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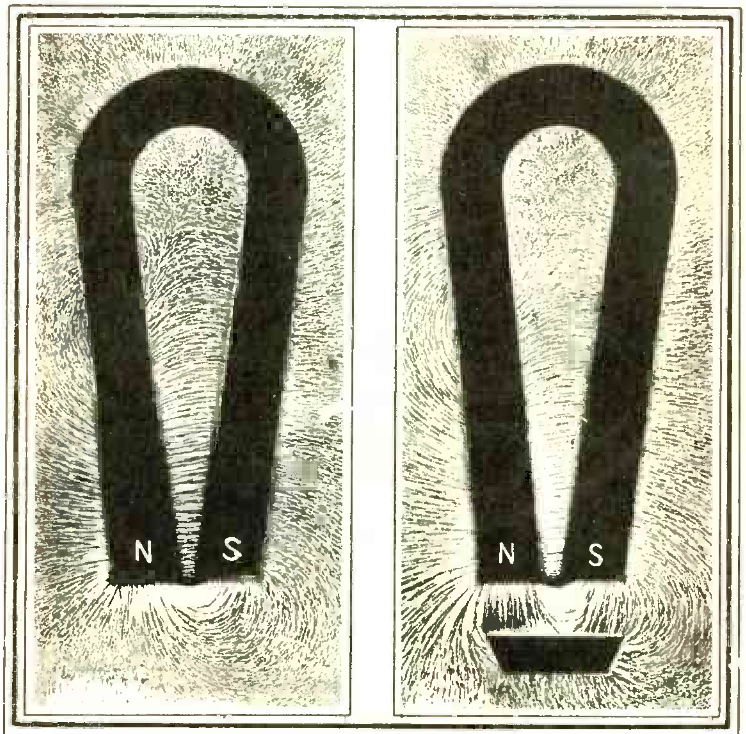

THE FIELD OF FORCE SURROUNDING EACH HORSESHOE MAGNET IS MAPPED OUT BY THE IRON FILINGS

THE THEORY OF MAGNETISM AND APPLICATION OF MAGNETS

VOL. 10 No. 2

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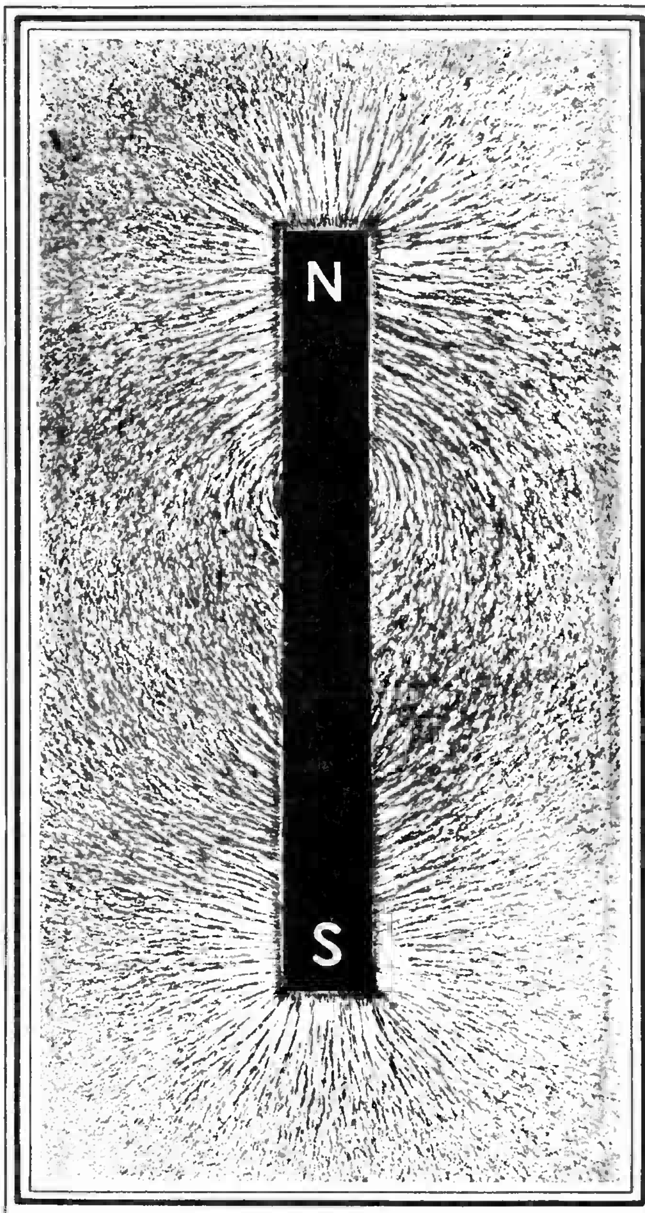

