuit of a bar magnet is always completed through the medium, usually air, surrounding the bar. When, however, a bar magnet is bent into the form, as shown in Fig. 5, it is called a *horse-shoe magnet.* When the poles of

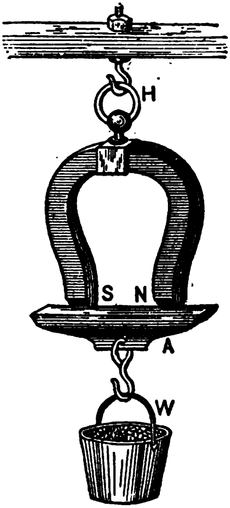

FIG. 6.—COMPOUND HORSE-SHOE MAGNET.

such a magnet are connected by a piece of iron, or *keeper*, the entire circuit of the magnet is completed through iron. A form of compound horse-shoe magnet is shown in Fig. 6, in which the keeper is represented as supporting a considerable weight by means of its attraction to the poles.

When a magnetized bar is rubbed against a piece of steel, the latter will thereby become magnetized, or will acquire magnetism from contact with the magnet. The magnetizing magnet, however, does not lose its magnetism, for reasons that will be considered later. If several bars of different kinds of steel be magnetized in this manner, it will be found that some of them retain their magnetism much better than others. In all cases, however, if the steel be fairly hard, they will retain their magnetic properties for a fairly considerable time after contact with the magnetizing magnet. But if a bar of soft iron be thus magnetized, it will be found that although it will acquire magnetic properties with great readiness, and will maintain its magnetism while in contact with the magnetizing pole, yet, as soon as it is removed, it will immediately lose its magnetism. Hardened steel, therefore, differs markedly from soft iron, both in its ability to receive and to retain magnetism. Hardened steel is difficult to magnetize, but it is also difficult to demagnetize. Soft iron, on the contrary, has very little power of resisting either magnetization or demagnetization. In other words, it is easy both to magnetize and to demagnetize.

The property possessed by hardened

steel of retaining its magnetism is sometimes called *magnetic retentivity.* This property was originally called *coercive force.* Magnetic retentivity refers only to the ability of the iron or steel to retain magnetism when imparted to it, or, as it has been very happily expressed by an English writer, the *magnetic memory* of hard steel for its past magnetic state is good, while that of soft iron is bad. As will be seen in the chapter on electromagnetism, the ability of soft iron to acquire and lose magnetism readily, forms one of the most valuable properties of the electromagnet.

As might be supposed from the preceding, experiment has shown, that when hardened steel is softened by annealing, it loses its retentivity; and, on the contrary, when soft steel is hardened, as for example by pressing, rolling, or heating and suddenly chilling it acquires a greater retentivity. Magnetic retentivity therefore is associated with molecular condition.

Contrary to what might be supposed, the iron or cast steel employed in the large magnets for dynamo-electric machines, is not selected for its retentivity, these magnets being always excited by electric currents so that their retentivity is not essential.

CHAPTER III.

THEORIES OF MAGNETISM.

If a magnetized bar of hardened steel, such as a watch spring, be rolled in iron filings, the filings will not be equally attracted to all parts of the bar, but will collect mainly at the ends, the central portions being practically uncovered. The actual state of things is represented in Fig. 7, where the filings are seen to be collected at the ends *N* and *S*, respectively the north and south poles of the magnet. A small compass needle approached to this bar, as shown, will indicate that all parts between the centre and the north pole are of north polarity, and all parts between the centre and the south pole are of south polarity. The point *O*, which acts as a point devoid of magnetism, is called the *neutral point.* The intensity of the magnetism increases from the neutral point toward each end or pole.

In order to explore the bar and determine its apparent distribution of polarity, suppose the compass needle be approached to the north end of the bar; it will then be found that its south pole will continue to be attracted by the bar until the neutral point *O*, is reached, when the

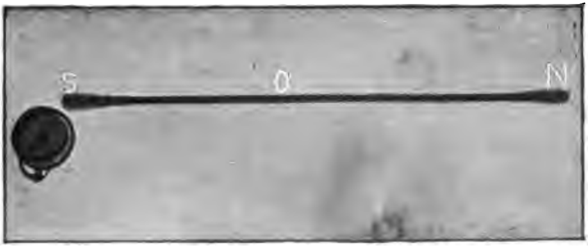

FIG. 7.—MAGNETIZED BAR WITH IRON FILINGS SHOWING POLAR CONDITION.

needle will turn and the opposite end will be attracted from *O* to *S*. Moreover, it can be shown that the strength of the magnetic influence, proceeding from the bar, is zero at the neutral point and increases rapidly toward the ends of the bar, following a curve similar to *NOB*, Fig. 8, the left-hand portion being drawn below the line to represent south polarity.

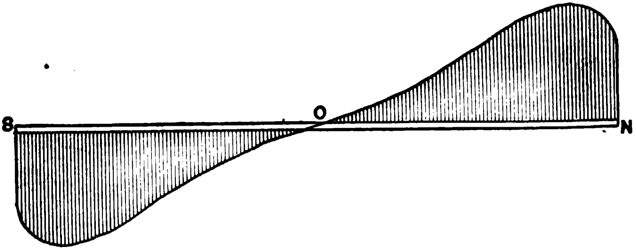

FIG. 8.—DIAGRAM REPRESENTING DISTRIBUTION OF MAGNETIC FLUX ENTERING AND LEAVING BAR MAGNET.

A magnetic bar possesses no external magnetism at its neutral point. It early occurred to investigators in magnetic phenomena, that if a bar, magnetized as in the preceding experiment, be cut or separated at the neutral point, two magnets would be obtained, one of which would possess nothing but north polarity, and the other, nothing but south polarity. A trial being made, however, to their astonishment it was found that a bar so separated did not possess separate polarities, but displayed opposite polarities at each end, each bar having, as before, two poles, shown by rolling them in iron filings which collected at the ends as in the figure. Moreover, the curve representing the intensity of the magnetic effect by each piece possessed the same peculiarities as in the first case. It was also found that if one of the two pieces be divided at the neutral point, there will again be produced two magnets, possessing poles at their extremities, and, that no matter how far this subdivision be carried, each of the separate bars would possess at its extremities, separate north and south polarities. This is shown in Fig. 9, where the bar employed in Fig. 7 was first divided into halves, one of which was left at *A*, and the other divided into quarters, one of which is shown at *B*, and then the remaining quarter was divided into eighths, two of

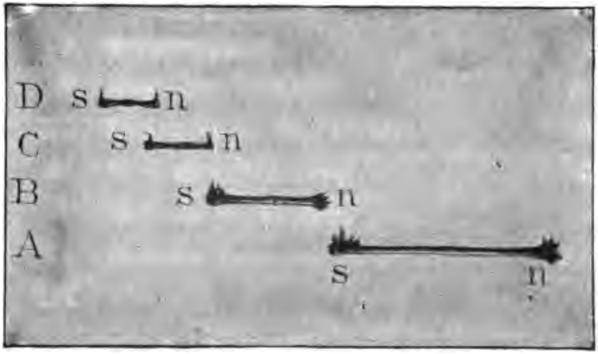

FIG. 9.—POLARITY OF DISSECTED MAGNET.

which are shown at *C* and *D*. Here the filings, collected at the extremities, show the existence of poles, the polarity of which is indicated by the letters *n* and *s*.

It would appear, therefore, to be impossible any longer to hold to the fluid theory of magnetism; namely, that a bar owed its magnetic properties to the accumulation of north and south magnetic fluids in the neighborhood of its poles; for this theory would necessitate the existence of absolutely no magnetism at the neutral point, whereas the experiment of the divided bar shows that the magnetism exists as strongly here as at any other part of the magnet, being, for reasons which were not then understood, in a masked or neutral condition at this point. An attempt was, therefore, made to modify the fluid hypothesis, by supposing that under the influence of a magnetizing force, a separation of the magnetic fluid occurred in each of the ultimate particles of the magnet. This modified theory has, in later years, given place to the theory which we will now discuss.

According to the more modern theory, the cause of magnetism in iron is ascribed to its ultimate particles, which are assumed to inherently possess north and south polarity. In other words, if we could isolate an ultimate particle of iron, we should find that it inherently possesses a north and south pole, and, therefore, tends to behave like a small compass needle. According to this theory, the act of magnetization consists in an alignment of all the ultimate particles of the bar, that is, causing all the poles to take the same direction, or to point along the same line. The bar acquires its full magnetization, or is magnetized to *saturation* when all its particles are thus aligned. In order to explain why a bar of unmagnetized iron should be devoid of sensible magnetic properties, when each of its ultimate particles is assumed to possess magnetism, it is only necessary to suppose that in unmagnetized iron there is a lack of definite alignment, the particles being arranged in a haphazard manner, so that the influence of their adjacent opposite poles would be to prevent any magnetic effects from being perceived outside the mass.

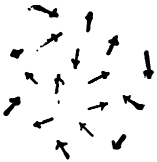

FIG. 10.—HETEROGENEOUS ASSOCIATION, CORRESPONDING TO ABSENCE OF MAGNETIZATION.

The above theory of magnetism is capable of accounting for the complete magnetization of a bar, for the complete neutral condition, or for any intermediate state. A partially magnetized bar, for example, is one in which there exists only a partial alignment of the ultimate particles. The condition of the molecules in an unmagnetized bar, where no definite alignment has been produced, is represented diagrammatically in Fig. 10. Here the arrows represent the assumed individual molecular magnets, the pointed end of each arrow being assumed to possess north polarity and the other end,

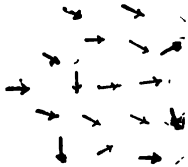

FIG. 11.—PARTIAL ALIGNMENT CORRESPONDING TO PARTIAL MAGNETIZATION.

south polarity. Evidently, a mass of iron with this interior molecular arrangement, would possess no resultant external magnetism since the opposing polarities would neutralize each other's external influence.

In Fig. 11, the arrangement of the molecular magnets is shown, when a partial alignment occurs. Here some of the molecular magnets, say thirty, or forty per cent., have a definite alignment, while the others are heterogeneously arranged. As before, these latter should neutralize each other's influence so far as

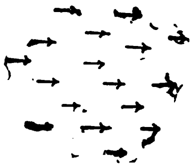

FIG. 12.—COMPLETE ALIGNMENT, CORRESPONDING TO COMPLETE MAGNETIZATION.

internal effects are concerned, while those which possess a definite alignment would necessarily produce external magnetic influence.

The condition of affairs shown in Fig. 12 is that in which all the separate molecular magnets are aligned in the same general direction, under the influence of some external magnetic force. Here the maximum external magnetic influence is produced.

Attempts have been made by investigators to study, on a large scale, the condition of affairs, which, according to the preceding theory, exists in the interior of a bar of iron, by grouping a fairly great number of separate compass needles, placed sufficiently near each other, but without actually touching, to sensibly influence each other's movements. Under these circumstances, it is found that subsequent disturbances of the needles, of as nearly as possible the same character and force, do not bring about the same groupings. The needles are then subjected to a more powerful magnetizing force, under the influence of which, either a partial or a complete alignment of the separate magnets is obtained, according to the strength of the magnetizing force employed.

According to the theory we have here discussed, the difference in the behavior of hardened steel and soft iron, as regards both magnetization and demagnetization, is due to the fact that in hardened steel, which, as we have seen, possesses considerable resistance to magnetization, but tends when once magnetized to retain such magnetization, the separate molecules, or individual molecular magnets, are not easily turned so as to become aligned; while the case of soft iron, which is easily magnetized, and which, with equal readiness, loses its magnetization, the resistance to this turning is comparatively small.

In the case of the model of a magnet just referred to, the condition of affairs somewhat resembling that of hardened steel, where the individual magnets display considerable resistance to motion, might be obtained by supporting the compass needles in some clear, viscid liquid like glycerine. In such a case, it would require a powerful magnetizing force to bring all the separate magnetic needles into alignment, but once this alignment had been obtained, there would also be considerable difficulty in breaking it up, on account of the fluid friction throughout the mass. The same hypothesis also explains a fact which has presented no little difficulty to experimenters; namely, the effects heat produces on a magnetized bar. When a magnetized bar is heated to redness it is found that it entirely loses its magnetism. Since the effect of an increase of temperature is to increase the ease with which the molecules of the bar can move to-and-fro, the facility with which a given alignment can be lost on account of their more frequent collisions and freedom of movements is thus explained.

A body is said to be soft when its particles can be easily displaced relatively to one other. On the contrary, a hard body is one whose particles cannot be easily displaced. It would, therefore, seem highly probable that the properties of a piece of iron, which should prevent magnetic displacement or alignment of the particles, should also be the property which is recognized as mere mechanical hardness. Naturally, therefore, according to this theory, a piece of soft iron should be readily magnetized because, being soft, its particles possess this necessary mobility, while, on the contrary, a piece of hard iron should tend to resist magnetization, because its particles, being hard, possess rigidity. In the same way, soft iron should readily lose its magnetic condition, when removed from the influence of the magnetizing force, while the bar of steel should, on the contrary, retain its magnetization for a considerably greater period. These are precisely the characteristics of soft iron and hard steel.

Since the ability of a bar of hardened steel to retain its magnetism is due to a physical rather than to a chemical property, the same bar of steel, if annealed or softened, should practically act like a bar of soft iron; while, on the contrary, if it be hardened, as by being raised to a high temperature and suddenly cooled, it should resist changes in its magnetization. These theoretical considerations are established as facts in actual practice. Bars of steel can be rendered so hard that magnetizing forces, sufficiently powerful to impart considerable strength of magnetism to the same bars when not so hardened, may be utterly incapable of producing any apparent effect as to their magnetization. In order, therefore, to obtain permanent magnetic effects in bars of steel, it is necessary to obtain such bars as hard as possible.

The preceding theory accounts satisfactorily for nearly all the observed phenomena of magnetism in iron. It will be noticed, however, that to a very considerable extent, the theory begs the question as to the real cause of this strange force, since it does not attempt to explain how, or by what means, the ultimate particles of iron become magnetized. It simply assumes them to be magnets. Attempts have, therefore, been made to supplement the theory by endeavoring to explain why the ultimate particles of iron should be magnetic.

One of such theories assumes that the magnetism produced by iron and other substances is due to *whirlings* or *vortices* in the ether. It assumes that a magnetized bar, or a magnetized molecule, produces a whirl or cyclonic motion in the surrounding ether, and attempts have been made to explain magnetic attractions and repulsions, as well as other magnetic effects, by these movements of the other. Another and somewhat similar theory ascribes magnetic phenomena also to a motion in the ether, but this motion is assumed to be one of a forward motion like wind; so that, according to this view, a magnetized molecule, or collection of molecules, produces actual *magnetic streamings*, or a streaming motion in the ether, along the direction in which the magnetic needle points.

Without giving a preference to either of the two theories just mentioned, we will adopt the latter throughout this little book, on account of the greater convenience which a theory of a simple streaming ether motion possesses over a vortical motion. No theory of magnetism can be considered worthy of credence unless it is also capable of accounting for the allied phenomena of electricity. Electric currents are never varied without at the same time producing magnetic phenomena, and, conversely, the intensity of magnetic streamings are never varied without, at the same time, producing electric phenomena.

In order to endeavor to obtain a conception of the state of affairs which exists in a magnetized bar of iron, let us suppose that each of the molecules of the iron has a structure such that permits it to act as a miniature fan motor, inherently possessing rotation. Since it is surrounded by the ether, which is a frictionless fluid, if this fluid be once set in motion it would require no additional force to keep it moving forever. Consequently, if once set in motion, it would continue moving forever. These molecular fans may be imagined to set up, by their rotation, a streaming motion of the ether through them. Looked at in this light, the theory of magnetism which ascribes the phenomena to the molecules themselves, regards each molecule as possessing magnetic properties because it causes a streaming motion of ether to take place through it. Since all molecules of matter probably possess rotation, and since they apparently do not all possess magnetism, it is presumable that the molecules of the magnetic metals only, owing, perhaps, to some peculiarity of shape, produce as a result of their rotary motion, the ether streamings above referred to.

It will be seen that the above theory,

like the one already referred to, traces the magnetism of a bar to its ultimate molecules. Instead, however, of assuming that these molecules are inherently magnetic, without explaining the ultimate causes of their magnetism, it possesses the merit of giving a working hypothesis as to the possible origin of their magnetism. The theory accounts for the unmagnetized condition of a bar of iron in its neutral state, on the assumption that the ether streamings, caused by the individual molecular magnets, possess no definite alignment, so that the tendency of the separate streamings is to neutralize one another. As soon, however, as an alignment is obtained, the effect must be that all these molecules produce a co-directed streaming in the ether, whose intensity is, therefore, appreciable at a considerable distance from the magnet.

Let us consider, therefore, what must occur, according to this theory, in the case of a small bar of iron, which has acquired external magnetic properties, that is to say, has become magnetized by reason of having all its molecular streamings similarly directed. The effect will evidently be to cause a powerful ether streaming to pass through the bar in the direction of its length, issuing at one pole, and, after having traversed the space outside the magnet, re-entering at its opposite pole. These streamings, as will be subsequently shown, take paths as may be traced by a small compass needle, which are geometrically of the same form as those which would be produced in a frictionless fluid, if all the molecules in the bar did actually consist of miniature mechanisms whereby ether could be continually pumped through them.

The theory of magnetic streamings is capable of explaining all the ordinary phenomena of magnetism. Take, for example, the directive tendency of the magnetic needle, as evidenced by its coming to rest in a definite direction under the influence of another magnet. Suppose, for example, a bar magnet be approached to a suitably supported magnetic needle; then this needle will come to rest when the ether streamings from the bar magnet pass through the magnetic needle in the same direction as the ether streamings produced by the magnetic needle itself. Of course, since the ether streamings are purely hypothetical, and, indeed, could not be seen, even if we were absolutely assured of their existence, it is impossible to say whether they emerge from the north pole or the south pole of the magnet, but since the theory supposes that in a magnet the streamings are all co-directed, it is clear that they must all come out of one magnetic pole and re-enter at the other pole. In order to fix definitely our ideas concerning this important point, it has been generally agreed to regard the magnetic streamings as issuing from the north pole of the magnet and re-entering it at the south pole, as represented in Fig. 13 by the arrows. Here, however, only a portion of the streaming paths is shown, each arrow being assumed to be extended until it forms a continuous path both outside and within the magnet.

FIG. 13.—CONVENTIONAL DIRECTION OF MAGNETIC FLUX.

In this light, therefore, let us again examine the action of a magnetic bar on a suspended needle. Suppose, for example, that it be the north pole of a magnet which is approached to a needle. Then the ether streamings, emerging from the north pole of the magnet, will penetrate the substance of the magnetic needle, and the needle will rotate until the two streamings are similarly directed; but, to do this, it is evident that the movable needle must turn around until it presents its south pole to the north pole of the approached magnet; for, in that condition only can the ether streamings produced by the approached magnet pass through the needle in the same direction as its own ether streamings. Suppose, however, that the magnetic needle be fixed, and that the north pole of the magnet be approached to its north pole. Then the ether streamings of the two magnets will be opposed, and a repulsive tendency will exist between them. It is under the influence of this repulsive tendency that the magnetic needle, as soon as free to move, will turn around until it presents its opposite pole to the approached magnet.

It might be supposed that if such streamings, as we have hitherto assumed, actually existed, that they would manifest their presence by actually carrying gross matter bodily along with them, though no such effect is actually observed, yet it is quite possible that ether streams might exist without necessarily producing translatory motion in material masses, since it might readily pass through their intermolecular space.

CHAPTER IV.

MAGNETIC CIRCUITS.

THE theory which we have provisionally adopted concerning the origin of magnetism; namely, that it is due to ether streamings, which issue from the magnet at its north pole, and re-enter it at its south pole, necessitates, as we have seen, the conception of a completed path, called the *magnetic circuit*, through which these streamings pass. This path consists of two distinct parts; namely, of the region outside the magnet, and that within its body or substance. A little reflection will show that this necessarily forms a closed path. Tracing the path of the ether stream issuing from the north pole of, for example, the bar magnet shown in Fig. 14, it will be seen that after having traversed the region outside of the magnet it re-enters the magnet at its south pole, from which, after passing

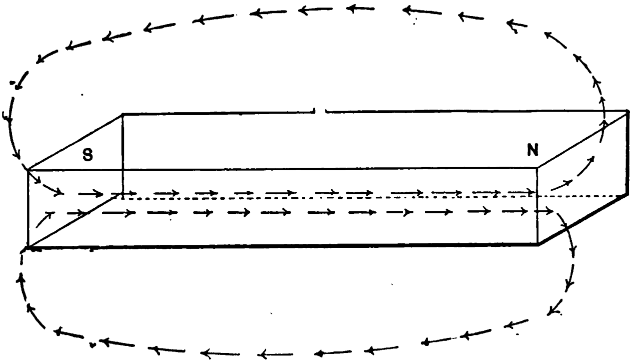

FIG. 14.—SIMPLE MAGNETIC CIRCUIT.

through the body of the magnet, it again issues from the north pole.

The ether streamings take various paths in the region outside of the magnet, some of the paths lying close to the body of the magnet itself, while others are situated at greater distances from it. They all, however, agree in this respect; they issue, as is conventionally assumed, from the magnet at its north pole and re-enter it at its south pole. In other words all magnetic *stream-lines* form closed paths or circuits, and no magnetic stream can terminate abruptly.

Magnetic streamings are generally known as *magnetic flux*. They were generally alluded to in the earlier writings as *lines of magnetic force*, or sometimes as *tubes of magnetic force*. The provisional theory, which we have adopted, regards them as actual ether streamings set in motion through the molecular mechanism of the magnet, and this conception is preferable to that of lines of magnetic force. As to what the velocity of these ether streamings may be, it is impossible to estimate; it might be very great, or it might be very small. In referring to Fig. 14, care must be taken to remember that the paths of the stream lines are here entirely diagrammatic. An inspection of the figure will show clearly, however, that a magnetic circuit consists, as already stated, of two distinct parts; namely, the portion of the circuit lying in the regions outside the

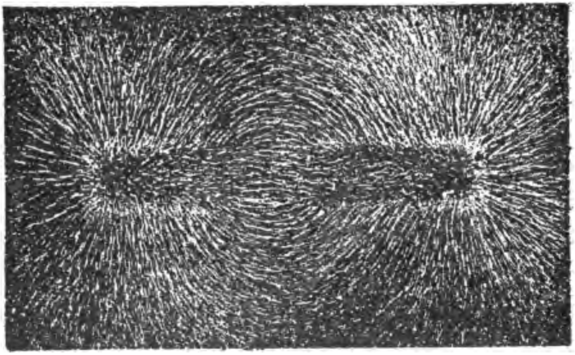

FIG. 15.—FLUX OF BAR MAGNET.

magnet, generally occupied by the air, and that portion which is formed by the mass of the magnet itself.