THE FIELD OF FORCE OF A BAR MAGNET

THE THEORY OF MAGNETISM AND APPLICATION OF MAGNETS

MAGNETIC POLES. Many centuries ago in the mining regions of a small town in Asia Minor, named Magnesia, there was found a dark colored stone, which possessed a very peculiar property -- one that could be described as a sort of pulling force -- which gave this substance the power to attract small pieces of iron. It was then discovered that if a piece of this stone was suspended by a thread and allowed to move freely it would swing about slowly, and upon coming to rest would assume a position nearly due North and South. Early mariners used this stone as an aid in navigation, guiding their vessels according to its position, and for this reason the stone became known as "lodestone," which means "leading stone." Another name given to this stone (which is an ore of iron) is "magnetic oxide of iron," or "magnetite." The peculiar property we refer to became known as "MAGNETISM" and the substance itself which possessed the property was called a "MAGNET." The lodestone retains its magnetic properties indefinitely for it is the result of a natural condition within the ore itself.

In later years it was discovered that by an artificial process ordinary hard iron, or steel, could be made to take on the same property of magnetism as the lodestone. Thus, the magnetic property imparted to steel gave it the power to attract bits of iron, and morever, it was noticed that when a thin strip of magnetized steel was suspended, and permitted a free motion, it would swing about and come to rest in a position exactly similar to the lodestone with regard to the earth's North and South poles. The needle of the common magnetic compass, which is in widespread use, is nothing more than an artificial magnet; it is a magnetized piece of steel suspended so that it can turn freely. As most of us know, one end of the compass needle points in a general direction toward the North geographical pole of the earth and the other end points toward the South geographical pole. Convention, or custom in the past, accounts for the fact that the North (N) of a needle is so designated and used to identify the location of our North geographical pole in a general way as explained in the following paragraph.

In order to avoid any misunderstanding in our study of magnetism, let us explain now that the north end of the needle is actually attracted by the earth's magnetism set up by the South magnetic pole. This magnetic pole is located on the Boothia peninsula, in Canada, a distance of more than a thousand miles from the geographical North pole. Our earth is really a huge magnet with magnetic forces evident all over its surface, the forces being very pronounced and concentrated at the upper and lower extremities, or, as we would say, "at the poles." Hence, to be strictly accurate in our statement we should say that the "N" end of a compass needle points towards the South magnetic pole of the earth and the "S" end towards the North magnetic pole. The magnetic concentration is very evident from the behaviour of magnetic compasses when used by mariners and aviators in these regions.

To make certain that you have a perfect understanding about polarity as indicated by a compass let us look at the conditions this way: Consider that if the north (N) end of the needle points toward a magnetic influence, the region of this influence must be of opposite attraction, or a south (S) pole. If, on the other hand, the south (S) end of the needle points toward a magnetic influence the latter region must also be opposite, or a north (N) pole.

INDUCED MAGNETISM. Figure 1 illustrates the principle of magnetic induction and attraction. When a steel bar magnet is dipped into soft iron filings, it will be found that a large number of the iron particles will cling to one another and to the bar with great tenacity. Most of the filings will cluster near the ends of the bar with very few distributed along the surface and practically none at or near the middle. The iron particles which are in contact and closest to either end of the bar will seem to grip on with great firmness while those further out from the end are more feebly attracted to one another and seem to be less rigid. This indicates that the magnetism emanating from the end of the bar is strongest near its surface and as we proceed outward into space the magnetism becomes weaker.

We use the term "density" to express this difference in magnetism, saying that the magnetic density is greatest close to the bar. It simply means there is a greater concentration of magnetic force closer to the magnet's poles than at some distance away from it.

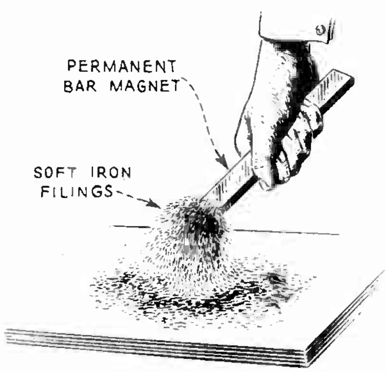

Figure 1

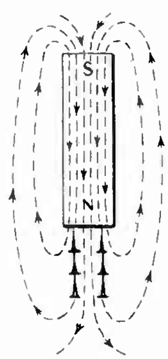

Figure 2

If a very strong steel magnet is used to attract the filings, and later you attempt to brush them off with your fingers, it will not prove an easy matter to remove absolutely every tiny iron particle from the magnet's surface. The manner in which these small iron bits cling to one another, and to the bar, indicates that regardless of the exact nature of this magnetic influence its force extends outward into the surrounding space which is called the "space medium." The iron tacks clinging to the magnet, in Figure 2, also serve to demonstrate the principles of induced magnetism.

The unseen influence around a steel magnet causes each individual filing in Figure 1 to become a tiny magnet possessing all of the properties of the large bar magnet itself. We usually express this action by stating that the large magnet induced magnetism into the iron filings. The filings would have magnetism induced in them whether they were in actual contact with the magnet, or merely in its presence. To prove the latter statement place the filings in a glass tube, or bottle, and then move the magnet against the outer surface of the glass and note how the filings are affected and shift around and cling to one another, assuming different positions according to the magnet's influence. Also, from this experiment we observe that glass is transparent to a magnetic force. Remember that each filing or tack assumes a position that enables it to accomodate the greatest amount of magnetism coming from the exciting magnet.

MAGNETIC PROPERTIES ALREADY EXIST IN IRON. The sketches in Figures 1 and 2 are intended to show that magnetism is not created but already exists in the iron tacks and filings. Nothing has been added to or taken from the iron to produce the results we have observed. It is simply a condition where this peculiar force (called magnetism) in the filings or tacks was made evident by the outside magnetic influence of the steel magnet. We know of several practical means for establishing magnetism and, also, ways to regulate its strength. This is a fortunate circumstance, indeed, because it permits us to utilize this invisible force in our electrical work.

Under ordinary conditions if we were to place materials like copper, paper, or wood, within the influence of a magnet we would not expect to observe magnetic effects such as the filings gave us in Figure 1. At first sight it might appear that any substance which is seemingly unaffected when subjected to a nearby magnetic force does not possess magnetic properties; but this is not the case. The phenomena of magnetism exists in all matter to a greater or less degree, only in some substances its detection becomes apparent quickly while in others it requires the most diligent research and delicate equipment to discover it. To make it pronounced in paper, wood, and all other so-called non-magnetic substances, would require an outside magnetic influence of considerable strength. If conditions were just right and if very strong magnetism was obtainable it could be shown that a piece of paper would be feebly attracted and would move toward the source of strong magnetism, whereas a piece of copper would be repelled.

We deal exclusively with iron and steel in our studies about magnetism because magnetic effects are especially pronounced in these metals, and for magnetic purposes they are the principal ones found in commercial use. However, it should be known that there is a certain compound consisting of iron and a small percentage of nickel that has magnetic properties superior to either iron or nickel alone. "Permalloy" is the name of one compound that can be magnetized about thirty times stronger than soft iron under similar conditions. "Perminvar" is the name of another magnetic compound.

TWO SOURCES OF MAGNETISM IN OUR PRACTICAL WORK. Let us mention at this point that the magnetic force set up by a fairly strong magnet is capable of not only attracting bits of iron and causing attraction or repulsion with other magnetic masses, but the force has the additional property of setting up a flow of current through coils, wires, and other elements composing an electric circuit. To produce a flow of current the magnetism which acts on the coils and conducting wires must be made to vary either in strength, or polarity, or both, and the circuit must be closed to form a complete conductive path for the current to flow. Or, if a magnetic force remains stationary and steady, a coil or conductor must be moved through it to produce a current of electricity therein.

It will be shown in a forthcoming lesson that an electric current passing through the turns of a coil sets up its own magnetic lines which completely encircle the coil. The lines set up by the current have precisely similar qualities in every way to magnetic lines produced by either a bar or horseshoe magnet. Bear in mind that magnetism, regardless of how or where it is made apparent (either through the use of magnets or from a flow of current) always exhibits the same general properties. Therefore, after having once mastered the fundamental principles outlined in this lesson, the student should find it easy to apply them to any action where magnetism and electric current are involved.