A more nearly accurate representation of the actual paths taken by some of the stream lines is shown in Fig. 15. The method by which this figure has been obtained will be explained later. An inspection of this figure will show a greater number of stream-lines and, moreover, will render evident the fact that the points of entrance and exit of the magnetic flux are by no means situated near the extremities of the bar, but exist over considerable portions of the surface. The stream-lines shown at the end of the bar are approximately straight paths, but in certain portions of the figure it can be seen where the paths actually emerge from one part of the magnet and re-enter at another part.

Were the area of the figure sufficiently enlarged, that is, if a sufficient length of the stream-lines had been represented, it would be seen that all form closed circuits, the stream lines issuing from any point of the magnet re-entering the magnet at some other point.

Magnetic flux may complete its path through a circuit entirely of iron, entirely of air, or partly of iron and partly of air. A magnetic circuit may, therefore, be formed entirely of iron, entirely of air, or partly of iron and partly of air. A magnetic circuit formed entirely of iron is generally termed a *ferric magnetic circuit.* A magnetic circuit formed entirely of air is generally termed a *non-ferric magnetic circuit* and a circuit formed partly of iron and partly of air is called an *aero-ferric circuit.*

Nearly all practical magnetic circuits are of the aero-ferric type. Fig. 16 represents a ferric-magnetic circuit. Here the flux paths lie completely in the mass of the iron ring which forms the complete circuit. Such a magnetic circuit, although possessing flux circulating through it, would, nevertheless, manifest no external magnetic effects, although all its molecular magnets would be aligned concentrically in annular paths; and, consequently. would have all their ether streamings co-directed, so that the streamings would

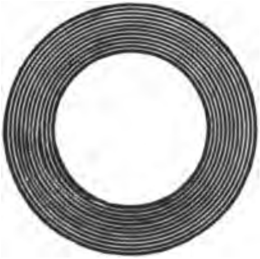

FIG. 16.—FERRIC MAGNETIC CIRCUIT.

take circular or annular paths through the bar. Although the ring would thus be powerfully magnetized, yet, since none of the flux escapes into the air, but is all contained within the iron itself, no external magnetism is perceived either by a compass needle or by iron filings.

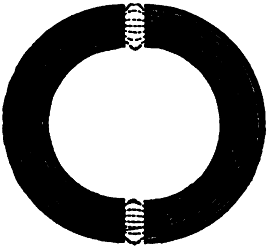

FIG. 17.—AERO-FERRIC MAGNETIC CIRCUIT.

That a closed iron ring actually possesses magnetism can readily be demonstrated by making an air gap, as by a saw, through one or more parts of the ring. If this be done, as shown in Fig. 17, in the case of a hard iron ring, powerful magnetic poles will be developed, at opposite sides of the gaps, the polarity of which, in accordance with the convention already referred to, will be respectively north and south, at the points where the magnetic flux issues from and enters into the iron.

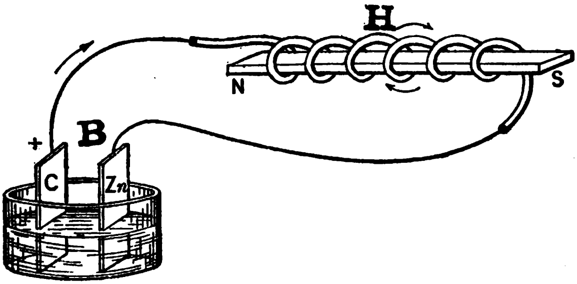

FIG. 18.—VOLTAIC CELL SUPPLYING CURRENT TO A HELIX.

We have now to describe a non-ferric circuit. If, as in Fig. 18, an electric current is sent from an electric source, such as a battery B, through a *helix* or *coil of wire H*, the helix acquires all the properties of a bar magnet, even though the bar of iron $N\,S$, be removed. Such a circuit, with the bar removed, is called a *non-ferric circuit.* It is evident that a ferric, or aero-ferric circuit, may be maintained entirely by a permanent magnet, but a non-ferric circuit necessarily requires an electric current to maintain it.

It is a well-known fact that a bar of soft iron is attracted and held to the poles of a magnet, such, for example, as a horseshoe magnet. If the magnet be fairly powerful, a plate of glass, interposed between the poles of the magnet and the piece of iron, will not prevent the iron from being attracted and held to the poles, although, of course, not so powerfully, on account of the distance intervening between the piece of soft iron and the magnet poles. The strength of the magnetic action rapidly decreases with the distance from the magnet. Since magnetic attraction is due to the flux from the magnet passing through the iron, it is evident that the glass does not interpose any obstacle to the passage of flux through it. Similarly, a piece of wood, porcelain, or copper, or, in fact, any material except the magnetic metals, would, like glass, permit attraction to take place through its mass; or, in other words, would permit the flux to pass through it. If we except the magnetic metals,all substances, whether solid, liquid, or gaseous, conduct magnetic flux with practically equal facility, all of these substances offering about the same resistance to its passage as does ordinary air. Consequently, in the case of the bar of iron attracted to the magnet through the plate of glass, the strength of such attraction, if measured, would be found to be practically the same as if prevented from moving to the magnet and separated by the same distance of air.

If a plate of glass be supported horizontally over a flat magnet, say a horseshoe magnet, and iron filings be sprinkled over the glass, as soon as these iron filings enter the regions traversed by the flux produced by the magnet, they will be magnetized. Consequently, in their passage through the air, they tend to form chains by the attraction between their adjacent poles; or, looking at the phenomenon from a different standpoint, the minute particles of iron practically become grouped in curved paths extending in the direction of the stream lines of magnetic flux. In order to assist in the grouping of the iron filings the plate is gently tapped after they have fallen on its surface. Under these circumstances, the filings will collect in certain groupings forming what are known as *magnetic figures*, such groupings only representing the direction of the flux lines in the plane of the glass plate.

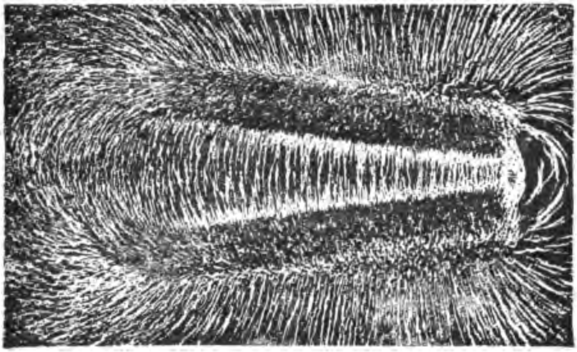

FIG. 19.—MAGNETIC FLUX OF HORSESHOE MAGNET.

Fig. 19 shows groupings of iron filings obtained in this way. Here, as in Fig.

15, which was similarly obtained, it will be observed that all the streamings by no means leave the magnet at its extremities or poles, but that such streamings exist between all portions of the surface of the magnet. Near the extreme poles, the filings will be observed to collect in denser masses than elsewhere, thus indicating a greater flux or flow of magnetism at these points. In the case of any magnetic working device, such, for example, as the horseshoe magnet, shown in Fig. 19, the useful work done by the magnetic flux is limited to some particular portion of the magnetic circuit, in this particular case, to the region surrounding or lying between the poles of the magnet. It is in this region that all the useful flux of the magnetic circuit passes. The remaining portion of the flux, from which no useful effect can be obtained, is generally known as *leakage flux* or as *magnetic leakage.*

Various processes have been devised for the purpose of permanently fixing the iron filings on the surface of the glass plate, or on the surface of the piece of paper, so as to render the groupings permanent. One of these processes consists in covering the surface of a sheet of paper or glass with a thin coating of wax or paraffine. The filings are applied to the sheet while the paraffine is cold, and, consequently, hard, and, after a suitable grouping has been obtained, the filings are fixed in place by heat gently applied to the wax, as, for example, by holding a hot iron near the surface, or by permitting the flame of a Bunsen burner to play gently over the surface of the plate.

When the groupings of filings are so fixed on the surface of a glass plate, the glass may be used as a positive for the purpose of obtaining negative photographic prints; for, if such a glass plate is placed over a sheet of sensitized paper, with the coated side in contact with the printing paper, and exposed in a printing frame to sunlight, all portions of the plate not protected by the iron filings will permit the sunlight to pass through, thus blackening the paper. Such a print will, therefore, contain white lights where the iron filings are collected, and black lines in the free spaces.

A modification of this process, which gives much better results, and is more easily manipulated, is carried out as follows: The grouping of iron filings is obtained on the sensitized surface of a dry, photographic plate, placed over a magnet in a dark room; and, when a suitable distribution of iron filings has been obtained, the plate is exposed momentarily to a flash of light, such as obtained, for example, by the lighting of a match, which is then instantly extinguished. On removing the iron filings from the plate, and developing it, a photographic negative picture of the groupings will be obtained. This picture may be employed for printing, by obtaining positive photographic prints in the usual manner, when the lines of filings will appear as dark lines in the print.

Figs. 20 to 26 represent magnetic flux paths or stream lines, obtained in this latter manner. Fig. 20, for example, is a representation of the flux lines obtained in the case of the horseshoe magnet used in Fig. 19 to obtain a negative print. In Fig. 20, it might appear that no flux lines or paths exist at the extremities in front of the poles, since this entire region appears destitute of flux paths. This, however, is due to the fact that on tapping the glass plate the powerful attraction of the poles for the magnetized particles

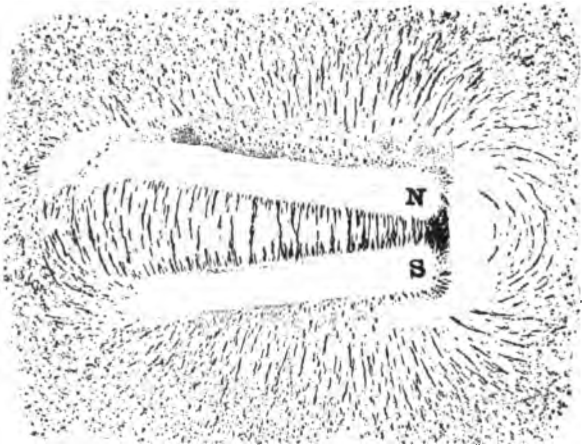

FIG. 20.—FLUX PATHS OF TWO ADJACENT BAR MAGNETS.

has caused them to here slide over the smooth surface of the glass and collect between the poles.

It should be remembered that representations of groupings of filings obtained by either of the above described processes cannot be regarded as marking accurately the exact flux paths; since, in reality,

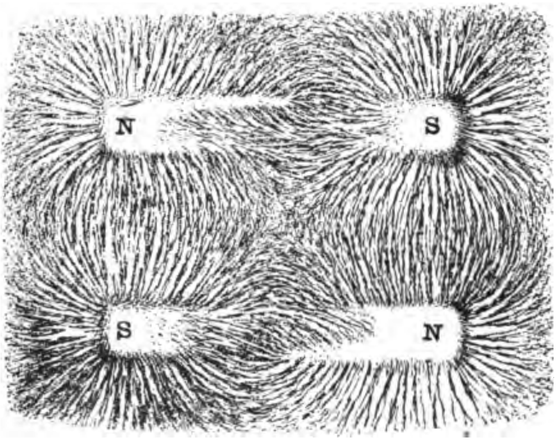

FIG. 21.—FLUX PATHS OF TWO ADJACENT BAR MAGNETS.

all portions of the space outside, as well as inside, the magnet are occupied by the streamings. Moreover, such figures, of course, are unable to show that portion of the flux lines which occurs inside the body of the magnet.

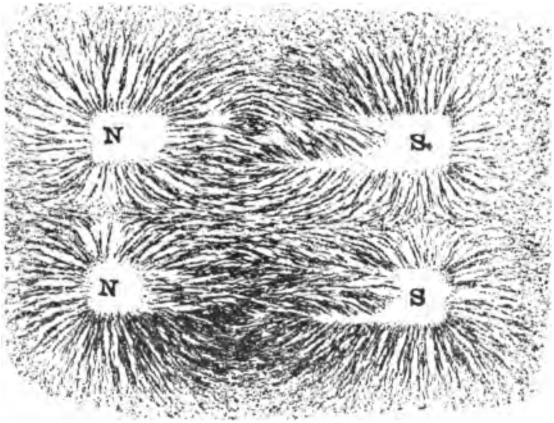

FIG. 22.—FLUX PATHS OF TWO ADJACENT BAR MAGNETS.

Fig. 21 shows the figure of flux paths that is produced when two bar magnets are laid side by side at a distance of approximately half the length of either, and with their poles of the polarity shown. Here, as will be seen, the south pole of one magnet is adjacent to the north pole of the other magnet. The flux streams passing out of the north pole of each magnet enter the south pole of the adjacent magnet, the flux from one magnet merg-

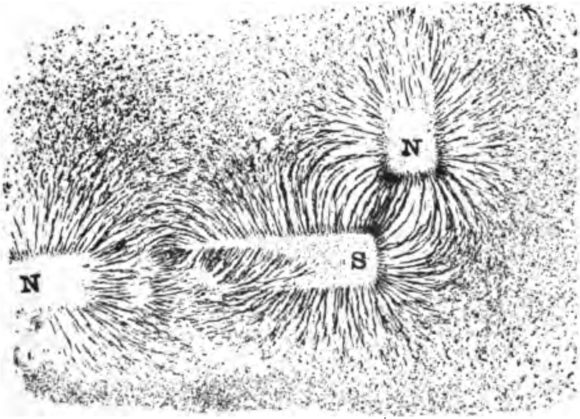

FIG. 23.—FLUX PATHS. UNLIKE POLES AT RIGHT ANGLES.

ing with that of the other. This merging, however, only occurs in the immediate neighborhood of the poles. In the regions between the poles, it is evident that the flux does not so merge, each magnet preserving an independent circuit. In the middle of the figure, a curiously shaped region exists, at the

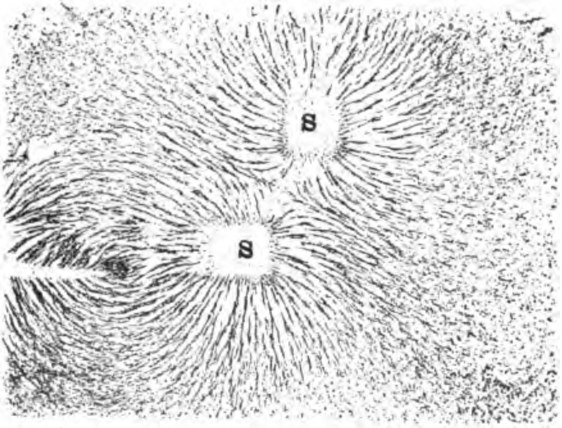

Fig. 24.—Flux Paths. Like Poles at Right Angles.

centre of which there is a neutral point or point devoid of magnetism.

Fig. 22 shows a field produced by the same two bar magnets, placed as in Fig. 21, but with like poles adjacent. Here the flux is oppositely directed, and produces, in the neighborhood of the poles, a hori-

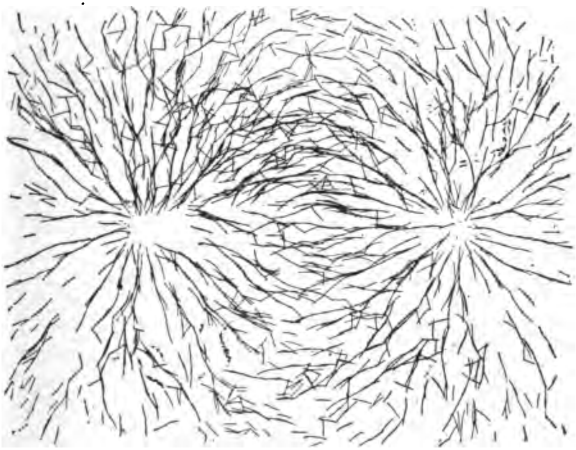

Fig. 25.—Flux Paths of Bar Magnet. Iron Wires.

zontal line of such a contour as would be formed if, in reality, liquid streamings were directed against each other. In this case there is no merging of the circuits, as shown in Fig. 21, the circuit of each magnet being independent throughout.

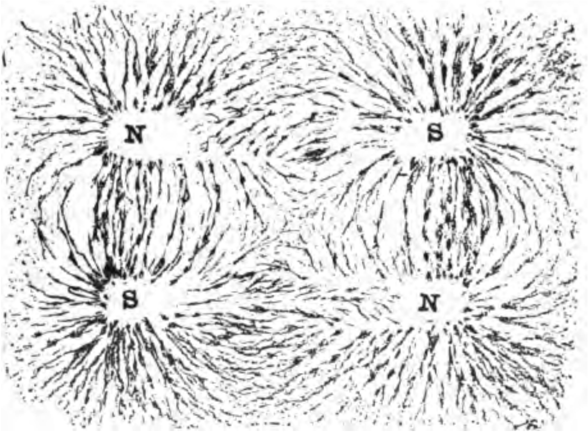

FIG. 26.—FLUX PATHS OF BAR MAGNETS. IRON WIRES AND FILINGS.

The effect produced by placing opposite

poles adjacent to each other is shown in Fig. 23, where the north and south poles of two bar magnets are placed at right angles to each other at a distance apart, about equal to the breadth of the magnet.

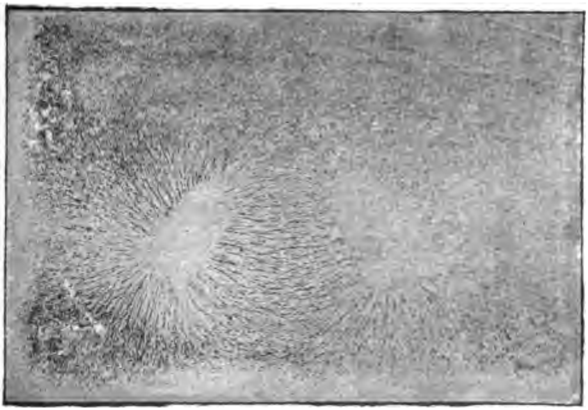

FIG. 27.—SEMICIRCULAR BAR MAGNET FLUX PATHS.

Here the flux streamings of the two magnets merge in the neighborhood of the poles, but, as before, are independent in the other regions. In Fig. 24, is shown the effect produced by two similar poles of two bar magnets, placed as in Fig. 23, except that like poles are adjacent. Here, as before, the flux paths of each magnet are independent. The effect of the conflicting streamings is to produce a line of no motion corresponding to slack water in a tideway.

A modification of the preceding magnetic figures can be obtained by employing short pieces of soft iron wire instead of iron filings. Fig. 25 is obtained in this way from the bar magnet shown in Fig. 15. Similarly Fig. 26 is a representation of the same arrangement of magnets, as is shown in Fig. 21. Here, however, a mixture of iron filings and wire has been employed.

Fig. 27 shows the flux paths obtained from a semicircular bar magnet.

Fig. 28 shows the field of two such semicircular magnets with opposite poles opposed.

Here also a neutral space is produced at the centre of the figure, and at this point there would be little or no directive tendency exerted upon a very small compass needle.

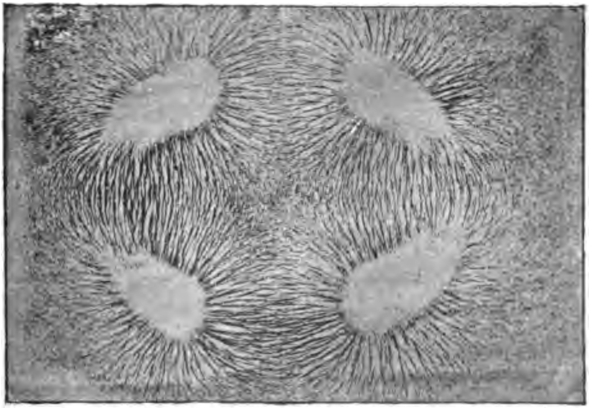

FIG. 28.—FLUX PATHS OF TWO SEMICIRCULAR BAR MAGNETS.

Although the general distribution of magnetic flux is shown by the paths of iron filings strewn in a suitably arranged horizontal plane, near a magnet, yet the density of the iron filings or of their chains is not to be relied upon as indicating with accuracy the density of the magnetic flux. A magnetic field of uniform density has very little power to attract and align iron filings, while an irregular field, independently of its density, has a powerful influence upon them.

CHAPTER V.

ELECTROMAGNETISM.

PRIOR to the famous discovery by Oersted, in 1820, of the magnetic properties of an electric circuit in which a current of electricity was passing, no relations had been proved to exist between electricity and magnetism, although, of course, such relations had been suspected. Oersted showed that a wire carrying a current, when placed near a magnetic needle, possesses the same power of attracting and repelling the needle as does an ordinary magnet. In other words, a conductor carrying an electric current sets up magnetic flux streamings, which become endowed with magnetic properties which they retain during the passage of such current.