From these statements it is seen that there are two principal sources of magnetism:

1. Magnetic effects resulting from the use of magnets.
2. Magnetic effects resulting from the flow of electrical currents.

The first mentioned source is treated under the topic of "MAGNETISM" and the second, under "ELECTROMAGNETISM."

Just what takes place in the "space medium," or in a "material," when a magnetic force is present, or just what the nature of magnetism is we do not definitely know. But the results obtained when forces of this kind act upon magnetic substances, or upon conductors of electricity, have enabled scientists to formulate numerous laws and rules governing their behavior.

Very simple experiments can be performed to demonstrate "magnetic" and "electromagnetic" phenomena with a minimum of equipment, as for example, with the use of a small pocket-size magnetic compass, a bar or horseshoe magnet, iron filings, coils of wire and a battery, or dry cell.

KINDS OF MAGNETS. Magnetic substances are divided into two classes, namely:

(1) Natural magnets, and (2) Artificial magnets.

It should be quite obvious that a lodestone is a natural magnet and that all manufactured or man-made magnets are in the artificial class. The artificial kind are placed into the following two groups:

(1) Temporary magnets, and (2) Permanent magnets.

Inasmuch as the soft iron filings in Figure 1, or the tacks in Figure 2, lose practically all of their magnetism when removed from the magnetizing force they are classed as temporary magnets. Suppose, on the other hand, that these filings, or tacks, after being shaken free from the bar were to retain their magnetic properties (assuming that even after a period of many months or perhaps years they still persist in clinging strongly to one another) they would be classed as permanent magnets. Assuming that a solid bar of iron or steel showed properties similar to the tacks and filings, as we have suggested above, the bar would also be called a "temporary" magnet, or "permanent" magnet, as the case may be. The point we wish to emphasize is that the size of a mass does not alter these conditions.

TYPES OF MAGNETS. There are in general three types of magnets. The path of the magnetic forces in each type is shown in Figure 3.

(1) Bar magnet........(Magnetic circuit consists partly of iron and air.)
(2) Horseshoe magnet..(Magnetic circuit consists partly of iron and air.)
(3) Ring magnet.......(Magnetic circuit consists only of iron; while seldom used it is given to aid explanations.)

SIMPLE WAY TO MAKE A MAGNET. Suppose that one-half of a bar of hardened iron or steel is repeatedly stroked with the "N" pole of a strong magnet, and each stroke is made the same way, beginning at the middle of the bar and stroking toward one end, then this end of the bar will presently become an "S" pole. Suppose the "S" pole of the magnet is now used to stroke the opposite half of the bar by the same process, then the latter end of the bar will become an "N" pole. If this bar, into which magnetism is being induced, is heated or slightly pounded during the process either treatment will assist the molecules in rearranging themselves in parallel rows (or in alignment) to make the bar a permanent magnet. It will be explained under the subject of "Electromagnetism" how a coil of wire through which current is flowing can be utilized to induce magnetism into a bar of hardened steel to make it a permanent magnet.

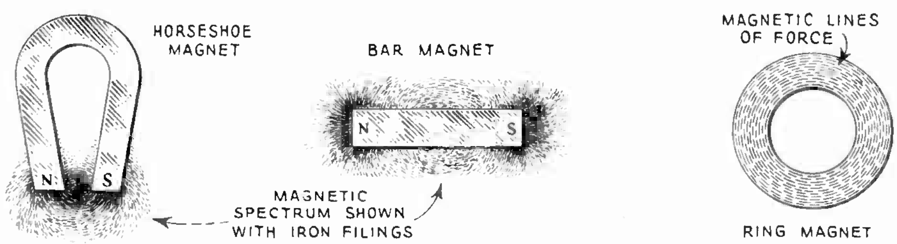

Figure 3

Magnets that are used for electrical measuring instruments and other devices requiring a constant magnetic flux must be aged. A permanent magnet becomes weaker with age but does not lose its strength uniformly with time. The strength decreases rapidly soon after the metal is magnetized and then falls off at a slower rate. The loss of magnetism is due to the haphazard arrangement of the molecules which will be discussed in detail later. In order to obtain a magnet which will lose very little strength over a long period of time we would ordinarily have to select a magnet which retained some magnetism although magnetized several years previously. However, manufacturers are able to obtain the effect of aging by a certain heating process. Heating a magnet to a red heat will, of course, destroy all magnetism but the application of a low temperature properly applied, will allow the molecules to hold their arrangement for an indefinite period.