If, for example, a copper wire *A B*, Fig. 29, carrying a current in the direction

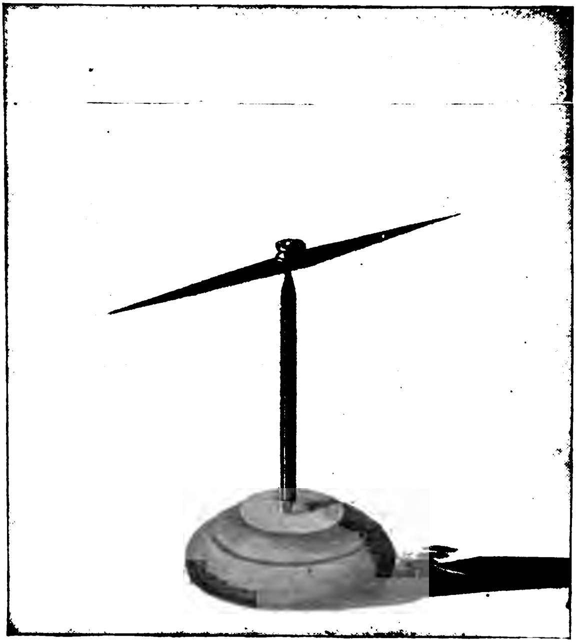

FIG. 29.—DEFLECTION OF MAGNETIC NEEDLE WHEN SUPPORTED BENEATH A WIRE CONVEYING AN ELECTRIC CURRENT.

from *A* to *B*, be held over the magnetic needle *N S*, the needle will be deflected as indicated. In virtue of the current it carries, the wire has evidently acquired magnetic properties. Moreover, if the conductor be placed beneath the needle, instead of over it, the needle will be deflected in the opposite direction. If in either of these positions, the direction of the current be reversed, the direction of the needle's deflection will also be reversed.

These deflections of the magnetic needle find their explanation in the fact that the passage of an electric current through a conductor always produces, in the region surrounding the conductor, a magnetic field in which the magnetic flux take circular paths, concentric to the conducting wire. In other words, the passage of an electric current through a wire produces magnetic streamings in circular paths around the wire. Figures of these magnetic streamings can be obtained, in the case of a conductor carrying a current, by passing the conductor perpendicularly through a horizontal sheet of paper, and

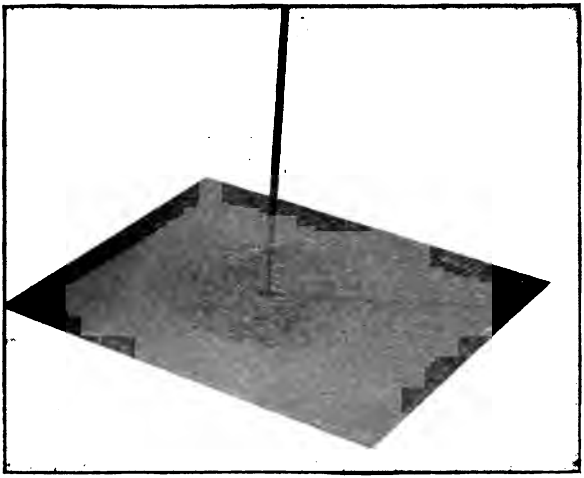

FIG. 30.—CIRCULAR DISTRIBUTION OF FLUX PATHS AROUND A WIRE CONVEYING AN ELECTRIC CURRENT.

sprinkling iron filings over the surface of the paper around the wire, while the current is passing.

A characteristic grouping of iron filings, so obtained, is shown in Fig. 30, where it will be seen that the iron filings surround the vertical conducting wire *A B*, in concentric circular paths.

Reference has been made to the assumed direction of lines of magnetic flux in the case of ordinary bar and horseshoe magnets; viz., that it had been agreed to regard the flux as emerging from the north pole of the magnet and as re-entering it at the south pole. Since, as we have seen, the direction of the needle's deflection is changed by reversing the direction of the current, it is evident that the circular flux streamings surrounding a conductor must also change with the change in the direction of the current through the wire, although, as before, no visible change takes place in the grouping of the iron filings. Since a magnetic needle tends to come to rest in a position parallel to the flux lines, with these lines entering

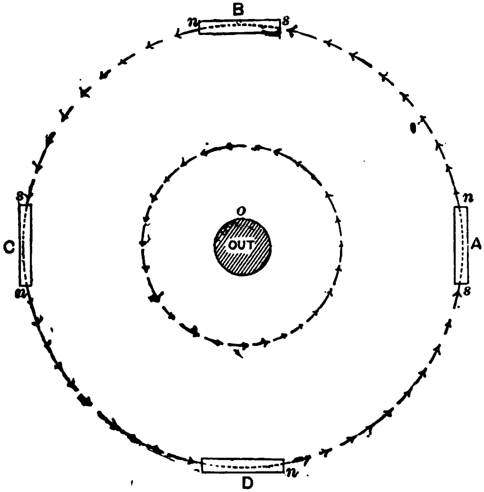

FIG. 31.—DIRECTIVE INFLUENCE OF CIRCULAR MAGNETIC FLUX AROUND ACTIVE CONDUCTOR CARRYING CURRENT TOWARD OBSERVER.

at its south pole and passing out at its north pole, it is evident, that having once assumed their direction for the case of permanent magnets, that their direction in relation to an electric current is thereby fixed.

Suppose, for example, that a current be flowing through a vertical conductor, placed at right angles to the plane of a sheet of paper at *O*, Fig. 31, *toward* the observer, and that it be found that a small magnetic needle supported at *B*, comes to rest in the position shown; *i.e.*, pointing across the wire and to the left. If now the needle be placed successively at *C*, *D* and *A*, it will come to rest in the positions shown. Since the directive tendency of the needle is caused by the passage through it of the magnetic flux established by the active conductor, and since the needle points in the direction of the magnetic flux at the point where it is placed, it is clear that the direction of the magnetic circular flux, which surrounds such a conductor, will be opposite to the motion of the hands of a clock; *i.e.*, counter clockwise.

If the direction of the current be reversed, so that the current now flows through the wire *from* the observer, the needle will still come to rest in the direction of the lines of flux, but in the opposite directions, so that the flux paths here circulate clockwise around the conductor. It is evident, therefore, according to the theory here assumed, that, could we see the ether surrounding an active conductor, the result produced by causing a current to flow through such conductor would be to set up circular streamings in the ether surrounding the conductor, and that the only effect produced by changing the direction of the current is to change the direction of these streamings.

We will now inquire as to what effect will be produced by bending an *active* *conductor; i. e.*, a conductor carrying an electric current, into the form of a loop. Suppose, for example, that the straight wire represented in Fig. 32, carries a current in the direction of the large arrow, and that the direction of the circular flux thereby produced, be indicated by short

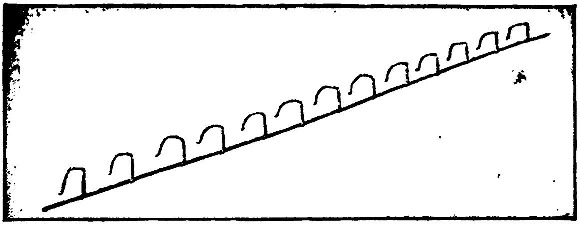

FIG. 32.—MODEL REPRESENTING DIRECTION OF FLUX AROUND WIRE.

pieces of curved wire mounted upon the conductor as shown. Then, if this straight conductor be bent into the form of a conducting loop, as shown in Fig. 33, it will be evident that all the circular flux paths around the wire will be so directed that the flux will enter from above and pass downward through the loop, and moreover, that if the direction of the current be changed, all the flux produced will still pass through the loop,

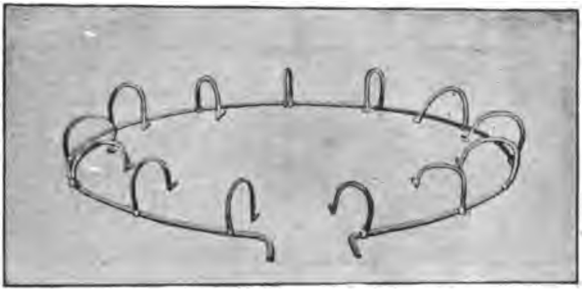

FIG. 33.—MODEL REPRESENTING DIRECTION OF FLUX THROUGH WIRE BENT IN FORM OF LOOP.

but now in the opposite direction. The effect, therefore, of causing an electric current to flow through a conducting loop is to cause an ether stream to flow through the loop. If the current strength flowing through the loop be increased, the ether stream, or magnetic flux passing through the loop will also be increased in the same proportion; or, according to our provisional theory, the amount of ether streaming through the loop in a given time will be increased.

The intensity of magnetic flux through a conducting loop will everywhere be increased by an increase in the current strength. In the case of a straight wire carrying a current of given strength, the intensity of the magnetic flux will be inversely proportional to the distance from the wire; *i. e.*, the ether streamings will be twice as weak at twice the distance from the wire. In the case of a loop, the intensity will be least at the centre of the loop, and greatest close to the wire, or at the edges of the loop, while outside the loop it will diminish rapidly with the distance. This intensity of magnetic flux may be represented by the speed of the ether streaming at the point considered, so that, according to this view, if we double the magnetic intensity of flux, we double the speed at which the ether is streaming.

The intensity of magnetic flux at a given point, say within a loop, can be increased without increasing the current strength through the wire; for, if another conductor be taken, of sufficient length to form two loops of the same diameter as the former one, and the same current strength be sent through these two loops, then, since each loop will produce the same intensity of streaming as a single loop, it is clear, if these streamings be similarly directed, that twice the amount of ether streaming will take place through the two loops as would through a single loop;

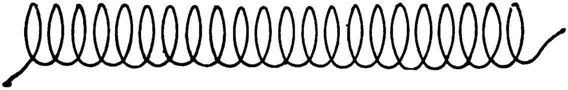

FIG. 34.—COIL OR HELIX.

or, in other words, the streamings due to each loop will be added together. Consequently, if a number of conducting loops be placed side by side, so as to form the hollow coil or helix as shown in Fig. 34, and a current be sent through these loops, a very powerful flux can be established through them.

We have already alluded to the fact

that when a bar of soft iron is introduced into a magnetic flux, the hypothetical molecular magnets, of which it is supposed to consist, are thereby aligned, so that they not only pour all their ether streams in the same direction, but that this direction is the same as that of the flux produced by the current in the loop. When, therefore, a bar of soft iron is introduced into a conducting loop, two results follow; viz,

(1) The bar of iron is magnetized in the direction of the flux through the loop.

(2) The strength of flux passing through the loop, instead of being weakened by the fact of its having magnetized or aligned the iron is, on the contrary, strengthened, since the flux of the iron is now aligned and is added to the flux from the active wire.

Such a bar of iron constitutes what is

called an *electromagnet*, this term being generally restricted to a mass of iron which does not acquire its magnetism until the passage of the current, and which immediately loses practically all its magnetism, as soon as the current ceases to pass, in other words, to a soft iron *core*, surrounded by a coil or helix of wire.

Before proceeding to discuss the properties of the helix, either when coreless or provided with an iron core, it may be advantageous to call attention to a common error concerning the source of magnetic influence in an electromagnet. It is, perhaps, very generally assumed that this source of activity is to be traced solely to the energy of the electric current; in point of fact, however, as we have just shown, a large part of the magnetism of the electromagnet; *i. e.*, its magnetic flux, already existed in the mass of the iron of its core. What the magnetizing current principally does is to align or to call into organized state the magnetic powers of the molecular magnets. In fact, nearly all of the magnetic flux in an electromagnet is, under practical conditions, obtained from the iron, and only a small portion resides in the exciting streamings around the wire.

A helix of active conductor; *i. e.*, a conductor carrying a current, behaves like a bar magnet in virtue of the magnetic flux it produces, forming, in fact, what we have already referred to as a non-ferric magnetic circuit. Helices, like bar magnets, possess the properties of direction and of magnetic attraction and repulsion.

For example, if the helix *A B*, Fig. 35, suitably supported at its terminals *P*, *P*′, by dipping the ends of the wire into mercury cups, *M*, *M*, be arranged so as to be free to move, then, when an electric current of sufficient strength is sent through it, the helix will set itself in the earth's flux in such a manner that its flux and

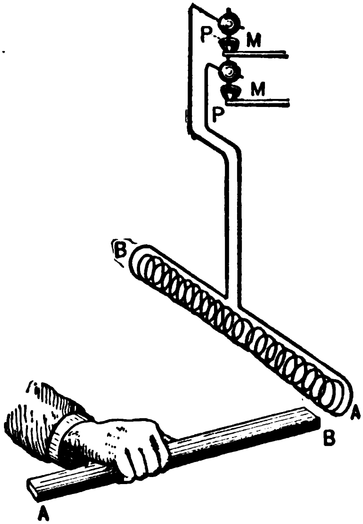

FIG. 35.—HELIX CONVEYING AN ELECTRIC CURRENT POSSESSING MAGNETIC PROPERTIES.

that of the earth will coincide or pass through its loop in the same direction. Moreover, if a bar magnet be approached to it, as shown, phenomena of polar attraction and repulsion will be exhibited, dependent upon the poplarity of the approached magnet pole and the direction of current in the helix. Or, the same phenomena can be produced by means of the simple apparatus shown in Fig. 36, where the helix or coil has its terminals connected to the plates *Zn* and *Cu*, of a small floating voltaic pile. When this

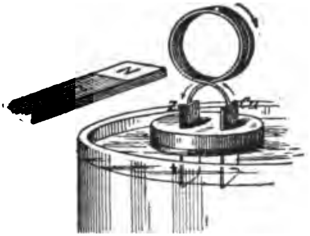

FIG. 36.—FLOATING HELIX CARRYING ELECTRIC CURRENT AND DISPLAYING POLAR EFFECTS.

pile is immersed in an acid liquid, as shown, the electric current produced, traversing the floating coil, will set up a flux in it, and the phenomena of attraction and repulsion can be exhibited by suitably approaching magnetic poles.

The direction of the flux paths through a helix; or, as it is sometimes called, a *solenoid*, depends on two circumstances.

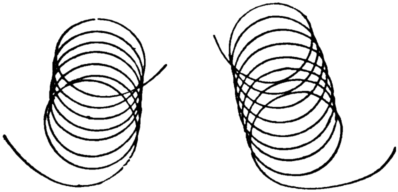

FIG. 37.—RIGHT-HANDED AND LEFT-HANDED HELICES.

(1) On the direction in which the helix is wound, whether *right-handed* or *left-handed.*

(2) On the direction in which the current passes through the helix.

A *right-handed helix* is a helix which is wound clockwise. A *left-handed helix* is one which is wound counter clockwise, as shown in Fig. 37.

Various rules have been devised in order to determine the polarity produced by any helix. Perhaps, one of the most convenient rules is represented in Fig. 38, in which the arrows point to the direction in which the current through the helix must circulate in order that the pole presented to the observer shall have the polarity indicated. It will be seen that

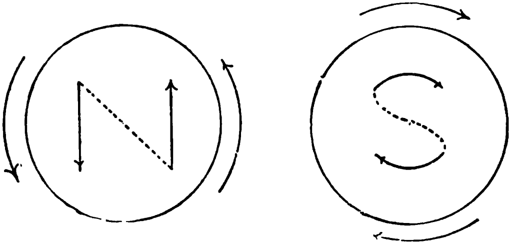

FIG. 38.—MNEMONIC FOR DETERMINING POLARITY OF ELECTROMAGNETIC POLES.

the arrows point in the direction of the terminations of the letters *N* and *S*, respectively.

Shortly after the discovery by Oersted of the magnetic properties of an active conductor, Ampere proposed a theory of magnetism in iron and steel. We have seen in Figs. 35 and 36, that a helix of wire, or solenoid, carrying a current, behaves like a magnet. This fact led Ampere to suppose that a magnet might be virtually an active solenoid. He showed that if the molecules of iron and steel had electric currents circulating round them, through paths of no resistance, that no power would be required to sustain these currents, and that the magnetic effects produced by aggregations of such molecules would be that due to aggregations of active solenoids, and, therefore, would account for the magnetic behavior observed in iron and steel magnets. Since our knowledge of molecules is as yet extremely limited, we are unable to say whether electric currents circulate around them or not. The theory may therefore be regarded as yet a hypothesis.

CHAPTER VI.

ELECTROMAGNETS.

PROBABLY, never in the history of electric invention, has a more useful piece of apparatus been produced than the electromagnet. Fortunately this piece of apparatus is extremely easy to make; for, as we have seen, it is only necessary to surround a core of soft iron by a conducting helix, and to send an electric current through the helix. If the core of iron be soft, the current produced by even a single voltaic cell will produce, through a comparatively few turns of conducting wire, fairly appreciable magnetic effects.

If, as in Fig. 18, a single voltaic cell, consisting of plates of copper and zinc plunged into an acid liquid, be connected, as shown, to the few turns of insulated wire surrounding the soft bar *N S*, the current will flow in the direction indicated by the arrows, and the direction of flux through the loops will be such as to produce a north pole at the point marked *N*, and a south pole at *S*.

Unless a powerful current is employed, the magnet shown in the figure above referred to would acquire only a comparatively feeble magnetic intensity. In order to increase its power, the turns might be placed nearer together on the bar, so that a greater number could be placed in a single layer. Moreover, instead of carrying the wire back again to the electric source, after forming a single layer, a number of layers might successively be wound on the core.

When several layers are placed on a magnet core, the wire is wound in closed spires from one end of the core *A*, to the opposite end *B*, say clockwise, and then another layer is superposed on the first, returning from *B*, toward *A*, the same clockwise direction being maintained. When *A* is reached, another layer may be put on, the winding being returned clockwise to *B*, and so on, for as many layers as is desired. The fact that the wire is carried alternately along the bar in different directions; namely, from *A* to *B*, and then back again from *B* to *A*, makes no difference in the polarity produced by the passage of the current through the magnetizing coils, provided only that the direction of winding be maintained throughout; namely, in this case, clockwise, as indicated above.

In order to keep the coils of an electromagnet in place, and to prevent them from spreading over the ends of the core, they are generally wound on a *bobbin* or *spool* of insulating material, as shown in Fig. 39, where the spool is represented both as empty and as filled with wire. When a soft iron core is placed in such a spool, the passage of an electric current through the wire causes one end of the bar to acquire

FIG. 39.—COIL OF WIRE WOUND ON INSULATING SPOOL.

north, and the other end south polarity, as shown in Figs. 40 and 41. In Fig. 40, the voltaic cell is directly connected to the ends of the coil, while in Fig. 41, a current is passed through the coil from a distant dynamo. The magnetic circuit, being aero-ferric, is partly completed through

FIG. 40.—ELECTROMAGNETIC EFFECT OF AN ELECTRIC CURRENT PASSING THROUGH A COIL OF WIRE.

the iron and partly through the external air. In order to enable the magnet to hold a greater weight on its armature, it is important that the length of that portion of the magnetic circuit which passes

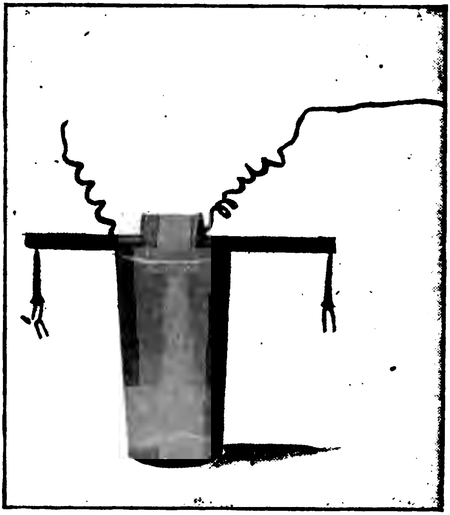

FIG. 41.—ELECTROMAGNETIC EFFECT OF AN ELECTRIC CURRENT PASSING THROUGH A COIL OF WIRE.

through the air be made as small as possible. This may be done either by bending a straight bar in the shape of a horseshoe, as shown in Fig. 42, or the same result may be accomplished by employing two straight bar magnets, placed with their opposite poles adjacent, and with a *yoke*, *y*, across one pair, thus only leaving one pair of their extremities or poles, as shown in Fig. 43.

FIG. 42.—HORSESHOE ELECTROMAGNET.

In order properly to connect the terminals of two separate magnetizing coils, so as to employ them in a single electromagnet, it is only necessary to remember that the direction of winding in the two spools must be that which would exist if the two cores formed a continuous straight bar, the wire being applied to it in a single coil, and the core and wire subsequently bent in the middle. Or, the rule for polarity, already referred to in connection with Fig. 38, will show which terminals to connect in order to obtain the polarity required.

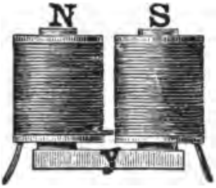

Fig. 43.—Ordinary Form of Horseshoe Electromagnet.

The placing of the yoke *y*, on the magnet shown in Fig. 43, provides an iron circuit for the magnetic flux both through the cores of the two branches of the magnet and the yoke y, leaving an *air gap* or space only between the two poles N and S.

It is evident that the two coils instead of being connected so that the neutral point is at the bent portion or yoke, which would result if the adjacent poles had opposite polarities, may be so connected as to produce a pole at the neutral point. This ensues when the polarity of the approached ends is the same as shown in Fig. 42, where each coil produces a south pole near the centre of their common iron core, and north poles at its extremities.

The magnet shown in Fig. 44 would appear to possess three poles only. In reality, it possesses four poles, the central pole at S being a double pole. Such a magnet is sometimes called an *anomalous magnet* from the apparent anomaly of the odd number of poles. An anomalous permanent magnet is shown in Fig. 45.

FIG. 44.—ANOMALOUS ELECTROMAGNET.

Fig. 46 shows the connection of two

separate spirals wound in the same direction, the current entering one spiral at *A*, and passing out at *C*, to the next spiral whence it emerges at *B*. Under these circumstances, the application of the rule will show that the polarity at *A* will be south, and at *B* north. In the electromagnet shown in Fig. 42, in order to provide a complete iron or ferric circuit, it is only necessary to connect the poles *N* and *S*, by a bar of soft iron, generally called an *armature*, as shown in Fig. 47, where the armature *a*, when placed on the electromagnet, completes the ferric circuit and enables the magnet to sustain a large weight placed on the platform as shown.

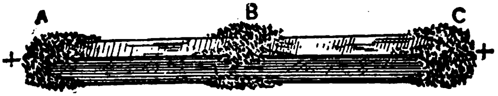

FIG. 45.—ANOMALOUS MAGNET.

In any of the magnets, shown in Figs. 42, 43 and 44, the flux passing through the magnetic circuit, when the same strength of current is sent through the magnetizing coils, will be far smaller when the armature is removed from the magnet poles, so that the magnetic circuit is aeroferric, than when the armature is in place, thus making it a ferric circuit. This is due to the fact that the armature, when placed on the magnet poles, adds its own magnetic flux to the flux produced by the magnet. In other words, under the influence of the magnetic flux of the magnet, the molecular magnetic flux of the armature is aligned and co-directed, so as to pass

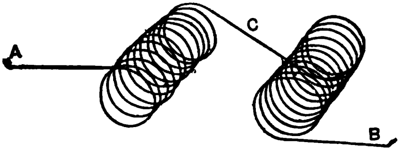

FIG. 46.—CONNECTIONS OF ELECTROMAGNETIC COILS.

through the magnetic circuit. This fact is sometimes explained on the assumption that iron possesses a much better conducting power for magnetic flux than does air; that is, its *magnetic permeability* is so much greater, that the amount of flux produced under the influence of the electric current increases. This explanation, indeed, forms a very convenient basis for practical applications, although it fails to strictly represent the facts.

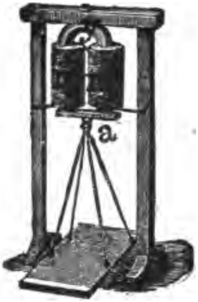

FIG. 47.—HORSESHOE ELECTROMAGNET PROVIDED WITH ARMATURE.

The amount of flux in any *non-ferric* circuit, such as that of an active coil of wire without an iron core, increases directly with the magnetizing current. Thus, if a coil of a given number of turns is traversed by a current of one ampere, the amount of flux passing through the magnetic circuit of the coil will be doubled if the current strength be increased to two amperes, and trebled, for three amperes, and so on. Since, in the above cases, no change occurs in the form of the magnetic circuit, but only in the strength of the current traversing it, it is evident, when the magnetic flux through the circuit is doubled, that the intensity of the flux is doubled at every point, and so on for all changes in the current strength. In other words, the magnetic intensity at all points of the circuit, within or without the coil, varies directly with the current strength.

If the number of turns in a coil be altered, the flux passing through the coil will also be altered. If, for example, a coil consisting of 1000 turns, wound on a certain spool, be unwound and replaced by a coil of 2000 turns on the same spool, the flux which will be produced in the magnetic circuit of the spool with an exciting current strength of say one ampere, will be approximately twice as great in the second case as in the first. In other words, the current strength remaining the same, the flux and intensity increase, approximately, directly as the number of turns. A single magnetizing turn, carrying a current of one ampere, is known, technically, as an *ampere-turn.* A single turn, carrying two amperes, has twice the magnetizing effect it would have if it carried one ampere, so that, in this sense, a single turn carrying two amperes is spoken of as having the effect of two ampere-turns. For example, in a horseshoe electromagnet of two coils, such as shown in Fig. 43, each spool having, say 200 turns, a current of $\frac{1}{2}$ ampere through the two coils connected *in series*, that is, passing consecutively through the two coils, will produce in each the effect of 100 ampere-turns, and, therefore, a total effect on the electromagnet of 200 ampere-turns. This *excitation*, or number of ampere-turns, is called the *magnetomotive force* in the magnetic circuit, because it is to this force that the magnetic flux produced in the circuit is due, just as in an electric circuit the electric flux or current is due to the electromotive force.

The term magnetomotive force is usually abbreviated M. M. F. The M. M. F. is an important consideration in all electromagnets. An ampere-turn is sometimes used as the *unit of magnetomotive force*, and this unit is sufficient for most purposes of computation. However, another unit of M. M. F., named the *gilbert*, is in use. The gilbert is a somewhat smaller unit than the ampere-turn, one gilbert being approximately 8-10ths of an ampere-turn. If we add 25 per cent. to the number of ampere-turns, we obtain practically the number of gilberts; or, if we deduct 20 per cent. from the number of gilberts in the magnetic circuit, we practically express the M. M. F. in ampere-turns. Thus, 100 gilberts are practically equal to 80 ampere-turns, or 100 ampere-turns are practically equal to 125 gilberts.

The magnetic flux produced in any circuit by applying a given M. M. F. to it, like the effect produced in any electric circuit by applying an electromotive force to it, depends on the conditions of the circuit. Before, therefore, proceeding to discuss the magnetic circuit in further detail, it may be well first to allude briefly to some of the conditions existing in an electric circuit.

The law of the electric circuit known as *Ohm's law*, from its discoverer, Dr. Ohm, may be briefly expressed as follows:

The current strength in any continuous-current circuit is directly proportional to the E. M. F. supplied to that circuit, and inversely proportional to its resistance.

Calling the unit of E. M. F., the *volt*, and the unit of electric resistance, the *ohm*, this being approximately the resistance offered by one foot of No. 40 A. W. G. copper wire, and calling the unit of current the *ampere*, Ohm's law may be expressed as follows:

The amperes in any circuit equal the volts applied to the circuit divided by the ohms in the circuit.

In order to apply Ohm's law to a magnetic circuit, it is necessary to obtain, beside the unit of M. M. F., units representing quantities similar to magnetic resistance and current. The *unit of magnetic resistance* or the *reluctance*, as it is commonly called, is the *oersted*, and is equal to the reluctance which is offered to the passage of magnetic flux by a cubic centimetre of air measured between parallel faces. The *unit of magnetic flux* is termed the *weber*, and represents the amount of flux which would pass through a magnetic circuit in which the reluctance was one oersted and the M. M. F. one gilbert. Consequently, the law for the magnetic circuit can be expressed as follows:

The webers in any magnetic circuit are equal to the gilberts divided by the oersteds.

In order to increase the magnetic flux in any circuit it is necessary either to increase the M. M. F. acting on the circuit, or to decrease the reluctance of the circuit. When, therefore, the magnetizing current is increased in any coil by increasing the current strength supplied through the coil, the M. M. F. in the magnetic circuit is thereby increased; or, when an armature is placed across the poles of an electromagnet, the flux passing through the magnetic circuit is increased, because the reluctance of the armature is much less than the reluctance of the air path through which the flux formerly passed.

There is this marked difference between the electric and the magnetic circuit; viz., in the case of the electric circuit, the current can be entirely confined to the conductor, usually a wire, forming the circuit, while in the case of the magnetic circuit, it cannot generally be so confined, but spreads through the surrounding air, which, though an electric insulator, is not a magnetic insulator. It is, therefore, only in the case of ferric circuits, or in aero-ferric circuits, in which the reluctance of the air is small, that Ohm's law can be applied satisfactorily.

In an electric circuit, the resistance of a given wire varies with the character of its substance, and, disregarding temperature changes, is independent of the current strength passing through it. That is to say, a given length of wire of a given substance, at the same temperature, will possess a resistance of the same number of ohms, whether the current which passes through it be one ampere or 100 amperes. In the case of the magnetic circuit, the reluctance of nearly all substances except the magnetic metals; namely, iron, steel, nickel and cobalt, is practically the same as that of air, or of air-pump vacuum. In the case of the magnetic metals, however, a marked difference exists in the reluctance offered by a given mass. When the *magnetic intensity* in the mass is weak; *i.e.*, when the *flux density* is small, the reluctance of the mass will usually be very small in comparison with a similar and equal volume of air, brass, porcelain or other non-magnetic material. As the magnetic intensity increases, the reluctance offered by the same mass of iron soon rapidly increases, until when the iron is said to be *saturated*, it possesses as high a reluctance as the same volume of air. For this reason, when a closed magnetic circuit, or ferric circuit, such as that shown in Fig. 48, is provided with a magnetizing coil *M*, and a gradually increasing electric current is sent through the coil, the flux through the magnetic circuit in the iron is at first feeble, then rapidly increases with the current strength, and finally increases very slowly after the iron has become nearly saturated.

FIG. 48. FERRIC MAGNETIC CIRCUIT.

Magnetic intensity, as has already been stated, refers to the density of magnetic flux. A large flux may not have a high density, or high intensity, if it be spread over a wide area. For example, the total magnetic flux produced by the earth, considered as a large magnet, is very great. But the area of the surface, over which this magnetic flux is distributed, is so great that the flux density is quite small. In other words, the flux is distributed over so many square miles of surface, that the amount of flux passing through a limited area, such as a square inch, or a square centimetre, is very small. The *unit of magnetic intensity* is called the *gauss*, and is the density of one weber passing through a perpendicular area of one square centimetre. Thus, if the value of the magnetic flux in any instance is equal to say 100 webers, and if this flux passes uniformly across a perpendicular area of 50 square centimetres, then the average density or crowding of the flux will be two webers through each square centimetre, or the intensity will be two gausses.

The intensity of the earth's flux, which aligns the compass needle, varies at different parts of the earth's surface, but is usually only a fraction of a gauss. The intensity which is practically required to saturate very soft iron is 20,000 gausses, or 20,000 webers per square centimetre. In cast iron about 10,000, or 11,000 gausses are practically saturating intensities, while in hard steel, 5000 gausses will suffice for saturation. In special cases, intensities in iron have been pushed, experimentally, as far as 45,000 gausses, or far beyond the saturation limit, the iron practically behaving as air, at such values.

From the preceding it will be evident that in the case of a non-ferric magnetic circuit, the magnetic flux or magnetic current, and, also, the magnetic intensity at any point in the circuit increases directly with the current strength or number of amperes supplied to the coil. When, however, the magnetic circuit is either aero-ferric or ferric, the magnetic flux through the circuit depends not only on the current strength but on the magnetic condition of the iron. By tabulating the reluctance of iron at different magnetic intensities, the magnetic flux can usually be calculated with a degree of accuracy sufficient for practical purposes.

CHAPTER VII.

THE ATTRACTIVE POWER OF MAGNETS.

Roughly speaking, the purposes for which electromagnets are generally employed, commercially, can be arranged under two classes; namely,

(1) Those in which the magnets have to attract their armatures with a certain degree of force at a distance.

(2) Those in which the magnets have only to sustain a powerful attraction upon their keepers.

Magnets of the former class are called *attractive magnets*, and those of the latter class *portative magnets.*

No rule can be laid down for the number of ampere-turns required to produce either a given attractive or portative effect, unless all the conditions of the magnetic circuit are known. These conditions, as have been briefly mentioned in the preceding chapter, are the M. M. F. which is to be applied to the circuit, the magnetic reluctance of the circuit, and the amount and character of the attraction required.

The amount of attraction existing between a magnet and its armature, or between any two parts of the magnetic circuit, depends only on the area of the attracting surfaces, and on the intensity of the flux passing through them. The intensity being equal, if we double the attracting surface areas, or *polar areas*, as they are usually called, we double the attractive force. Again, other things being equal, if we double the magnetic flux through the surfaces we quadruple the attractive force. The attractive force between two polar surfaces, therefore, increases directly with the surfaces involved, and as the square of the magnetic intensity through these surfaces.

In order to obtain a powerful electromagnet, it is necessary to have as large a polar surface as possible, and, at the same time, to reach magnetic saturation in these polar surfaces as nearly as possible. In other words, it is necessary to obtain the maximum possible magnetic flux passing through the polar surfaces. If we merely increase the area of the polar attracting surfaces, without increasing the total quantity of magnetic flux, we necessarily reduce the intensity or flux density through the surfaces, and, probably, reduce, rather than increase, the attractive force. Every square inch of soft iron, practically saturated; *i. e.*, having an intensity of say 19,000 gausses through it, can support a perpendicular pull of, approximately, 210 pounds, so that in order that a horseshoe magnet may sustain from its two poles a total weight of 2100 pounds, it will be necessary to have, at an intensity of 19,000 gausses, in the polar surfaces, a total polar surface of 10 square inches, or 5 square inches on each pole.

Approximate magnetic saturation is, therefore, necessary for the production of a powerful portative electromagnet. In the case of ferric magnetic circuits, the reluctance of the circuit is so small that a comparatively feeble M. M. F. is required to produce a powerful magnetic flux and intensity, Consequently, neither a great number of turns nor a strong magnetizing current is required to produce an approach to saturation, so that electromagnets of the ferric type, which complete all of their magnetic circuit through iron, do not require to be very long, since a comparatively small number of turns suffices to produce a saturating flux. Since however, powerful attractive magnets require large polar surfaces, it follows that such magnets should have a large cross-section and be of short length. Or, in other words, a short, stumpy electromagnet, when properly designed and excited, possesses powerful portative properties.

For an electromagnet to possess marked attractive power at a distance, it is, of course, necessary that the circuit of the magnet be aero-ferric, or, that the magnetic flux passes through some length of air. In such cases the reluctance of the circuit will be considerably greater than in the case of the portative magnets, and, consequently, the M. M. F. required for powerful intensities must also be increased. Such magnets are, therefore, usually longer than the portative magnets, in order to provide sufficient space for the magnetizing coil, and also because such magnets, when short, would waste much of the flux by *leakage*, that is, flux which would not pass through the armature, or body, which the magnet attracts.

A portative magnet needs a high polar intensity more than a large polar area, for the reason that, as already observed, while the attraction increases with the square of the intensity, it only increases directly as the extent of surface area of the polar surfaces. This fact is utilized to increase the portative power of permanent magnets by employing soft iron

FIG. 49.—COMPOUND PERMANENT MAGNET WITH CONSTANT POLE SURFACES.

or soft steel *pole-pieces;* with a cross-section considerably less than the cross-section of the permanent magnet itself.

Thus, in the form of horseshoe magnet shown in Fig. 49, the pole-pieces, *n* and *s*, are of soft steel, of comparatively small cross-section, fitted by clamps to the ends of the horseshoe, formed of strips of hard magnetized steel. The intensity in these permanently magnetized steel strips, probably does not exceed 2000 gausses, but by crowding the flux into these soft iron pole-pieces, on its passage into and out of the *armature*, the intensity in the polar surfaces may be increased to, perhaps 16,000 gausses, or eight times as much as in the magnet strips, and the intensity of the attractive force per square inch of polar surface is, therefore, 8 × 8, or 64 times as great as it would be if the poles were not so *armed*. For a similar reason, the *compound-bar magnets*, shown in Fig. 4, are armed with masses of soft iron having a diminished cross-section at their poles.

In a magnetic circuit the resistance to the passage of the magnetic flux increases directly with the length of the circuit and inversely as its area of cross-section. Consequently, in designing the dimensions of the core and yoke of a magnet, the same area of cross-section should, when possible, be maintained throughout; since, otherwise, the iron in the narrowed cross-section would be magnetically saturated much sooner than in the balance of the circuit, and would thus render saturation more difficult to be reached at the needed points; namely, in the polar faces.

Care must be taken that constriction should take place in a magnetic circuit, only at the polar faces, since, as has been explained above, the reluctance offered by a given volume of air at ordinary flux densities is much greater than that of iron. Where yoke pieces are used for connecting two branches of an electromagnet, it is necessary that the *joints*, or contact surfaces, be fitted together as truly as possible, so as to ensure an intimate contact between the two portions of iron and thus reduce the reluctance at these points. A well-fitted joint, between soft iron masses, offers the same amount of reluctance as would a film of air approximately 1-1000th of an inch in thickness.

When a core of soft iron is employed for an electromagnet, it can, as we have seen, both lose and gain its magnetism with great rapidity. A very large core, say two feet in diameter, such as exists in the electromagnets employed in some large dynamos, requires an appreciable time for the full development of the magnetic flux near its centre, although the superficial portions will acquire their magnetic condition almost instantaneously. Thus, four minutes might be required for the development of the full magnetic intensity within, say two per cent. of its maximum, at the centre of a two-foot core, and the rapidity with which the core thus completely gains or loses its magnetism varies inversely as the square of the diameter of the core.

Iron wire, of about one-tenth of an inch in diameter, will acquire and lose its magnetism in approximately $\frac{1}{100,000}$ of a second. In some forms of electromagnets, as in the case of some telegraphic instruments, which are capable of transmitting 300 words per minute, the magnetism has to be reversed 150 times per second.

The rapidity with which any magnetic circuit loses its magnetism, on the cessation of the magnetizing current, varies markedly with the character of the magnetic circuit. In a non-ferric circuit, as, for example, that produced by the coil of wire shown in Fig. 50, the magnetic flux instantly appears and disappears with the appearance and disappearance of the current in the coil. In an aero-ferric circuit, however, as is shown in Fig. 51, where

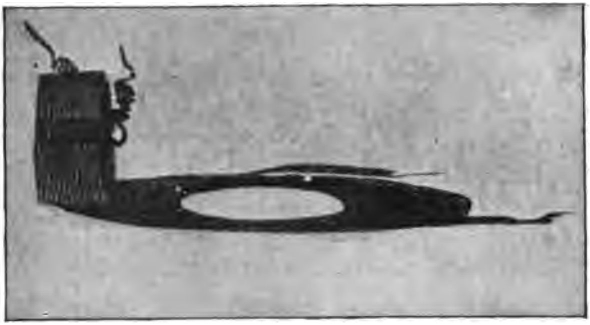

FIG. 50.—NON-FERRIC MAGNETIC CIRCUIT.

the magnetic flux completes its circuit through a considerable air-gap, the bar neither immediately acquires its magnetism on the establishment of the current, nor immediately loses it on its cessation, but tends to retain a small quantity of what is called *residual magnetism*, after the current has entirely ceased.

FIG. 51.—AERO-FERRIC MAGNETIC CIRCUIT.

In the ferric circuit, as shown in Fig. 52, where the entire path of the flux produced by the magnetizing coil is completed through the iron, the core tends to retain a large percentage of its magnetism for an indefinitely great period after

FIG. 52.—FERRIC MAGNETIC CIRCUIT.

the cessation of the magnetizing current, but if the core were arranged in two halves with tightly-fitting joints, so that the reluctance of the air-gaps might be disregarded, it would be found that although the two halves of the ring would as the result of this residual magnetism tend to adhere, yet, as soon as a separation was made, the ring would instantly lose, practically, all its magnetism. This is the reason for providing permanent horseshoe magnets with *keepers*, the effect of which is to reduce the reluctance in the magnetic circuit between the poles, and thereby reduce the demagnetizing tendency of the poles upon the molecular structure of the steel. In other words, there exists a greater tendency for the demagnetization of a permanent magnet, when its keeper is removed from it, than when its keeper is in contact with its poles. Consequently, blows received by the magnet while its keeper is removed, will be more likely to effect its demagnetization than when the keeper is on.

The effect of rapidly pulling the keeper from the poles of a magnet is to strengthen its magnetism, owing to the fact that this movement of the keeper sets up little *local* or *eddy currents* of electricity, in the pole-pieces, in such a direction as tends to strengthen the magnetism. Since the putting on of the armature of a magnet sets up currents in the pole-pieces in a direction tending to weaken the magnetism, it is advisable to put the keeper on slowly, so as to decrease the strength of such currents. The keeper may be detached as suddenly as may be desired.

Dangerous explosions sometimes occur in flour mills, from the ignition of clouds of flour dust, by a spark produced by the friction of the mill stone against a piece of iron wire, a nail, a screw, or a bit of hoop iron, accidentally introduced with the wheat. Considerable loss, both of life and property, has occurred from this cause, a cloud of flour dust possessing highly explosive properties. In order to avoid this danger, various applications of magnets have been employed. Fig. 53 shows an arrangement of permanent magnets for the purpose. The wheat, prior to its introduction into the mill, is caused to fall in front of the magnets, and in this way any stray bits of iron, or of iron ore, are effectually removed.

FIG. 53.—COMPOUND PERMANENT MAGNET EMPLOYED FOR THE REMOVAL OF IRON PARTICLES FROM WHEAT.

That finely divided inflammable material should possess explosive properties, is readily explained by the fact that explosive combustion simply means extremely rapid union of the combustible with the oxygen of the air. The divided condition of the material permits rapid combination from all sides. Even such ordinarily slightly combustible materials as iron are readily burned in the flame of an ordinary gas-light if the cohesion be overcome by filing.

CHAPTER VIII.

SOME PRACTICAL APPLICATIONS OF ELECTROMAGNETS.

Even a casual examination will show the extent to which the different practical applications of electricity are dependent for their operation on the existence and use of electromagnets. Without this valuable piece of mechanism, nearly all the practical applications of electricity would be impossible. For example, telegraphy and telephony are based absolutely on the attraction of an armature by an electromagnet. Electric bells, annunciators, and electromagnetic signaling apparatus are equally dependent on the operations of this important device. All dynamo machines are electromagnets, in which the armature revolves. Consequently, without the application of electromagnets, such machines could have no existence. The electric motor, consisting as it does of a dynamo in reversed action, is equally dependent upon electromagnetism. Without the electromagnet, the alternating-current transformer would disappear, and, although the incandescent lamp would remain, yet at the present time it would be impossible to supply the current it requires, even with the use of storage cells, which could not exist without the use of dynamo generators. Arc lamps, employing, as they do, electromagnets in their feeding mechanism, would be similarly debarred.

Since without the electromagnet, there

would be little of practical value left in electricity, it will be of interest rapidly to review some of the many uses of the electromagnet in different branches of electro-technics, calling attention, at the same time, to some of the peculiarities needed in their construction in order to meet the requirements of each particular case.

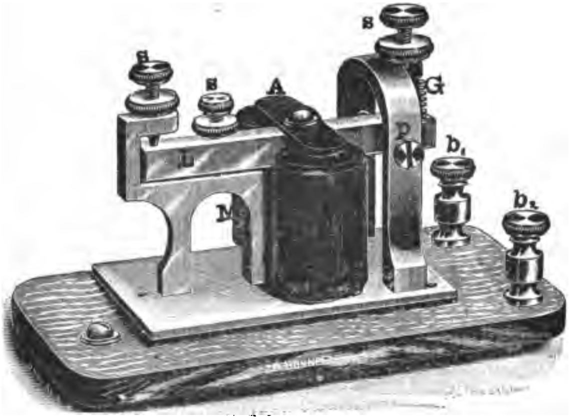

FIG. 54.—TELEGRAPH SOUNDER.

Fig. 54 represents a form of *sounder* employed in telegraphy. Here the message is received as a series of sounds produced by the striking of a lever against two metallic stops, the movements of the lever being obtained by the attractions of the armature *A*, of the electromagnet *M M*.