FLUX - MAGNETIC FIELD - MAGNETIC LINES OF FORCE. To illustrate a "force" on paper is just like attempting to draw something one cannot see. For instance, you couldn't illustrate your "thinking powers" on paper, nor could you graphically show the "force" of an explosion. With this in mind you will appreciate why it has become the custom to merely draw a line to illustrate the line of direction of a force and then to place an arrow somewhere in that line to denote the exact direction in which the force is being applied. That is, the arrow shows the tension along the line. The magnetic forces which exist within a magnet and in the region surrounding it are, therefore, best illustrated by lines and arrows as shown in many of the drawings.

The total magnetic lines of force set up in a magnetic circuit (either by a magnetic material or by an electric current) are called magnetic flux, or simply flux. The flux is shown by dotted lines in our drawings. These lines take the form of ever-widening loops which may be thought of as a sort of magnetic whirl.

The field of force which is evident in the region outside a magnet is called the magnetic field.

The idea of presenting an unseen force graphically on paper is similar to that already used in our lesson on "Electrostatics." The difference is mainly that unbroken lines are drawn in the region where an electrostatic field of force exists, whereas, dotted lines are used to represent a magnetic field of force. Note particularly the formation of the magnetic lines of force in each of the different types of magnets in Figure 3. See how the majority of the lines come out at the region around one pole and go in at the region around the opposite pole, with comparatively few lines at or near the middle of the magnet. Of course, in the case of the ring magnet the lines are confined entirely within the iron mass because this magnet has no poles.

MAGNETIC LINES OF FORCE CAN BE VISUALIZED ONLY BY INDIRECT OBSERVATION. Magnetic forces cannot be seen, as you know, but their effects can be. In order that you may actually visualize the strain lines (lines of force) present about a magnetized substance it is suggested that the following simple experiment be performed. Obtain a small bar magnet or horseshoe magnet, a sheet of cardboard or glass, and a small quantity of soft iron filings. Someone connected with a machine shop in your neighborhood will no doubt give you the filings; a thimbleful or two will be plenty, or you may easily make them by filing part of an iron bolt, or any piece of ordinary iron for that matter.

Let the bar magnet be placed under the cardboard, or glass, and let the iron filings be sprinkled evenly over the flat surface. Then gently tap the surface a dozen times or more with a pencil and observe how the iron particles actually turn about and arrange themselves in lines or loops in a symmetrical formation according to the diagram in Figure 3. The energy in the magnet induces magnetism into the filings, causing each one to become a tiny magnet having its own "N" and "S" poles; the induced magnetism making the filings attract one another and causing them to form loops or whirls.

Each of the lines of force completes an independent circuit as shown by the continuous loops. The loops (or lines) tend to shorten themselves at all points, that is, they tend to take the shortest route in the space they occupy between opposite poles. However, the lines remain separated and spread out an infinite distance from the bar because of the strong repulsion which adjacent lines exert on one another. One line never crosses over, cuts through, nor merges into neighboring lines. See Figures 4 and 5.

The force lines exert a tension in a direction outward from the "N" end of the magnet as they pass around the bar through space and re-enter at the "S" end, the tension being continued on through the bar from "S" to "N," as indicated by the loops and arrows. When speaking about this characteristic of magnetism we say that lines of force are in a direction from "N" to "S" around a magnet and from "S" to "N" inside. (Note: The exception to this rule is a ring magnet which forms a closed iron circuit; in this type there are no open ends or poles and therefore the lines are confined within the iron. However, if a section of a ring magnet is cut out, the open ends thus made then become "N" and "S" poles respectively, with a magnetic field set up in the space between them.)

In the action explained in the foregoing paragraphs, where the force lines originating in the bar magnet exert their influence on the iron filings and cause their re-arrangement, it may be added that this action in turn places the filings in a position so that they exert their individual influences on one another. Keep in mind that each little filing becomes a magnet in this process. Consequently, we have a greater total magnetic force existing in the region around the magnet when filings are present than without filings, because the force lines set up by the filings when they are magnetized add to the force lines coming from the bar magnet.

<u>EXPLORING A MAGNETIC FIELD WITH A SMALL COMPASS</u>. Suppose we explore the magnetic strain set up in the region about a steel magnet by moving a compass in various positions as suggested in Figure 4. We will see that when the needle comes to rest at some particular location it will take up a definite direction acting along the lines of force at that point. The several positions of the compass in the drawing shows that the needle coincides with the lines of force in every case.