The electromagnet generally employed in a telegraphic sounder, like that shown in the figure, consists of two straight vertical cores of soft iron connected together at their lower ends by a *yoke* or cross-piece of soft iron. The coils are wound on hard rubber spools, incased in hard rubber shells, so as to protect them from injury. The length and size of the wire employed are such that the resistance of the two coils in series varies from one ohm to six ohms according to circumstances. The two ends of the wire wound on the coil are connected to the binding posts b_1, b_2, by which the exciting current enters and leaves the instrument. On the passage of the current through the magnetizing coils, the M. M. F. of the coils produces a magnetic flux through the magnetic circuit of the apparatus; namely, through the two cores and their connecting yoke, the armature and the *air-gaps*, or spaces between the armature and the poles, and produces an attraction between the poles and armature. Other things being equal, the greater the distance between the armature and poles, the feebler the attraction between them. On the other hand, if the armature be brought so close to the poles as to come into contact with them, the amount of residual magnetic flux left in the magnetic circuit, after the cessation of the magnetizing current, may be so considerable as to cause the armature either to cling to the poles, or to leave them sluggishly. For this reason the poles are often protected from contact with the armature by a small wedge, or projection, of non-magnetic material. The adjusting screws *s*, *s*, *s*, limit the play of the armature, the distance between the armature and the poles, and the tension of the spring *G*, which opposes the magnetic attraction.

When a telegraphic sounder is situated at a considerable distance from the sending station, the currents received by it are too weak to energize its coils with sufficient intensity to make the sound clearly audible. In order to obviate this difficulty, the sounder, instead of being placed directly in the circuit, is replaced by an instrument called a *telegraphic relay*.

Such an instrument is shown in Fig. 55. The telegraphic relay, by the movement of its armature, acts to open and close the circuit of a *local battery* through the coils of a telegraphic sounder. Since the amount of power required to open and close the local circuit is very small, compared with that necessary to operate the telegraphic sounder, a comparatively feeble current is sufficient to properly operate the relay. The amount of current required to operate a sounder is about $\frac{1}{8}$th ampere, while that required to operate a telegraphic relay, powerfully, is only about $\frac{1}{50}$th ampere, while it may be adjusted to work under favorable conditions, with $\frac{1}{500}$th ampere.

Fig. 55 shows a form of telegraphic relay in extensive use. The magnet *M*, *M*, attracts the armature and causes the lever connected with the armature to oscillate between the stops T_1, T_2, in obedience to the changes in the current taking place in the relay coils. The magnet consists of two straight bars, or cylinders, of

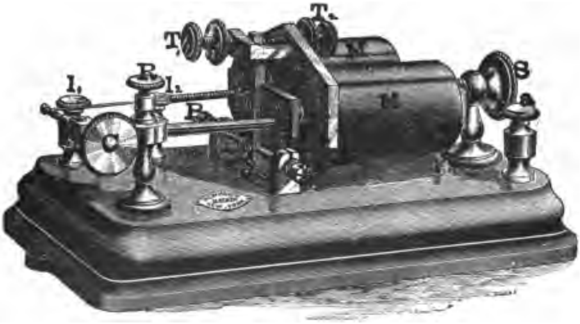

FIG. 55.—TELEGRAPHIC RELAY.

soft iron, connected by a yoke of soft iron at the back. The armature of soft iron is supported on a contact lever pivoted on the screw pivots P, P. This contact lever closes the local circuit of the sounder through the pivots P, P, and the metallic stop of the screw T_2, a small spiral of thin wire *W*, assisting in maintaining good metallic connection between the base of the pivots and the moving armature. The ends of the local circuit are connected with binding posts l_1, l_2. The magnet coils *M*, *M*, are wound with fine wire so as to develop the necessary M. M. F. from the feeble line currents, and are protected by being encased in hard rubber shells, or cylinders. The magnet can be moved forward and backward, for purposes of adjustment, in a vertical frame under the action of the screw *S*. The tension of the opposing spring, attached to the armature, can be varied by a rapid motion clamp *R*, and a slow motion screw *C*. The ends of the magnet coils are connected to two terminals, one of which only is seen in the figure at *a*. The resistance of such a relay is usually about 150 ohms.

Fig. 56 represents the parts of an ordinary Bell telephone. Here the compound, permanent magnet *G*, is provided at one extremity with a magnetizing coil *L*, which is connected to the line circuit through the terminals *T*, *T*. by the wires

FIG. 56.—PARTS OF AN ORDINARY BELL TELEPHONE.

shown. Immediately facing the end of the permanent magnet is a diaphragm *D*, of ferro-type iron, which affords a thin elastic plate or diaphragm of soft iron, serving as the armature of the magnet. When an electric current is sent through the coil *L*, the M. M. F. in the magnetic circuit is varied, being either increased or decreased, according to the direction of the current. The magnetic flux through the iron core, the air and the diaphragm is, therefore, varied. On an increase in this flux, the attraction between the diaphragm and the magnet is increased, and on a decrease, the attraction between the diaphragm and magnet is diminished, the elasticity of the plate causing it to move away from the magnet. When a rapid series of electric currents passes through the coil of the receiving instrument, the attraction upon the diaphragm is rapidly varied, and the diaphragm vibrates under the influence of the varying attraction and agitates the air in its vicinity, thus permitting the transmission of speech.

Fig. 57 shows a form of electromagnetic

bell, in which the bell *B*, is struck by the repeated blows of the hammer under the attraction of the armature *A*, by the electromagnet *M*, *M*. Here the electromagnet consists of two soft iron cores, or cylinders, screwed directly into the cast-iron frame of the box, which thus serves as a yoke to connect them. The ends of

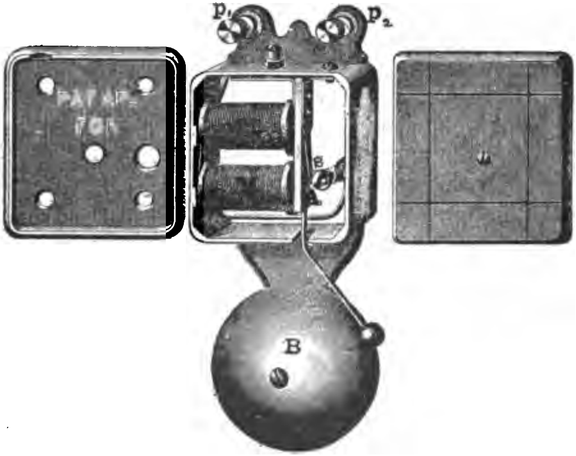

FIG. 57.—ELECTROMAGNETIC BELL.

the coils *M*, *M*, are brought to the binding posts p_1, p_2. When the current passes through the apparatus it enters the binding post p_2, passes to the armature *A*, through its spring support, thence by the small spring *s*, to a contact screw *c*, to the magnets *M*, *M*, and the binding post p_1. As soon as the M. M. F. of the magnet coils is sufficient to produce a flux through the armature, capable of attracting it against the tension of its spring support, the hammer moves forward to strike the bell and breaks the circuit, by the spring *s*, moving away from the point of the contact screw *c*. The flux in the magnetic circuit then disappears and the tension of the spring support causes the armature and hammer to return to their original positions, again completing the circuit. There is thus set up a rapid automatic vibration, or to-and-fro motion of the armature, so that the bell continues to ring, as long as the circuit is closed at the push button from which the bell is operated.

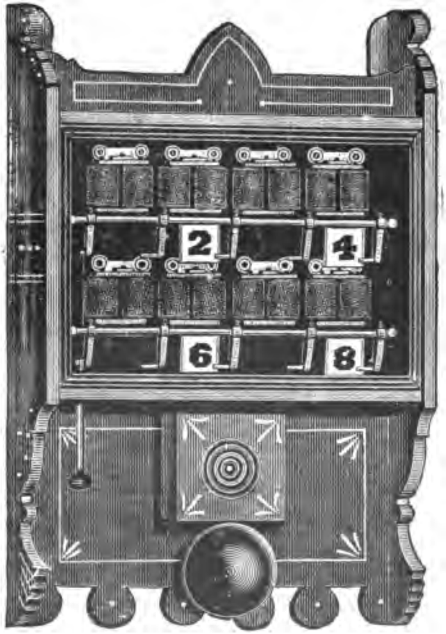

FIG. 58.—ELECTROMAGNETIC ANNUNCIATOR.

Fig. 58 shows a form of electromagnetic

annunciator. In this apparatus a number of electromagnets have their circuits connected with various rooms or other stations, provided with push buttons. Each push button is connected with its own electromagnet. Each electromagnet is so arranged that on the closing of its circuit, by the pushing of its particular button, its armature is attracted and allows a disc to fall under the action of gravitation, thus indicating the number of the circuit, or push button, from which the signal was sent. Such apparatus is used in connecting the rooms of a hotel with a central office, to enable the guests to communicate with the office. The electromagnets of annunciators are of the ordinary double-coil type, connected by a yoke of soft iron. Various methods are adopted so that the attraction of the armature shall result in the display of a signal, the circuit connections being such that the attention of the attendant at the annunciator board is called to the falling of the drop by the ringing of a bell.

An ingenious application of the movements of a small electromagnetic motor

FIG. 59.—EDISON'S ELECTRIC PEN AND DUPLICATING PRESS.

is to be found in the case of the *electric pen* illustrated in Fig. 59. Here the to-and-fro motions of a bar connected to a small motor are utilized for the perforation of a sheet of paper, by a rapidly moving needle. The matter to be duplicated is either written or printed as perforations in a stencil sheet of paper, which is afterward employed in the usual manner, with an inking roller, for manifolding or duplicating.

An electromagnet forms an essential feature in all *arc-lamp mechanism.* Most arc lamps contain at least two electromagnets; namely, one for the separation of the carbons, and another for the *feeding mechanism.* In addition, most lamps that are employed in series circuits, use a third electromagnet for the purpose of automatically cutting a lamp out of the circuit and providing a by-path by which the current can flow past the faulty lamp to the others in the circuit. Fig. 60 shows the interior mechanism of a form of arc lamp in which the arc is maintained between the carbons C, C. The magnets M,

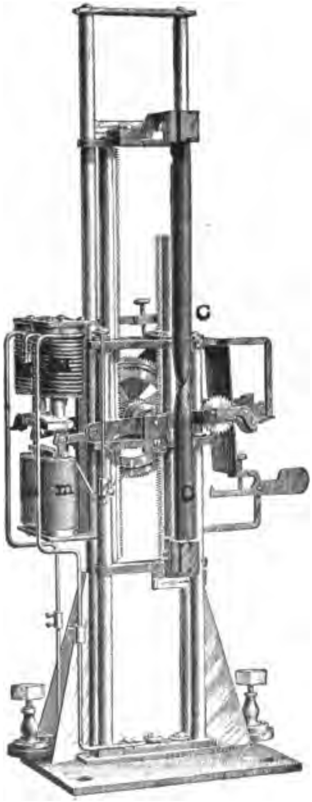

FIG. 60.—ARC-LAMP MECHANISM.

M, wound with coarse wire, placed directly in the circuit of the carbons, are employed as the *lifting magnets*. The magnets *m*, *m*, wound with fine wire, are placed in a shunt circuit around the lamp terminals. These magnets are employed to attract the same armature *A*, but in opposite directions, and by their joint action maintain a constant distance between the carbons.

Nearly all our readers are familiar with the method of electric gas lighting, where the pressing of one button turns the gas on and lights it, and the pressing of another button turns the gas off and extinguishes it. A form of mechanism employed for this purpose is shown in Fig. 61. It consists, as shown, of two distinct electromagnets *M* and *m*, the armatures of which act on a valve, in the interior stem, through which the gas is supplied to the burner at the top. When the magnet *M M*, is excited by the passage of a current through the coils, and the contact of the platinum-tipped wire *p*, with the projection on the ring *r*,

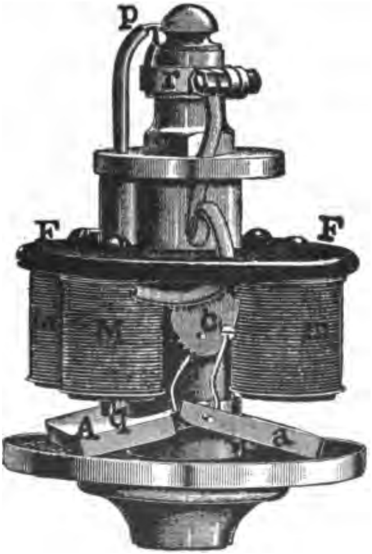

Fig. 61.—Electric Gas Lighting and Extinguishing Mechanism.

the armature *A*, is lifted against gravitational force and strikes the lower end *q*, of the wire *p*, thus raising the wire and causing it to break contact with the projection *r*. This causes the current through the coils to cease and the armature to fall back until contact is again made at *p*, thus acting as an *automatic make-and-break* device, not unlike that in an electric bell. During the impulses, the ratchet *c*,is moved forward by the projection on the armature *A*, until the gas is fully turned on, and at every interruption of the circuit, when the wire *p*, escapes from the ring *r*, a spark produced by a *spark coil* included in the circuit passes between them, thus igniting the gas which is at that time escaping from the burner. When the magnet *m*, is excited, its armature lifts without any interrupting mechanism, and acting on the ratchet cam *c*, turns the valve and cuts off the gas. The magnets in this case consist of short, soft iron cylinders screwed directly with iron screws to an iron plate *F*, *F*, which serves as a common yoke for both.

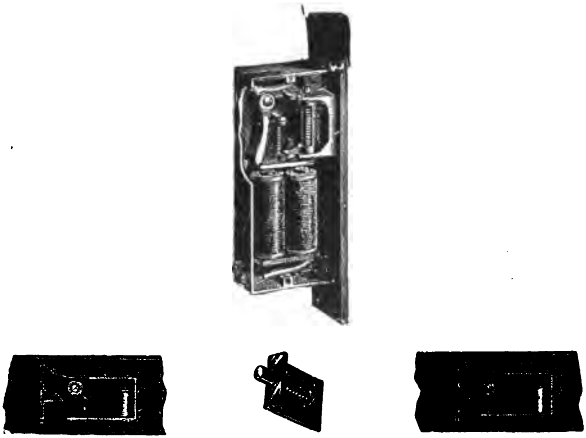

FIG. 62.—ELECTRIC DOOR-OPENER.

Electromagnets have been employed for opening doors from a distance, thus permitting the services of an attendant to be dispensed with. By the closing of a circuit, on the pushing of a button, the armature of an electromagnet is attracted, and the door is allowed to open. The method of operation of this may be followed by an examination of Fig. 62.

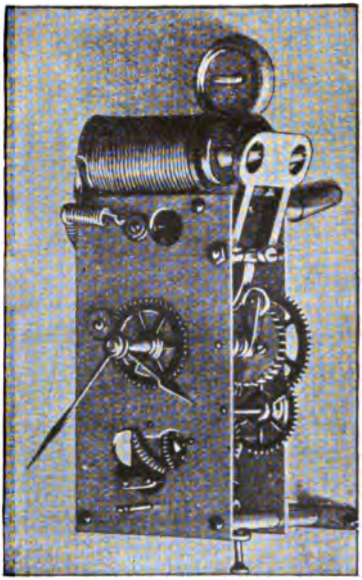

FIG. 63.—SELF-WINDING CLOCK.

The use of an electromagnet in a self-winding clock is represented in Fig. 63. Here the electromagnet at the base of the clockwork receives a brief electric current, say every fifteen minutes, and attracts its armature which is so perforated that a fairly long motion of the armature is obtainable. The armature is so connected with the spring of the clock that it slowly winds it, to compensate for the unwinding that has taken place in the preceding fifteen minutes.

A novel use for an electromagnet is seen in a form of *lightning arrester* shown in Fig. 64. It not infrequently happens, during the progress of a thunderstorm, that a spark, due to a discharge from the lines supplied by a central station, establishes an arc between the line and the ground in the apparatus at the station. This arc practically short circuits the generator, and, if not promptly extinguished, is apt seriously to injure the apparatus. In the form of mechanism shown in the figure, the arc is caused to be set up between the two metallic plates *P*,*P*, placed in the field of flux of the magnet, excited by the current which will flow when the arc is established. The effect of a powerful magnetic flux upon a voltaic arc is to push it aside or violently distort it. The electromagnet, therefore, acts as an extinguisher of the electric arc, and, in the

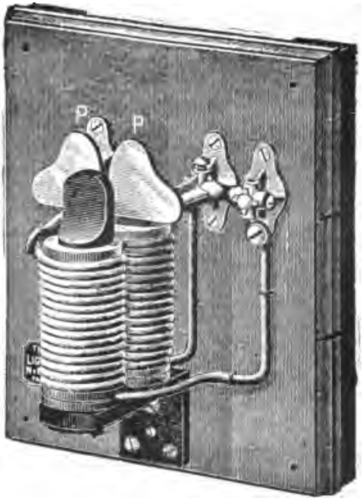

FIG. 64.—ELECTROMAGNETIC LIGHTNING ARRESTER.

relative positions occupied by the magnets and the point where the arc forms; namely, at the narrow gap between the plates, the arc is repelled upward to the wider portion of the gap where it is finally extinguished.

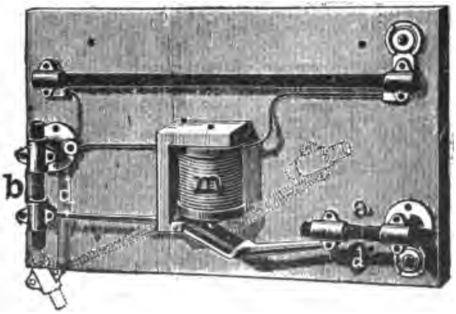

Fig. 65.—Electromagnetic Lightning Arrester.

Another form of electromagnetic lightning arrester is shown in Fig. 65. A spark gap is placed between the carbon points at *d*, so that if a powerful discharge from the line should enter the station, it will jump to ground through this spark gap. If the dynamos connected with the lines should cause a powerful arc to follow this discharge, the current must pass through the electromagnet *m*, which, by the attraction of its armature, lifts the bar into the dotted position, thereby breaking the arc at both *a* and *b*.

Perhaps the most important use of the electromagnet is found in the dynamo electric machine. This apparatus consists essentially of powerful field magnets, whose purpose is to produce the magnetic flux with which the conducting loops on the armature are successively emptied and filled, during its revolution. By the filling and emptying of this flux, E. M. Fs. are set up in the loops, by means of which either alternating or continuous currents are delivered at the terminals of the generator, to the circuit with which it is connected.

A form of generator is shown in Fig. 66, called a *quadripolar* or *four-pole generator*, such as is frequently used in a central station for supplying currents to electric railway systems. Here the magnets are shown at *M*, *M*, *M*, and the armature between their poles at *A*. In this form of machine, the alternating or reversed currents, generated in the armature during its rotation, are caused, by means of the commutator *c*, *c*, to flow in one direction into the external circuit. The cores of the electromagnets in this case are masses of cast iron forming part of the entire cast-iron frame *F F*, which acts as the common yoke of all four cores. The alternate poles of these magnets are of opposite polarity. The currents required to excite

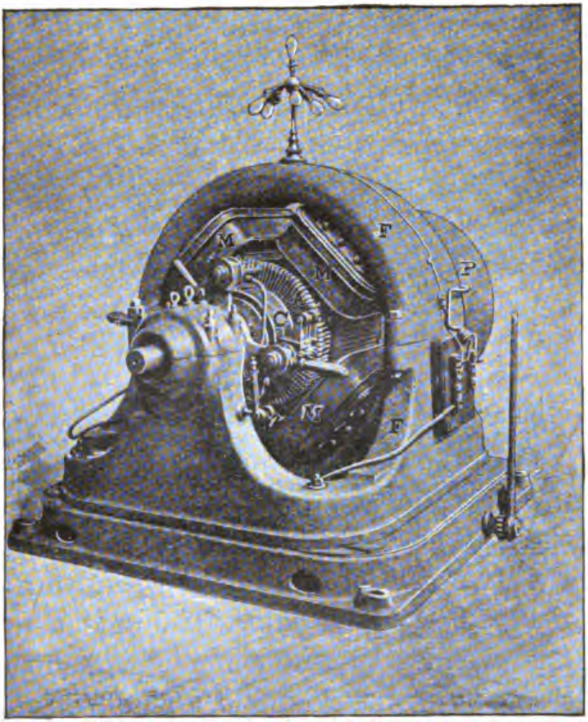

FIG. 66.—QUADRIPOLAR BELT-DRIVEN RAILWAY GENERATOR.

these large magnets are obtained from the rotating armature. When the machine is at rest there will be no current in the armature. In order to bring the machine into operation, it is necessary to rely upon the residual magnetism of the field magnets for the developing of the initial current in the armature, which in its turn will aid in restoring the field magnets to their full intensity.

The power which must be exerted upon a dynamo armature, through its driving belt on the pulley *P*, is expended against the magnetic attraction of the current in the armature for the four powerful magnetic poles in the field. The amount of flux, which a large dynamo will produce, may be very considerable. Thus each of the four poles here represented may readily carry a flux of 2,000,000 webers.

An equally important application of the electromagnet is found in the *electromagnetic motor*, which is itself a dynamo ma-

FIG. 67.—ELECTROMAGNETIC MOTOR.

chine in reversed operation. The machine represented in Fig. 67 has a capacity of about 10 horse-power. The electric motor, like the dynamo, consists essentially of a magnet, or collection of magnets, the function of which is to produce a powerful magnetic flux. The armature carrying an electric current is situated in this flux. Under these circumstances, the tendency will be for the conducting loops on the armature to revolve and deliver power from the pulley *P*, to a belt. Here the magnet coils *m*, *m*, receive their exciting current from the source of electric pressure to which the motor is connected, and the armature *A*, situated between the poles, receives the flux which the M. M. F. of the field magnets creates.

An ingenious application has been made of the ability possessed by an electromagnet to attract to it particles of iron ores, in various forms of *electromagnetic ore concentrators*, the design of which is to concentrate granular ores of iron that are admixed with so large a quantity of other material, as to render their smelting, in the untreated state, unprofitable. Such apparatus consists essentially of powerful electromagnets, so arranged that a stream of the pulverized ore is permitted to fall before their poles. Under these circumstances, the particles of ore, while falling, are sufficiently deflected from the vertical, in their downward path, by the action of the magnet, to permit them to fall into a compartment provided for them, while the non-magnetic residue falls vertically in a separate heap.

The different types of electromagnets that have been described in the preceding paragraphs, possess different attractive power on masses of magnetizable material brought near their poles. When the mass of iron in the magnet is sufficiently great, and the magnetizing current employed sufficiently powerful, remarkable strengths of magnetic attraction can be obtained. An illustration of this will be found in the powerful magnet which has been formed at the United States Torpedo Station, at Willett's Point, New York Harbor, by winding a sixteen-foot gun weighing fifty thousand pounds, with magnetizing coils of wire of about ten miles in length. This length of wire produced 5250 turns, so that when the current of 21 amperes was employed as the magnetizing current, the M. M. F. obtained was over 110,000 ampere-turns. As might be expected, such a magnet produced marked magnetic disturbances at fairly great distances from the gun, and powerful magnetic attraction in the neighborhood. For example, at a distance of over 70 feet from the gun, the intensity of flux produced in the air was equal to that of the earth's magnetism. At a distance of about 250 feet from the gun, the flux is so feeble that it is difficult to detect. Fig. 68 shows the general appearance presented by the gun magnet,

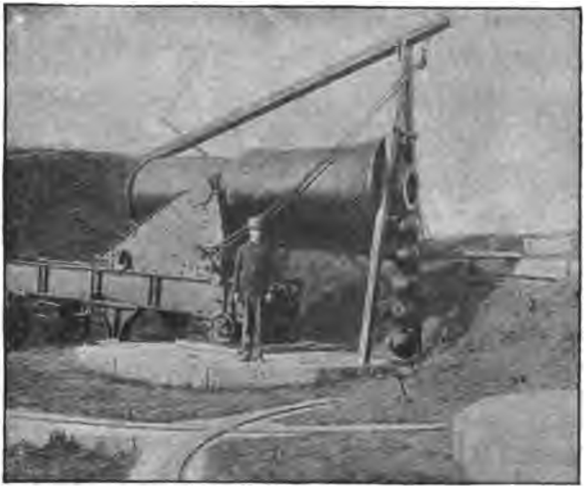

FIG. 68.—GUN ELECTROMAGNET, U. S. TORPEDO STATION, WILLETT'S POINT, LONG ISLAND SOUND.

which is represented as sustaining five large cannon balls, weighing 230 pounds each.

We have heretofore referred to the fact

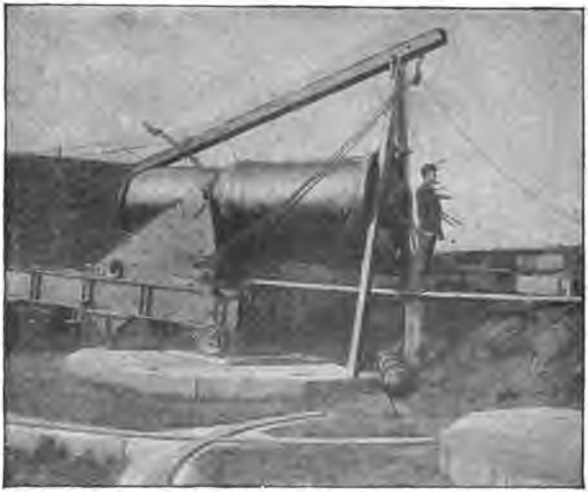

Fig. 69.—Gun Electromagnet. Attraction of Iron Through Body of Soldier.

that magnetic flux can pass through

most substances with the same facility that it does through air, or air-pump vacuum. A striking illustration of this is

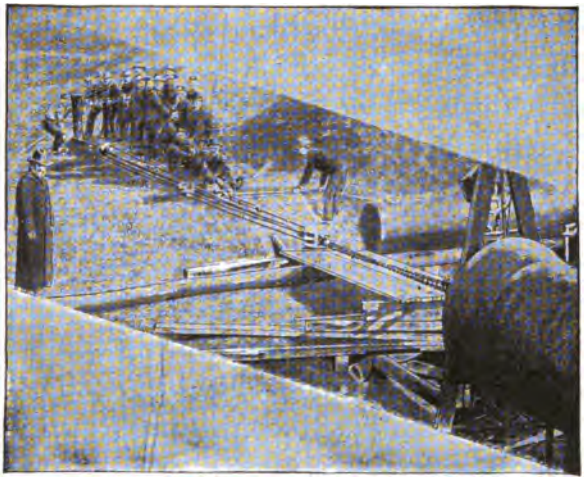

Fig. 70.—Powerful Force of Gun Electromagnet.

seen in Fig. 69, where a man, standing in front of one of the poles of the Willett's Point gun-magnet, does not prevent the flux from passing through his body, as is evident by the fact that heavy spikes of iron are readily supported at different parts of his body in opposition to gravitation. To a person so standing in front of the gun, no physiological effects are experienced by the passage of the flux through his body.

Some idea of the force with which the armature is held to the gun-magnet can be gained by an inspection of Fig. 70, where a number of men are represented as pulling at a rope and tackle, in an endeavor to separate the armature from the magnet pole-pieces.

While the total magnetic effects produced by this large electromagnet are of a striking character, yet it must be borne in mind that many of these effects arise from the size of the magnet, and the scale upon which the magnetic flux is produced, and not so much from the intensity of the magnetic flux per square inch of polar surface; for, it is doubtful whether the magnetic intensity in the metal of such a gun having so extended an aero-ferric circuit can be made as great as that within the substance of an ordinary ferric electromagnet powerfully excited. Consequently, it is doubtful whether in this case the attractive force per square inch of the polar surface exceeds 200 pounds' weight.

It was at one time asserted that some persons possessed the power of perceiving magnetic flux. It was claimed for these persons that when an electromagnet, situated in a perfectly dark room, was suddenly excited, they could, by watching the magnet closely, perceive a luminous appearance emanating from the magnet. More recent experiments have, however, thrown doubt on these statements, and at the present time, magnetic flux is incapable of being directly recognized by any of our senses.

CHAPTER IX.

MISCELLANEOUS MAGNETIC PHENOMENA.

Of all known substances, none possess such powerful magnetic properties as iron. The *magnetic metals*, ordinarily so-called, include iron and steel, nickel and cobalt. Beside these there are many other substances which possess magnetic properties, though in a less marked degree. Indeed, the experiments of Faraday, and others, have shown that the property of magnetism is possessed, although in a very feeble degree, by nearly all substances. Alluding to these investigations of Faraday, it may be said that this early experimenter found, when the substances were made in the form of slender needles and so suspended between the poles of a powerful electromagnet as to be able to move in a horizontal plane, that when the magnetizing current was turned on, and the flux passed between the magnet poles, nearly every substance experimented on came to rest, under the influence of the ether streamings, either like iron, with its greatest length in the direction of the streamings, or like bismuth, with its least dimensions in the direction of the streamings, that is, with its length at right angles to the streamings.

Faraday, consequently, divided all bodies, magnetically, into two classes; namely, *paramagnetic* substances, or those which behave like iron, and point axially in the magnetic flux, and *diamag-*

netic substances, or those which behave like bismuth, or point equatorially, that is, come to rest at right angles to the flux. Faraday's views found general acceptance until more careful observations led most investigators to discredit them. According to the views of those who followed Faraday, *diamagnetism* was supposed to be a force distinct and separate in itself, the diamagnetic rods or bars being regarded as possessing a distinct polarity termed *diamagnetic polarity* which caused them to point at right angles to the direction in which a paramagnetic body would point.

According to the more modern view, the existence of diamagnetism, as a distinct entity, is discredited. When a slender needle of bismuth is suspended in a powerful magnetic flux, and comes to rest equatorially, or in a position at right angles to the flux, the action is

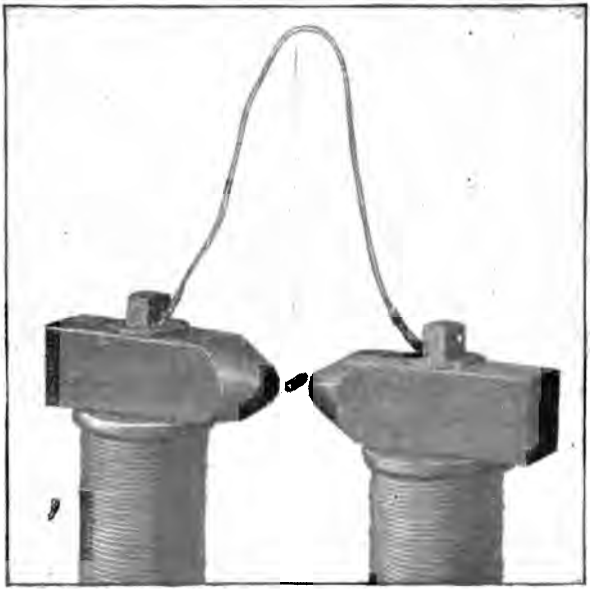

FIG. 71.—DIAMAGNETIC SUBSTANCE BETWEEN MAGNET POLES.

not to be regarded as being due to any repulsive property, or peculiar polarity, possessed by the bismuth, but rather to the fact that the *magnetic conductivity* of the ether in the bismuth is less than the magnetic conductivity of the ether in the air surrounding the bismuth. Consequently, the ether streamings will continue to act on the bar until it assumes a position in which it offers the least resistance to their passage in the space between the poles, and this position will obtain when the bar is at right angles to, or presents its least dimensions in the direction of the flux paths as shown in Fig. 71. When the experiment is made in atmospheric air, which is generally the case, it is quite possible that oxygen, which possesses distinct magnetic properties like those of iron, assists in the displacement.

This explanation of the phenomena

formerly attributed to diamagnetism, but now recognized as being only the ordinary phenomena of magnetism, has only been reached through the efficient and laborious investigations of many able scientists. This case affords an excellent illustration of the fact that in a scientific inquiry, a danger exists of fixing the attention entirely on the phenomena produced under given conditions, and losing sight of the fact that the causes of these phenomena may not be found in the particular regions where they apparently wholly manifest themselves, but are rather to be sought in the surrounding region where their manifestation is seemingly absent.

Fig. 72 shows a convenient form of electromagnet suitable among other purposes for making experiments on diamagnetism and paramagnetism. It consists,

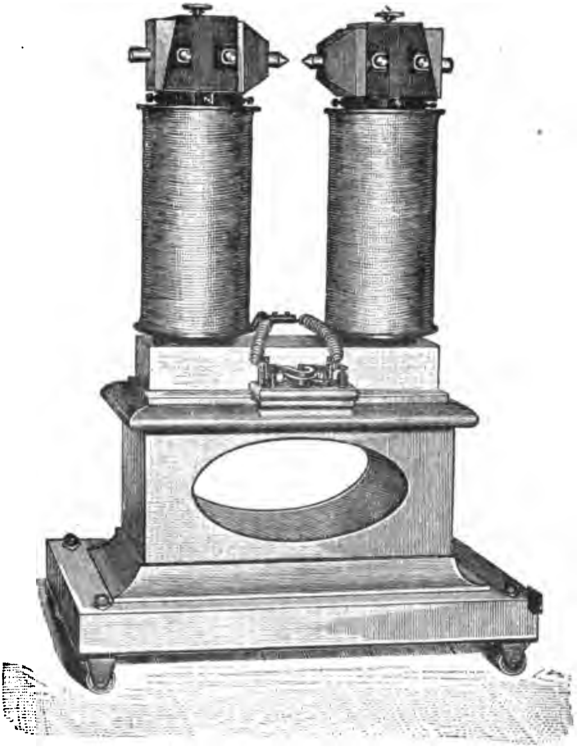

Fig. 72.—Form of Electromagnet Suitable for Experiments on Diamagnetism.

as shown, of two powerful magnetizing coils placed on cores connected at their lower extremities by a yoke of soft iron.

The poles of the magnet are furnished with massive pole-pieces of soft iron, provided with smaller projections, so arranged that the distance between them can be readily adjusted. The smaller pole-pieces can be removed and replaced by others of different shapes. Under these circumstances, it is evident that an extremely intense magnetic flux can be made to pass between the conical extremities of the adjustable pole-pieces. For investigating the para- or diamagnetic behavior of solids the apparatus is employed as follows: A suitable stand is placed so that a needle-shaped mass of the substance is suspended directly between the poles as shown in Figs. 71 and 73. If the bar experimented on be of a paramagnetic substance, like iron, it will, under the influence of the magnetic flux, come to rest in the position

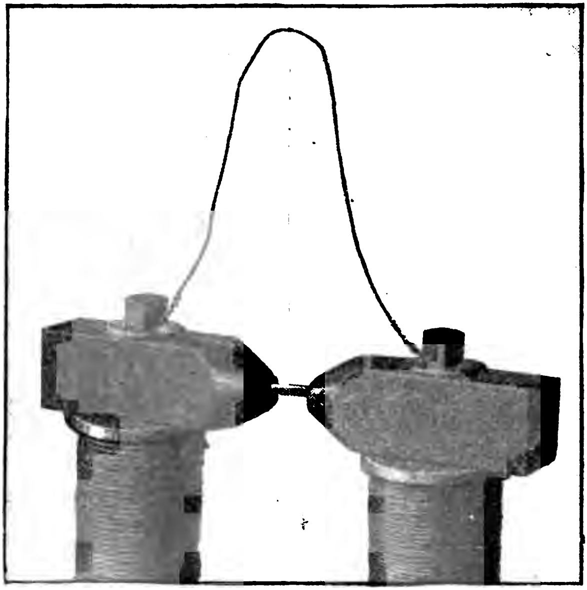

FIG. 73.—PARAMAGNETIC SUBSTANCE BETWEEN MAGNET POLES.

shown in Fig. 73. That is, it will point axially, but if it be of bismuth or of other diamagnetic substance, it will come to rest equatorially as shown in Fig. 71.

Diamagnetic and paramagnetic properties are possessed not only by solid substances, but also by liquids and gases. When liquids are experimented upon, they are placed in suitable capsules or watch-glasses. In the latter case, the movable projecting pole-pieces are replaced by pole-pieces shaped so as to properly support the watch-glass or other vessel holding the liquid. Figs. 74 and 75 show, in general, the shape of the movable pole-

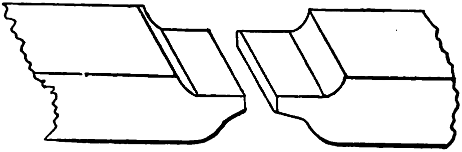

FIG. 74.—MOVABLE POLE-PIECES EMPLOYED IN TESTS ON POLAR BEHAVIOR OF LIQUIDS.

pieces and the arrangement of the apparatus when the substances to be experimented on are in the liquid form. Here, as will be seen, the liquid is placed in a shallow glass vessel, shaped like a watch crystal. If the liquid under examination be para-

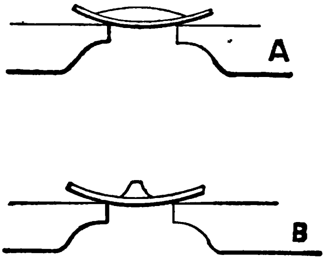

Fig. 75.—Behavior of Paramagnetic and Diamagnetic Liquid in Powerful Magnetic Fluid.

magnetic, such, for example, as solutions of iron or cobalt, then on the passage of the flux between the poles, the column of liquid will undergo curious distortions, elongating between the poles, or tending to place the greatest mass of its substance in the direction of the flux. On the contrary, if the solution be diamagnetic, it will elongate in the opposite direction, the shapes in each case being represented in Fig. 75, at *A* and *B*, respectively.

Another way of experimenting with para- and diamagnetic liquids, consists in placing them in thin tubes of glass, and in supporting the tubes like needles between the poles. It is to be observed that the effect produced is dependent both on the effect produced by the glass itself and its liquid contents. For this reason the glass tubes are made as thin as possible.

When tubes containing the liquids are so suspended in the flux, they will, when filled with diamagnetic solutions, tend to set themselves axially in the direction of the flux, and, when filled with diamagnetic solutions, at right angles to the flux.

Gases also possess marked diamagnetic and paramagnetic properties. If a stream of gas be permitted to flow between the poles of a powerful electromagnet, it will be sensibly deflected on the passage of the flux. Most gases are invisible, but these effects can be rendered evident by mixing a small quantity of some visible vapor with the gas, such as smoke, or iodine vapor. Under these circumstances, the streams of gas tend to set themselves as would the needles before referred to, paramagnetic gases endeavoring to align themselves axially, and diamagnetic gases equatorially.

The effect of magnetic flux on a stream of gas, such as that produced in a candle flame, is very striking. If, as shown in Fig. 76, a candle flame be placed between the poles of an electromagnet, on the passage of the flux, a marked repulsion occurs. Here, as will be seen, the issuing gas jet is placed at right angles to the flame, or is diamagnetic.

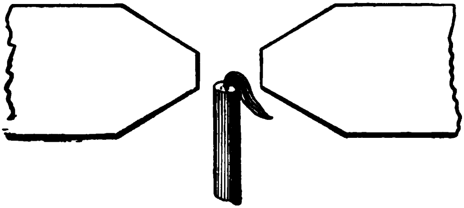

FIG. 76.– CANDLE FLAME INTRODUCED INTO POWERFUL MAGNETIC FLUID.

If the field is strong, the displacement is powerful enough to extinguish the candle.

The phenomena of paramagnetism and diamagnetism are by no means at variance with the working theory of magnetism which we have provisionally adopted in this book. Take, for example, the case of a paramagnetic gas, like oxygen, enclosed in a needle-shaped tube. No matter in what position the tube may be placed, prior to the passage of the flux, as soon as the flux passes through the tube, owing possibly to the peculiarity in the shape of the oxygen molecules, an alignment tends to occur in the molecular magnets, the ether streams possessing the power of taking hold of and moving them into line. The entire tube, therefore, becomes a magnet like the iron bar, although very much feebler.

In the case of a tube filled with a diamagnetic substance, the ether streams are powerless to produce any molecular alignment, since the molecules do not possess the requisite structure. The molecules, therefore, instead of facilitating the passage of the ether through them, tend rather to displace or resist the ether, so that equilibrium will exist only when the tube is in a position which offers the least resistance to the passage of the ether stream between the poles, that is to say, when its least dimensions are at right angles to the stream, as when it assumes the equatorial position.

The following list gives, in the order of their paramagnetic properties, the names of some of the commoner magnetic metals; namely, iron, nickel, cobalt, manganese, platinum, cerium, osmium and palladium.

The following list gives in a similar order the names of the principal diamagnetic substances; namely, bismuth, antimony, zinc, tin, mercury, lead, silver, copper, gold and arsenic.

Although manganese has been mentioned as a paramagnetic substance, fourth in order of power, and although iron and steel are the most powerful paramagnetic substances known, yet an alloy of manganese, carbon and iron, known as *manganese steel*, containing about 12 per cent. of manganese, is almost completely incapable of being magnetized.

Temperature exerts a marked effect on the magnetic qualities of substances. For example, iron, the most powerfully magnetic metal, loses all traces of magnetic properties, and cannot be magnetized at a dull red heat. It again becomes magnetizable on cooling.

An alloy of steel and nickel, containing about 25 per cent. of nickel, has been found to be almost non-magnetic in its ordinary condition, but if heated to 600° C., it becomes magnetizable on cooling, unless cooled to about 4° C., when it again becomes almost non-magnetic unless re-heated.

We have alluded on page 27 to what is called the *magnetic retentivity* of iron; namely, that property in the molecular structure of iron whereby the magnetic condition tends to persist after the cessation of the magnetizing force which produced it. This effect, although very pronounced in iron and steel, can, nevertheless, be rendered appreciable in a great variety of substances, such, for example, as glass, quartz, sulphur, celluloid, etc. These effects can be observed by suspending a sphere of the material to be experimented on by a thin silk thread in a powerful magnetic flux and deflecting the sphere through an angle about the thread, while under the magnetic influence. The sphere will not return to its original position, but will assume a distinct deviation in the direction toward which it was moved, thus indicating the existence of a polarized condition in its mass. As these effects are always very feeble, it is not yet certain whether they are due to retentivity in the materials, or whether they may not be due to the presence of accidental impurities of iron or its salts.

The marked difference presented in the behavior of hardened steel and soft iron is due, as already mentioned, to a difference in the readiness with which the molecular magnets are aligned. In soft iron they are both readily brought into alignment and readily dislodged; while in hardened steel they resist both tendencies. When a bar of iron is subjected to cyclic changes in magnetization, as, for example, when its magnetism is periodically reversed, the magnetization of the bar does not instantaneously follow the magnetizing forces which produce it, but lags behind them. Thus, if the bar has been magnetized by the application of a directing magnetic flux, and this latter is reversed, the magnetization of the bar is not reversed at the same time that the magnetizing flux is reversed, so that the magnetizing flux may be negative while the magnetism in the bar may still remain positive. This phenomenon is assumed to be due to the grouping of the magnetic molecules which resist breaking up, and also to the hardness of the material undergoing magnetization. The phenomenon is called *mag-*

netic hysteresis, from the Greek verb, "I lag behind."

Owing to the existence of hysteresis, work is expended in the bar both in magnetizing and in demagnetizing it. If a non-ferric magnetic circuit, such, for example, as the coil of wire represented in Fig. 41, has its magnetism rapidly reversed, the magnetic flux will develop, disappear and reverse without appreciable loss of energy from the magnetizing coil. In other words, air does not possess appreciable magnetic hysteresis, or does not waste energy in its magnetization and demagnetization; but, if the same process of magnetic reversals be carried on in a ferric magnetic circuit, such as a ring of iron, or even in an aero-ferric circuit, the alternate magnetizations, and demagnetizations, of the iron are attended by a small loss of energy in the iron during each cycle. This energy is taken from the circuit of the magnetizing coil and appears in the iron as heat; so that the electrical circuit loses energy in the form of electrical energy at each reversal of magnetization, and the iron becomes heated.