Hence, a magnetic compass is useful for detecting the presence of a magnetic field and determining the direction in which the lines pass. The diagram of the field about the magnet and the compass, in Figure 4, teaches you how to determine the polarity ("N" and "S" poles) of a magnet.

<u>MAGNETIC SPECTRUM</u>. In Figure 5 we observe a bar magnet and the region surrounding it placed under a strain by the force lines leaving at points toward one end of the bar and re-entering at similar locations toward the opposite end. This gives a symmetrical appearance to the formation of the lines as mapped out by the iron particles in the bar magnet in Figure 3.

The shape or image of the magnetic lines, as viewed with the aid of the filings, is called a "magnetic spectrum."

Since strain lines always exist around a magnet then for any change made in the position of a magnet the strain lines will move along with it. Try moving the bar magnet in Figure 1 slightly back and forth in different positions and note the effect on the filings.

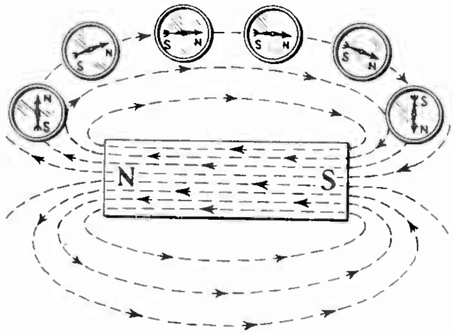

Figure 4

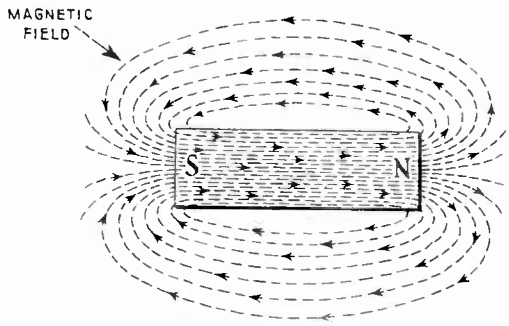

Figure 5

THE LAWS OF ATTRACTION AND REPULSION

(1) Magnetic poles of like kind repel each other.
(2) Magnetic poles of unlike kind attract each other.

To prove the laws just stated we will make use of two steel bar magnets whose "N" and "S" poles are known and marked as shown in Figures 6 and 7. One magnet is suspended by a thread so that it will move freely under the influence of the other magnet.

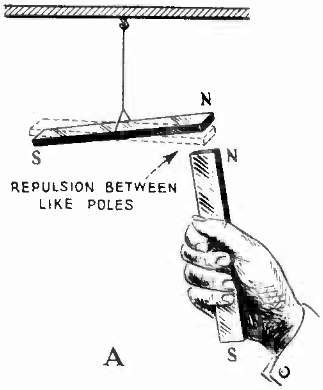

Figure 6

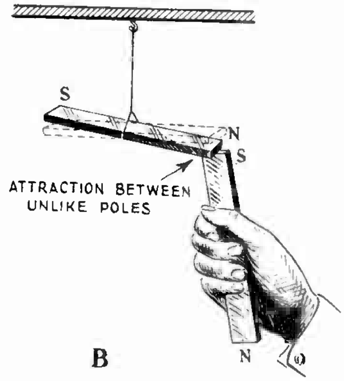

Figure 7

The conditions illustrated by Figures 6 and 7 are as follows:

(1) If one of the magnets is held in the hand and slowly moved, as shown in Figure 6, so that its north pole end is brought near the north pole end of the suspended magnet we will immediately see the latter move away and come to rest in a position as far as possible from the first magnet. This demonstrates the law of repulsion.

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(2) Now suppose the south pole end of the magnet in the hand is brought near the north pole end of the suspended magnet, as shown in Figure 7, then we will obtain an effect just opposite to the one observed in (1). This time the north end of the suspended magnet will swing toward the south pole of the approaching magnet, with the swinging magnet coming to rest in a position as close as possible to the magnet held in the hand. The ends of the magnets will actually come into contact if you permit them. This demonstrates the law of attraction.