To a novice in magnetic science one of the most curious experiments in magnetism is the following: A heavy copper disc is so mounted on a horizontal axis between the poles of a powerful electromagnet, as shown in Fig. 77, as to be capable of easy rotation about its axis. The rotation of the disc is started when the magnetizing current is not passing, and little resistance is offered to its acquiring a high velocity. If now, while rapidly rotating, the current is suddenly turned on, the space between the poles, through which the magnetic flux is passing, will apparently acquire a retarding power on the disc not unlike that which would be produced by the presence of a very viscous liquid, such as molasses. The same effect will be observed if a strip of copper be moved through a magnetic field. When the copper disc is fairly thick and the field very intense, a powerful resistance

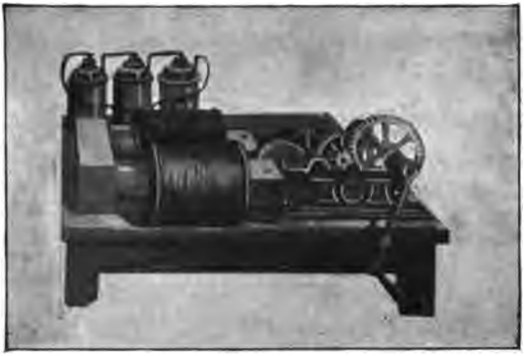

FIG. 77.—COPPER DISC ROTATED IN A POWERFUL MAGNETIC FLUX.

is offered to its motion, and, if the disc be moved against this resistance, it will become heated just as if it had actually overcome a frictional resistance. The explanation of this phenomenon is not so simple as it might seem at first sight. The cause of the resistance is not to be found in the direct frictional resistance of the ether streams, but to the production of *eddy currents*, or currents of electricity, set up in little whirls throughout the substance of the disc. The presence of these eddy currents serves to produce local electromagnetic action in the disc, as though it were wound with a coil of wire and a current circulated therein. Electromagnetic forces set up between these eddy currents and the magnetic flux which produces them, causes the retarding effect observed.

The ability of eddy currents to produce retarding motion in a disc rotating in a magnetic field, has received a number of practical applications in the arts. One of

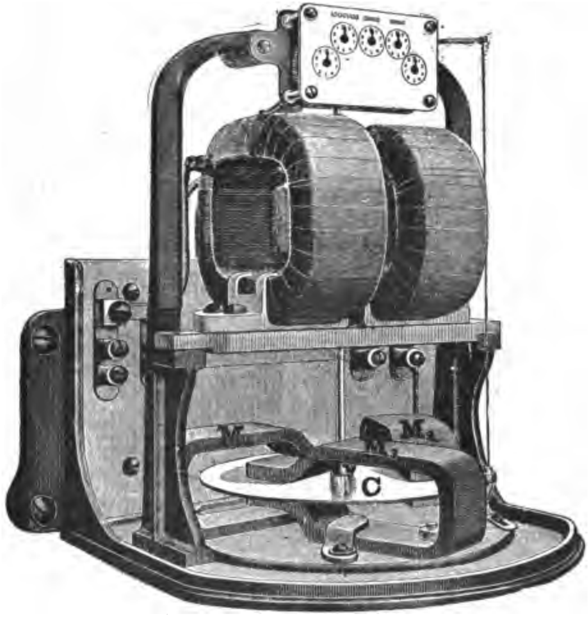

FIG. 78.—RECORDING WATTMETER WITH MAGNETIC BRAKE.

the most noted of these is to be found in the form of *recording wattmeter* shown in Fig. 78. A horizontal disc of copper *C* revolves about a vertical axis in the flux produced by three magnets M_1, M_2, and M_3. Each magnet sets up eddy currents, both at the part of the disc which is entering and at the part where it is emerging from its field. Consequently, six of such eddies are produced in the mass of the rotating disc. The influence of these eddies is to produce magnetic retarding forces, whose intensity depends upon the rapidity with which the disc is rotating. The disc, therefore, forms a *magnetic brake*, without the friction produced by contact of material substances.

The recording wattmeter represented on page 213, is designed for measuring and recording the electric energy delivered through the particular conducting circuit with which the apparatus is connected. It consists essentially of a magnetic motor, rotated by the current passing through the instrument. The number of turns made by the axis being recorded on the dial, forms a basis for determining the quantity of energy delivered, the retarding disc being necessary in order to prevent an unduly high speed being attained.

There remains to be described a peculiar action which magnetism exerts on a ray of light while passing through a powerful magnetic field. As shown in Fig. 79, two co-axial, powerful magnetizing coils, *M* and *N*, are wound on hollow cylinders of soft iron with their poles facing each other, the iron framework of the apparatus serving as a yoke to connect their distant poles. When a piece of heavy flint glass is placed between the poles as shown, a ray of light caused to pass through the hollow cores and the glass from the object glass *l*, to the eye-piece *a*, undergoes no change in its properties, provided the magnetizing current is cut off and no flux is passing through the glass. On the completion of the circuit, and the passage of the flux, the light which passes through the glass undergoes

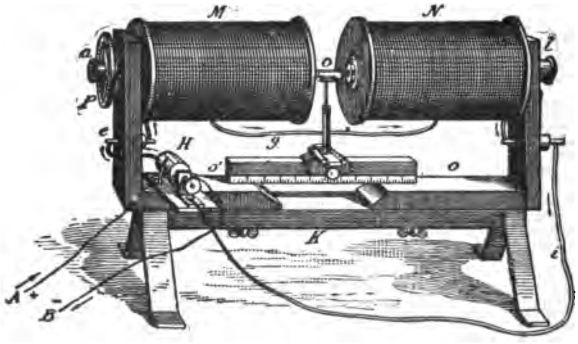

FIG. 79.—APPARATUS FOR PRODUCING MAGNETIC ROTATORY POLARIZATION OF LIGHT.

an alteration known as *rotary polarization.* That is to say, the plane in which vibrations of the ether occur, which constitute light, is rotated as the light advances through the magnetized glass. This effect is most powerfully observed in heavy flint glass, but exists also in a great variety of transparent substances to a greater or less degree.

The property of rotary polarization; *i. e.*, of rotating the plane of polarization of light, is not confined to magnetized transparent substances. Many transparent substances possess this property in their ordinary condition, while in others it is called forth only under the action of magnetism. All substances, however, which possess this property can be divided into two sharply marked classes; namely, those which possess *right-handed rotary* *polarization*, or the ability to deflect the plane of polarization to the right, and those which possess *left-handed rotary polarization*, or the ability to deflect the plane of polarization to the left. But the curious fact exists, that bodies which acquire this property under the influence of the magnetic field, can be made to deflect the plane of polarization either to the right or to the left according to the direction of the magnetic flux. In the majority of cases, when the flux is passed through the substance in a certain direction, a rotation takes place, say right-handed, and when the direction of the flux is reversed the rotation becomes left-handed, as it would appear to an observer who does not change his position. A few substances, however, form an exception to this rule, since in them the passage of flux in the direction named produces left-handed instead of right-handed polarization.

Referring to the theory of magnetism provisionally adopted in this book; namely, that it is due to a streaming motion of the ether, rather than to a vortex or whirling motion in the ether, it might be assumed, as has been done by some, that the phenomena described in the preceding paragraphs; namely, of *magneto-optic rotation*, would establish the claim of the vortex or whirling theory of magnetism, since such whirls might reasonably be expected to produce in matter a rotary stress, capable of deflecting the plane of the ether vibrations constituting light, but the fact of the exceptions above alluded to, and also of the fact that mechanical stresses are capable of producing a similar rotation of the polarization plane, calls into question the alleged superior claims of the vortical theory of magnetism over the theory of ether streamings.

When an ordinary time-piece, such as a watch, is brought into a powerful magnetic field, the magnetization of the steel it contains in its mechanism will produce magnetic disturbances, which will probably stop its motion entirely; and, when removed from the field, the magnetism it will permanently retain may considerably alter its rate. A very small change in the rate of vibration of the balance wheel of a watch, say to the extent of $\frac{1}{10}$ of one per cent., will produce an error in one day amounting to $86\frac{4}{10}$ seconds.

The cause of the change in the rate of a magnetized watch lies in the fact that at least two of its parts become magnetized;

namely, the large, steel main spring and the small hair-spring. If the hair-spring, or the main spring, only were magnetized, it would have very little influence upon the rate of the watch, but the magnetized hair-spring acts like a small compass needle, in the presence of a bar magnet, and tends to oscillate either more rapidly or more slowly, according to the position in which its poles lie, with respect to the poles of the main spring.

When a watch has once had its rate affected by permanent magnetism, there are two ways in which this injury can be remedied; namely, either to demagnetize the watch, or to replace the hair-spring by an unmagnetized spring. The demagnetization of the watch can be effected by exposing the entire watch to a rapidly *alternating magnetic flux*, that is, a magnetic flux, the direction of which is rapidly reversing. The watch is exposed to the full influence of the field and then gradually withdrawn from its influence so as to be exposed to a gradually decreasing intensity of magnetization and demagnetization. The effect produced by this treatment is to alternately magnetize all the parts in a definite direction; so that by rapidly exposing the parts to successive magnetizations and demagnetizations, on the gradual withdrawal of the watch from the field, the successive magnetizations become weaker and weaker, until, when the watch is finally completely withdrawn from the magnetic flux, there is no sensible magnetization left in it.

A similar method of demagnetization of watches, which is apt to be less effective, consists in the employment of a continuous flux, such as the flux in the neighborhood of the poles of a dynamo machine, the reversals in the magnetization of the watch being obtained by a spinning or rotation of the watch while exposed to magnetic flux and the gradual withdrawal of the same while this rotation is continued.

A few decades ago, magnetic fields of sufficient intensity to seriously effect the rate of a watch were very rare. At present, however, the rapid introduction of apparatus employing powerful magnetic fields renders such injury far more common. A necessity, therefore, exists to protect watches from this source of injury. Various methods have been introduced with this end in view. They are, however, of two general classes; namely, those in which *magnetic watch shields* are employed, and those in which the hair-spring is made of some *non-magnetic alloy.*

The first of the above-named methods consists essentially in placing the watch inside an iron case or shell, provided for carrying in the pocket. When a watch, so protected, is brought into a magnetic field, the iron shield will protect the watch inside it by conducting practically all the magnetic flux through its mass, and thus preventing any appreciable portion from passing through the watch. If, however, the field be powerful, the protective influence of the shield will be insufficient, and the watch may become seriously injured. Such shields will ordinarily protect a watch outside a radius of three or four feet from a dynamo.

The other method for the protection of

a watch from accidental exposure to magnetic flux, requires that the hair-spring be made of non-magnetic material. But in order to prevent a change in the rate of the watch it is necessary that these materials shall not be liable to oxidation, shall possess the requisite elasticity, and shall not have their elasticity seriously affected by changes of temperature. The obtaining of such an alloy has been a very serious problem for watchmakers, since the elasticity of steel is so marvelous that millions of vibrations are executed by a hair-spring without any evidence of fatigue, and no pure non-magnetic metal possesses elasticity in so eminent a degree. A number of alloys have been produced, but the most successful have been either alloys of palladium or of nickel.

Watches possessing a hair-spring of

a non-magnetizable alloy, can be carried with impunity into the strongest magnetic fields. The main spring which has yet to be made of steel, becomes, indeed, magnetized, but such magnetization is not found to exert any appreciable influence upon the rate of vibration of the non-magnetic hair-spring, and, consequently, on the rate of the watch. Experiments made with watches so protected have shown that when such a watch is placed in a very powerful magnetic flux the hair-spring is momentarily accelerated, owing to the development in its spires of eddy currents of the same general character as those produced in the case already referred to, of the copper disc between the poles of a magnet, but as soon as the watch is removed from such flux it regains its original rate.

Electromagnets are almost invariably

excited by continuous currents. It is possible, however, to obtain some very curious effects of electromagnetic attractions and repulsions by sending alternating currents through the exciting coils. In such cases, the cores of the magnets are still made of soft iron, but instead of forming one continuous mass, it is necessary that they be thoroughly divided or *laminated*, so as to avoid the formation of eddy currents by the rapidly alternating magnetic flux. In such cases, the laminations are made at right angles to the conducting loops. Consequently, a suitable core, for an alternating-current magnet, can be readily obtained by wrapping the magnetizing coils or spirals around bundles of soft iron wire. Although the magnetic polarity produced in such magnets alternates with the change in the direction of the current, yet, under certain circumstances, effects both of attraction and repulsion can be obtained.

An ordinary continuous-current electromagnet does not possess the power of directing or repelling other than the magnetic metals, but in the case of the alternating-current magnet, both the magnetic and the non-magnetic metals are capable of presenting such phenomena. For example, discs of copper can readily be made to manifest strong attractions and repulsions when brought between the poles of a powerful alternating-current magnet. The causes of these attractions and repulsions can be traced to the formation of eddy currents in the metal masses brought into the flux.

CHAPTER X.

PHENOMENA OF THE EARTH'S MAGNETISM.

PROBABLY one of the most important generalizations made in the history of magnetism was that which resulted from a series of simultaneous magnetic observations, undertaken in 1836, at the suggestion of Humboldt. These observations were made simultaneously, at points on the earth's surface widely distant from one another, and extending from the Arctic to the Antarctic Circles. As a result, the remarkable fact was ascertained that not only were many of the marked variations, which, as we now know, occur in the strength of the earth's magnetism, but also some of the minor variations, occurred simultaneously. The only apparent explanation for this phenomenon is to regard the earth as a huge magnet, so that if the magnetization varied in any portion of its substance it would necessarily produce a variation in its flux, which would affect the distribution throughout its entire mass and not be confined to any particular locality.

It is now generally conceded by scientific men that the phenomena of the earth's magnetism can best be studied by regarding the entire earth as a huge magnet, with its south magnetic pole situated near Baffin's Bay, at about latitude 70° N. The popular belief that the magnetic needle unerringly points to the north geographical pole, over all parts of the Northern Hemisphere, is far from being correct, although, for considerable portions of the earth, the needle generally points to the earth's geographical north, yet in some districts, the deviations from the north pole of the earth, or, as it is called, the *magnetic declination*, may be so great that the needle may point due east, due west, or even due south. Indeed, the number of places on the earth's surface, where the north pole of the needle points accurately to the geographical north, are comparatively few and may be readily arranged on two lines known as *agones*, or lines of no declination of the needle. The declination is said to be east or west according as the needle points east or west of the geographical north. The declination is measured in degrees east or west, or minus and plus; thus, in a locality which has a magnetic declination of 30 degrees east, the magnetic needle at that locality comes to rest with its north end pointing 30 degrees eastward of the true north.

In order best to study the variations in the magnetic needle at different parts of the earth's surface, a map or chart, called a *declination chart*, may be employed, on which are traced lines connecting all places on the earth's surface that have the same value of the declination. Such lines are called *isogonal lines*, or lines of equal magnetic declination, and are marked on such maps in degrees east or west of the true North. The lines of no declination are called *agones* or *agonic lines*, and are here indicated by a zero. Such a declination chart is shown in Fig. 80.

An inspection of this isogonal chart for the United States, will show that the agone, or line of no declination, marked 0°, passes through South Carolina, Ohio and Michigan, so that places on this line had the needle pointing truly north and south in 1890. Places east of this line have westerly declination, as indicated by

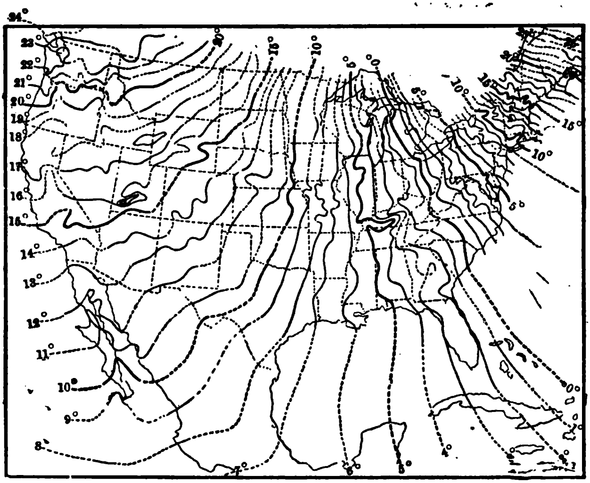

FIG. 80.—ISOGONIC CHART OF THE UNITED STATES FOR THE YEAR 1890.

+, and all west of this line, easterly declination, as indicated by —.

Fig. 81 shows a similar isogonic chart of the United States calculated for ten years later, or for A. D. 1900. It will be

FIG. 81.—ISOGONIC CHART OF THE UNITED STATES FOR THE YEAR 1900.

observed that the agone has traveled westward about half a degree. A study of the chart will show the amount of variation that has occurred in the other line.

When a magnetic needle is so suspended as to be free to move in a vertical, as well as in a horizontal, plane, as shown in Fig. 82, it will, as in the case of an ordinary needle, come to rest in the direction of the magnetic flux at that point of the earth, but, except in a very few parts of

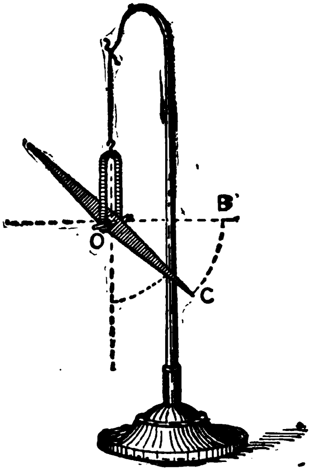

FIG. 82.—DIPPING NEEDLE.

the earth, it will no longer remain in a horizontal position, but will incline or dip toward the earth. This departure of the needle is called the *inclination* or *dip* of the needle. In order to prevent the dip from occurring in an ordinary compass needle, which is only intended to move in a horizontal plane, the needle is purposely balanced, not at its centre of gravity, but at a sufficient distance from this point to remain horizontal despite the force tending to make one end incline.

The phenomena of the dipping of the magnetic needle, or of the earth's *magnetic inclination*, is best studied by reference to a magnetic chart called an *inclination chart*. Such a chart consists essentially of lines connecting all places on the earth's surface whose magnetic inclination possesses the same value. Such lines are called *isoclinal lines*, and, as shown in Fig. 83, extended irregularly east and west. It will be seen that in 1885, the dip of the needle on the northern shore of Lake Superior was 78°, while at the southern extremity of Florida it was 55°. In the Northern Hemisphere, it is the north magnetic pole of the needle which dips,

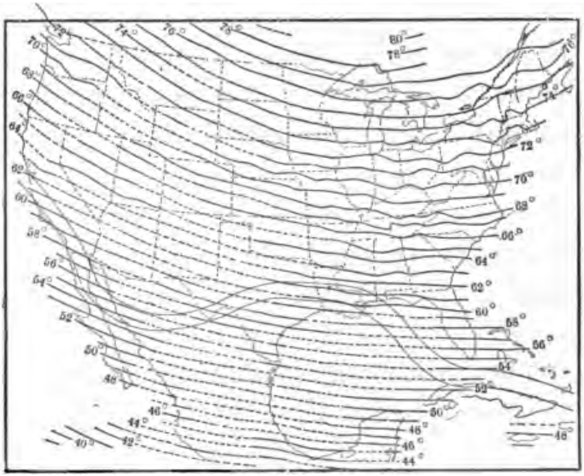

Fig. 83.—Isoclinic Map of the United States for the Year 1885.

and in the Southern Hemisphere, the south magnetic pole. A line connecting points on the earth's surface possessing no dip or inclination is called the *magnetic equator*, or *aclinic line*, and lies not far from the geographical equator.

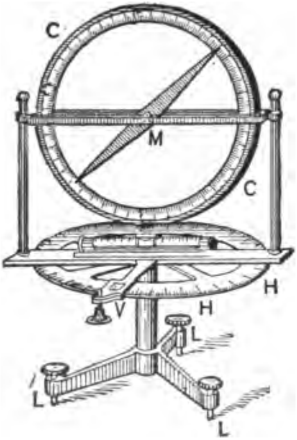

FIG. 84.– DIPPING NEEDLE.

In order to measure the angle of magnetic inclination at any place an instrument called a *dip circle* is employed.

Such an instrument is shown at Fig. 84. It consists of a magnetic needle *M*, suspended so as to be free to move in a horizontal plane, and provided with two graduated circles; namely, a vertical circle *C*, and a horizontal circle *H*. The instrument is provided with levelling screws at *L*, so as to ensure horizontality. In order to ascertain the *angle of dip* at any place, the vertical circle is moved over the horizontal circle until its plane lies in the plane of the magnetic meridian, and the angle of dip is then read from the vertical circle, being measured between the horizontal line and the extremity of the needle.

Recalling the statement made in a previous chapter that a magnetic needle comes to rest when placed in any flux, when its flux coincides in direction with that of the flux in which it is placed, it will be seen that the phenomena of the inclination of the magnetic needle are merely an exemplification of this principle. Could we see the magnetic flux of the earth issue from a region in the vicinity of its south geographical pole, and, after passing through the air surrounding the earth, re-entering at the south magnetic pole in the Northern Hemisphere, we should see these lines were nowhere generally parallel to a water surface; *i. e.*, nowhere horizontal, except in the neighborhood of the magnetic equator. The inclination of the needle over other parts of the earth arises simply from the tendency of the needle to set itself in the direction of the earth's flux. Consequently, over the earth's magnetic poles the inclination of the needle would be 90°, or the needle would point vertically downward.

Beside the direction of the earth's magnetic flux at any point on the earth's surface, which is defined by the dip and declination, that is to say, by the inclination and declination of the needle, the intensity of the magnetic flux requires to be separately considered. Since all the flux may be either conceived as leaving the earth's north magnetic pole in the Southern Hemisphere, whence it spreads over and re-enters at the earth's south pole, in the Northern Hemisphere, it is evident that the intensity of the earth's flux must be greatest in the neighborhood of the poles and weakest near the equator, in general increasing with increasing latitude. Its directive tendency, however, on a compass needle, is greatest at the equator for the reason that although the total force is weakest in this region, yet, acting entirely in the horizontal plane, its effect on the compass needle is comparatively great, while at the magnetic poles, where the force is strongest, the effect on a magnetic compass needle disappears.

Various methods may be adopted to measure the intensity of the earth's magnetic flux in any locality, though all consist in comparing the earth's local intensity with that produced by a standard magnet at a given distance, or by a stand-

FIG. 85.—MAGNETOMETER.

ard electric current. A form of apparatus called a *magnetometer*, employed for this purpose, is shown in Fig. 85, consisting of a magnetic needle, suspended at the centre of the apparatus by a bundle of silk threads, so as to be free to swing in a horizontal plane. The standard bar magnet M, is supported at a definite distance from the swinging magnet on the horizontal bar B, B, and a deviation produced by this magnet on the swinging magnet is observed through the eyepiece e.

A map or chart, connecting places on the earth's surface possessing the same magnetic intensity, is called an *isodynamic chart*, the lines of equal intensity being called *isodynamic lines.*

The three characteristics of the earth's magnetism; namely, the declination, inclination and intensity, are called the *elements* of the earth's magnetism. One of the most valuable discoveries in the phenomena of the earth's magnetism, made at an early date in the history of the science, was the fact that none of these elements possessed fixed values, but are constantly changing. In order to ascertain the character and extent of such changes, buildings called *magnetic observatories* have been established, provided with instruments capable of continuously measuring and recording such changes. Magnetic observatories are carefully built so as to be as free as possible from local magnetic disturbances. For this reason, no magnetic materials are employed in their construction. The records made by the instruments are continuously recorded by suitable photographic means. A very great number of such magnetic observatories are now in existence, and, by means of the continuously recording instruments, the various phenomena concerning changes that occur in the earth's magnetism are receiving careful study.

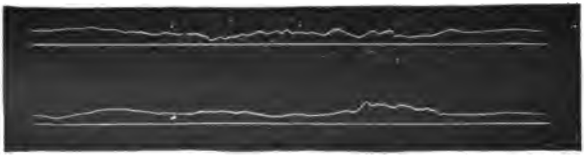

FIG. 86.—PHOTOGRAPHIC RECORD FROM RECORDING DECLINATION MAGNETOGRAPH, AT A MAGNETIC OBSERVATORY SHOWING DISTURBANCE PRODUCED BY ELECTRICAL RAILWAY IN THE NEIGHBORHOOD.

Figs. 86 and 87 are taken from the photographic records of a magnetic observatory. Fig. 86 represents the horizontal force curve taken on two consecutive days. The straight line in each case is the zero or reference line representing a fixed value of magnetic intensity, and the wavy line is the photographic trace of the position of a beam of light reflected from a mirror attached to the recording magnet. The curve commences on the right hand at 9 P. M. and progresses toward the left until 9 P. M., the day following, at the left-hand end of the line. The main waves or irregularities are variations in the earth's intensity on the day considered, while the smaller and more rapid fluctuations are due to the magnetic influence of electro-magnetic motors on a street railway about a quarter of a mile from the observatory. It will be observed that the disturbances

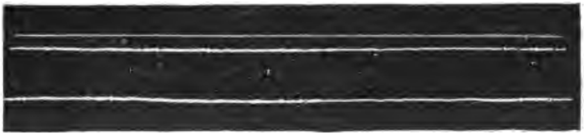

FIG. 87.—PHOTOGRAPHIC RECORD FROM RECORDING DIP MAGNETOGRAPH AT A MAGNETIC OBSERVATORY, SHOWING DISTURBANCE PRODUCED BY ELECTRICAL RAILWAY IN THE NEIGHBORHOOD.

from the street cars stop at 1 A. M. with the last car, and recommence shortly before 6 A. M. when the cars begin running.

Fig. 87 is similar to Fig. 86, except that it is a photographic record of the dip instead of the declination. The street car disturbance is still more clearly indicated in this figure.

The variations in the elements of the earth's magnetism can be arranged under four distinct heads; namely, first, *diurnal variations*, or those which take place at different hours of the day; second, *annual variations*, or those which occur at different times of the year; third, *secular variations* or those which occur at considerable intervals of time; fourth, *irregular variations* or those attending so-called magnetic storms.

All three elements of the earth's magnetism simultaneously undergo variations. The most important of the three variations is, however, that of the declination, since such variations immediately affect the direction of the compass needle and, consequently, all the purposes for which the directive tendency of the compass needle is employed; as, for example, in steering a vessel across the ocean, or surveys made by the aid of the needle on land. The diurnal variation of the magnetic needle is as follows: in the morning, between eight and nine o'clock, the north pole of the needle moves slowly to the west. This movement continues until shortly after noon, when it is reversed, slowly returning eastward until about ten o'clock at night, when a smaller oscillation occurs in the opposite direction. The cause of these motions, although not definitely known, is ascribed to the influence of the sun's heat upon the air. The total range of daily variation in declination is

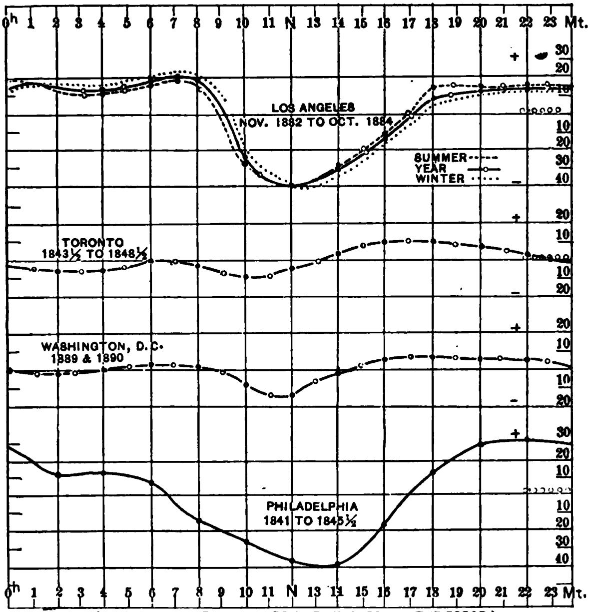

FIG. 88.—DIURNAL VARIATION OF THE VERTICAL COMPONENT OF THE MAGNETIC FORCE AT LOS ANGELES, CAL., 1883-1884.

very small, amounting only to $\frac{1}{8}$th of one degree. The annual variations of the needle are quite small, and, like the diurnal variations, correspond to the distribution of the solar heat throughout the different seasons of the year.

Fig. 88 shows the diurnal variation of that portion of the earth's magnetic intensity which acts in a vertical direction, or, as it is usually called, the *vertical component*, at four different localities in North America—Los Angeles, Toronto, Washington, D. C., and Philadelphia. Here, it will be observed, that the greatest variation occurs at each place near noon, the time of variation, and also the amount of variation, being different at the different localities.

Fig. 89 represents the average diurnal

variation of the horizontal component in the earth's magnetic intensity at one lo-

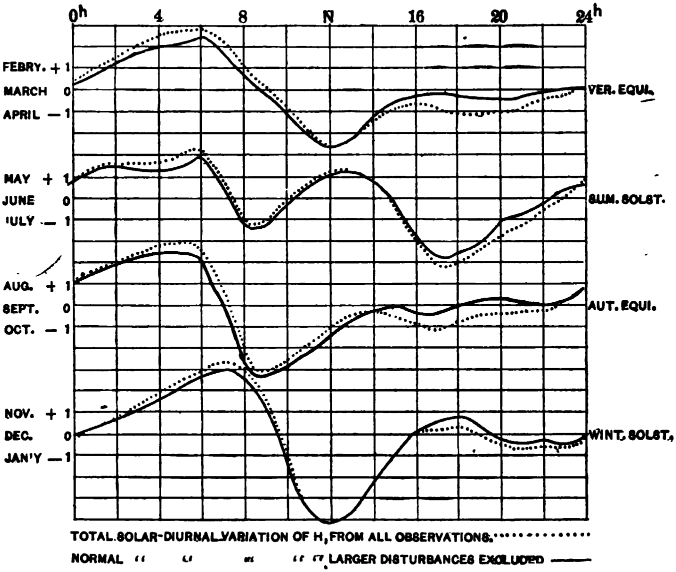

FIG. 89.—CURVES OF TOTAL SOLAR DIURNAL VARIETIES OF THE HORIZONTAL COMPONENT OF MAGNETIC FORCE FOR LOS ANGELES, CAL., COMPILED FROM OBSERVATION IN 1883–1888.

cality, Los Angeles, at different times of the year, compiled from observations during the years 1883–1888 inclusive. In the curves for the vernal and autumnal quarters there is only one marked maximum and minimum, while for the summer and winter quarters, there are two well-marked maxima and minima. It has been suggested that these diurnal magnetic variations, differing for different places, and for different seasons at the same place, are due to local influences depending on the solar rays.

The secular variations of the needle are slow variations which apparently repeat themselves in periods of about 320 years. Too little is yet known about them to hazard any general statements.

It may be mentioned, as an example of secular magnetic variations, that in London, England, observations made cn the needle as early as 1580, showed that the declination was 11° 30′ East. In 1657, the declination was zero, the needle pointing due north and south. In 1816, the needle had attained its maximum westerly declination, amounting to 24° 30′. It then returned toward zero and is expected in 1976 to again point due north and south.

Beside these regular variations of the magnetic needle there are others which occur with apparent irregularity, accompanying the development of any unusual electrical discharges in the air, such as are effected by the *aurora*. That a relation exists between the occurrence of *sunspots* and variations in all the elements of the earth's magnetism is proved by the general coincidence between the two sets of phenomena. If, for example, a curve be plotted of sunspot activity at different times, and also of the magnetic activity, or of *magnetic storms*, it will be found that the two curves present unmistakable evidence of agreement in their general features.

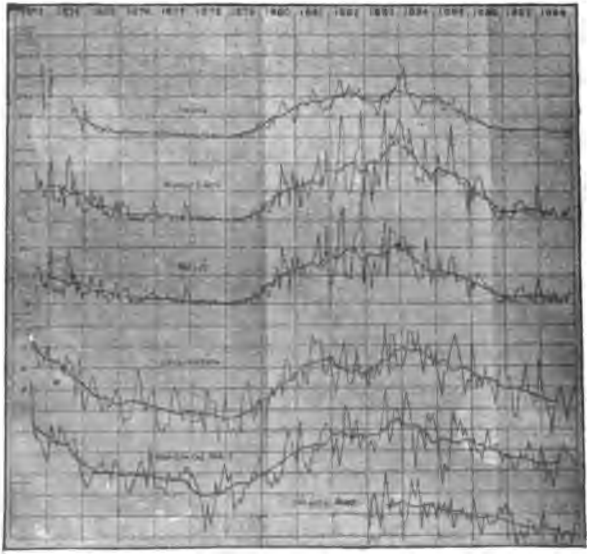

FIG. 90.--CURVE SHOWING CONNECTION BETWEEN SUNSPOTS AND TERRESTRIAL MAGNETIC DISTURBANCES

Such a set of curves is shown in Fig. 90. These comprise observations taken between the years 1873 and 1888. The first line represents the area of the sun covered by faculæ, or cloudy areas; the second, the area covered by whole spots, including both nuclei and faculæ, while the third gives the area of the nuclei, or black areas, only. The fourth, fifth and sixth curves show the range of magnetic disturbance from the mean or average instrumental records. It is evident from the figure, that the period of solar activity and of magnetic disturbance is completed in about eleven years.

Fig. 91 shows a form of appearance in the heavens presented during the prevalence of the *aurora borealis.* This phenomenon is now generally believed to be due to discharges of electricity in the upper regions of the air. The presence of these discharges is very frequently attended by the existence of marked electrical

FIG. 91.—AURORA BOREALIS.

currents in the earth, called *earth currents*, which cause considerable disturbances on telegraphic lines due to the passage through them of electric currents. Whatever may be the explanation, the times when these phenomena occur are coincident with marked magnetic disturbances.

The *mariner's compass* consists of an apparatus for suspending a magnetic needle on board a ship, in such a manner that its directive tendency shall be least interfered with by the motions of the vessel. In order to accomplish this, the compass is suspended on what are called *gimbals.* In the apparatus shown in Fig. 92, these consist of two metallic rings *AB*, and *CD*, pivoted on two horizontal axes at right angles, in the manner shown. *Sights* are provided at *G* and *H.* The ball of the compass is wide, so that the centre of gravity of the apparatus is well below the axis. The magnetic needle is fixed to the lower surface of a card called the *compass card* which bears upon its face 32 points, called the *cardinal points* of the compass. It used to be an invariable custom to steer vessels by reference to the points of the compass, the course of the vessel being counted as north, north by east, north north east, north east by north, north east, etc., according to the particular point toward which the vessel was sailing. In modern navigation, however, the course is frequently expressed in

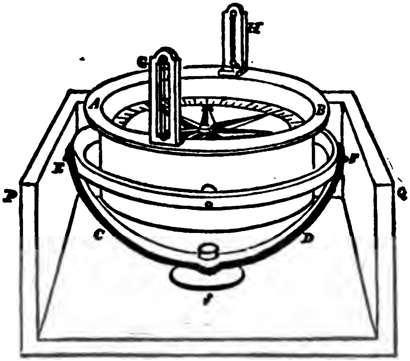

FIG. 92.—MARINER'S COMPASS.

degrees, so that North East would be N. 45° East., etc.

To the popular mind, the steering of a ship by means of a compass, is, apparently, an easy task; for, in the absence of the heavenly bodies, it is apparently easy to determine the exact course the vessel is taking by reference to the compass needle. In the olden times, when ships carried little or no iron with them, provided the local variations of the compass were known, laying out a course by *dead reckoning* was indeed a simple process. Since the introduction of iron vessels, and the massive iron machinery they employ, the local deviation of the needle caused by the magnetism of the ship is so great as to render the plotting of a course by the mere variations of the needle very fallacious. This difficulty is enhanced not only by the fact that all masses of soft iron change their polarity on crossing the magnetic equator, but especially by the fact that the value of the deviation, caused by the local attraction of the ship, undergoes marked variations in intensity, according to the direction in which the vessel is sailing. When the magnetic axis of the ship coincides with the magnetic meridian, the local variation is a minimum, but when they are at right angles, such variation is a maximum, and when, in addition to this, there are required to be taken into account the local declination of the needle, the problem becomes exceedingly intricate.

The errors in the direction of the ship's compass needle, owing to magnetism of the ship, are capable of being classed as follows; namely, the semi-circular error, the quadrantal error, and the heeling error.

(1) The *semi-circular error*, or that due to the permanent magnetism of the ship's iron considered as a steel bar magnet. This is called the semi-circular error because it produces easterly deviation throughout one half circle, and westerly deviation when the ship's head points anywhere in the remaining half circle.

(2) The *quadrantal error*, or that due to the induced magnetizations of the ship's iron considered as a bar of soft iron under the influence of the earth's magnetism. As we have seen, the ship's magnetism not only undergoes variation of intensity, but even changes its direction when the ship crosses the magnetic equator. It is called the quadrantal error because it is easterly in two quadrants, or quarter cir-

cles, and westerly in the remaining alternate quadrants.

(3) The *heeling error*, or that due to the induced and permanent magnetism of the ship in a vertical plane, and which produces no influence upon the needle until the ship heels over, as under a press of canvas.

Compensation for local deviation of the ship's compass by these errors, is usually obtained both by the use of permanent magnets placed near the compass, so as to exert upon it an influence approximately equal and opposite to that of the ship's iron, and also by the use of masses of soft iron so placed in the neighborhood of the compass that their induced magnetism under the earth's flux shall be approximately equal and opposite in its effects upon the compass to that of the ship's soft iron. The *compensating magnets* employed for this purpose are usually fastened to the wooden deck of the vessel, under pieces of sheet lead, at the proper distance in the fore and aft lines from the centre of the needle. The compensating masses of soft iron are supported on each side of the compass needle, usually in the form of hollow iron spheres.

The best form of compass provided with these compensating adjustments is shown in Fig. 93. The compass card is formed of a thin disc with its centre cut away as much as possible, so as to combine stability with lightness. Six slender rods of hard steel are suspended in a cradle near the centre of the card, and form a compound magnetic needle possessing the maximum directive force,

FIG. 93.—THOMPSON'S COMPENSATING BINNACLE.

united with the minimum of weight. The bowl of the compass is usually filled with oil, or other viscid liquid, to check oscillation. Beneath the compass case is a magnet fixed in such a position as to compensate for the semi-circular error, as well as a magnet to compensate for the heeling error. A soft iron globe to compensate for quadrantal error is placed on each side of the compass. The optical apparatus which surmounts the cover, is intended for checking the deviation of the needle by reference to the sun's position in the heavens at any time.

Various theories have been advanced as to the cause of the earth's magnetism. Any theory for this purpose should be able to satisfactorily account for the variations which exist in the observed elements of the magnetic flux which have already been alluded to in discussing the variations which occur in the declination, inclination and intensity. Ignoring some of the earlier theories which were offered, a theory, which is held to some extent at the present day, ascribes the earth's magnetism to the effect of electric currents circulating around it from east to west, approximately parallel to the equator. The cause of these currents, according to this theory, is ascribed to the unequal heating of the materials of the earth's crust by the sun. The maximum temperature of the earth, of course, is situated approximately under the vertical rays, and since by the earth's rotation this point of maximum heat would cross the earth's surface once during a complete rotation, there would, it is claimed, be electric currents developed by this unequal heating, which would cross the earth in a direction opposite to that in which it rotates; namely, from east to west. Such an electric current would produce a south magnetic pole in the northern hemisphere and this, as we have seen, is what is required to explain the earth's action upon a magnetic needle. It is difficult to conceive how the difference of temperature would produce the requisite electric currents, especially since the greater part of the earth's surface in the equatorial regions is composed of water areas. Moreover, the varying obliquity of the sun's rays, at different seasons of the year, should produce a greater influence in the variations of the current distribution and, consequently, on the magnetic distribution, than is actually observed.

A modification of this theory refers the cause of the earth's magnetism to practically the same source; *i. e.*, solar heat, but places the region in which this disturbance occurs in the atmosphere, rather than in the earth's crust. Judging from experiments in air-pump vacua, it is probable that at an elevation of about 80 miles above the earth's surface the rarefied air has an electric conductivity higher than that of the best conducting solutions of sulphuric acid in water. When it is remembered that variations in the solar radiation occurring during the difference of temperature of day and night, or during the different seasons of the year, or possibly during different cycles of time, may account for the diurnal, annual, and secular variations of magnetism, some theory which connects the magnetic phenomena of the earth with the solar radiation would appear to be extremely probable, but here, as before, the fact that variations in obliquity of the sun's heat do not produce more marked variations with the seasons, would appear to render these theories far from satisfactory. Some have even ascribed the earth's magnetism to magnetic flux produced by the sun or by the moon, but calculations show that neither the sun nor the moon could produce at their distances any sensible magnetic effect on the earth, even if composed of hard steel, powerfully magnetized. It must be acknowledged that there has yet to be produced a theory which shall account in a satisfactory manner for the phenomena of the earth's magnetism.

The insufficiency of any theory to account for the earth's magnetism is especially seen in the case of some obscure terrestrial magnetic phenomena that are apparently irreconcilable with any theory which has yet been proposed. For example, Fig. 94 shows the isoclinic lines served in the northern part of France referred to in the "Annuaire of the Bureau of Longitudes of Paris 1895," for the year 1891. The dotted lines represent the general course of the isogonals 15°, 16° and 17° West. In the neighborhood of

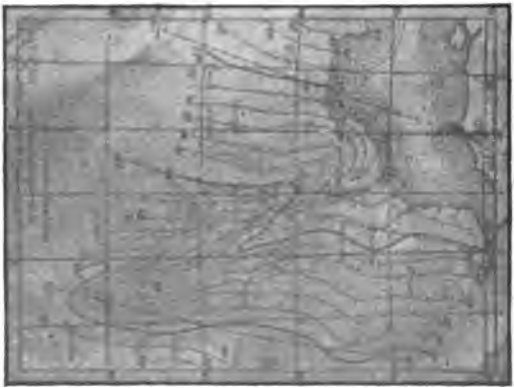

FIG. 94.—ISOCLINIC LINES IN THE NORTHERN PART OF FRANCE.

Paris, it will be observed that the general course of the isogonals undergoes a very marked and sharp bending which can, it would appear, only be accounted for by local terrestrial causes not connected with the general phenomena of the earth's magnetism as a whole.

In order to account for the secular variations in the earth's magnetism, it was formerly assumed that the positions of the earth's magnetic poles changed their situation cyclically upon the earth's surface. More recent observations seem to indicate that in each hemisphere there is a magnetic pole over which the needle stands vertically, and, that in addition to these, there are in each hemisphere two places where the intensity of the earth's flux is a maximum. It would seem that these poles and positions of maximum intensity do not sensibly vary in position, but that the earth's flux varies along certain lines of magnetic activity. In other words, there would appear to be regions of periodically waxing and waning magnetic influence, whereby the intensity of the flux alters, as though feeble *false magnetic poles* were developed.

When dynamos are operated on board ship, an additional source of local magnetic disturbance is produced on the compass needle. This may be due either to the electromagnetic influence of the wires carrying currents, in the neighborhood of the compass needle, or it may be due to the magnetic influence of the poles of the dynamo situated within the sphere of the needle's influence. The first difficulty can be entirely overcome by employing double wires throughout the vessel; *i. e.*, employing an outgoing and a return conductor, placed side by side throughout their length, so that the magnetic influence of the current in one wire is equal and opposite to the influence of the opposite current in the other wire. The second difficulty can be entirely overcome by employing an ironclad type of generator; *i.e.*, a dynamo in which the magnetic poles are completely sheltered by and enclosed within the yoke or frame of the machine.

The irregularities observed in the distribution of the isogonal, isoclinal and isodynamic lines on the earth's surface, as seen, from an inspection of Figs. 80 and 81, to naturally arise from the varying character of the materials forming the earth's crust. The occasional presence of large beds of magnetic oxide of iron, or other magnetizable material, is apt to produce local magnetic poles, and so disturb what might be otherwise a more uniform distribution of the earth's flux. That beds of iron ore do exist in the earth is not only established by actual mining operations, but also by the use of a suitable dipping needle.

An apparatus, employed for the above purpose, has sometimes been called a *magnetic divining rod*; for, by its use, the localization of large bodies of magnetic iron ore is possible without uncovering the surface. Unfortunately, however, owing to the fact that a thin mass of ore near the surface produces approximately the same effect as a thick and concentrated mass of ore at a greater depth, the indications of the needle have to be taken with great caution; but, when taken in connection with borings, outcrop observations and other evidence of a geological character, they furnish valuable data for mining interests.

THE END.

INDEX.

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