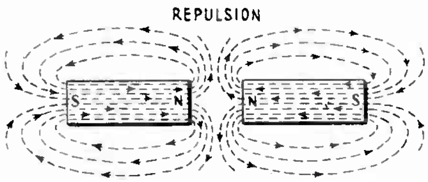

Figure 8

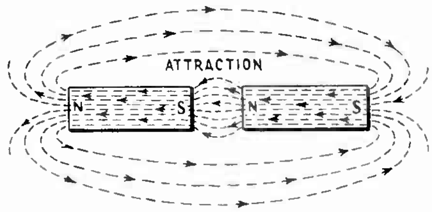

Figure 9

(1) The explanation for the action in (1) relating to repulsive effects will be understood after examining the sketch in Figure 8 and keeping in mind that the magnetic forces act along the lines and in the direction indicated by the arrows. Observe how the lines representing each field are distorted from the normal arrangement they occupy when not under the influence of each other. The shape of a normal field is shown in Figure 5. A similar effect of repulsion would be produced if two south poles were brought near to each other.

(2) The explanation governing the action in (2) relating to attractive effects will be understood by an examination of Figure 9 and reasoning as follows: The attraction or pulling effect between adjacent magnetic poles of unlike kind is caused by the lines coming out from the "N" end of the first magnet and going in at the "S" end of the second magnet, that is, the tension of the lines are acting along the same direction as shown in the drawing.

THEORY OF MAGNETISM IS BASED ON THE ENERGY STORED UP IN A MOLECULE AND ATOM. Now, examine the drawings in Figures 10, 11, and 12 for the purpose of studying the molecular action within an iron bar when it is demagnetized, or magnetized, or saturated with magnetism. Before we go into a detailed explanation of these drawings let us first mention a few facts about "energy" and the general conception that all magnetic effects in iron are thought to be due to an alteration in the position the molecules normally occupy. You should, at this point, recall some of the explanations given in a previous lesson about the composition of matter. You learned that all substances are composed of molecules, and that the molecules in turn consist of atoms, and finally the energy within the atom is a combination of positive and negative electrical forces. The negative forces are the rapidly vibrating electrons as previously explained.

Our explanations also stated that magnetism and electricity are inseparably associated in all kinds of "matter," and that energy in different forms is accounted for by the action of electrons in constant motion. It may be of more than passing interest to mention that according to the belief of scientists the many different kinds of substances found on our earth and the energy they possess were produced ages ago when our earth was in the process of cooling and formation.

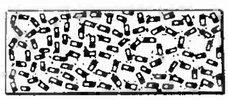

Figure 10

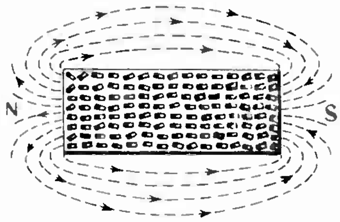

Figure 11

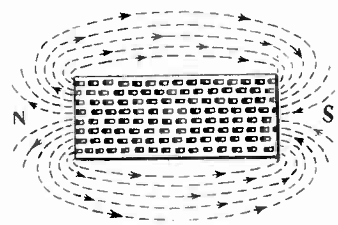

Figure 12

It is quite evident that energy already exists in iron and steel molecules and this energy is capable of doing "work" when properly directed. The results of the "work" performed by a magnetic force were observed in Figures 1 and 2 when iron particles and tacks were attracted toward a bar magnet and their weight was supported by it. Also, we saw that magnetic properties, similar to those of the steel magnet itself, were induced in the iron particles. This ability of iron and steel to become magnetized and to do work permits us to consider any material displaying such qualities as a storehouse of energy.

USE OF THE TERMS MAGNETIZED AND DEMAGNETIZED — ATTRACTION AND REPULSION. The power of either attraction or repulsion which one magnetized material exerts upon another was illustrated in the experiment with the bar magnets in Figures 6 and 7. Although these principles have been discussed before let us again repeat that each bar magnet has a north and south pole and, also, if two like poles, north poles for instance, are brought together the bars will move away from each other due to repulsion. Two south poles placed in the same neighborhood would also repel each other. On the other hand, if two unlike poles, north and south, are brought together the bars will move toward one another, and will touch if permitted to do so, due to attraction.

If you obtain some soft iron filings and actually try the experiment previously suggested in Figure 1 you will notice that after the filings are shaken off and removed from the magnet they cease to cling together; as far as all outward signs are concerned they have lost their individual magnetic properties. In other words, just so long as the filings are subjected to the magnetizing influence they continue to remain magnets, but when they are not subjected to this influence they lose practically all of their power to attract one another as you observed. In this process the filings were first magnetized and then demagnetized.

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There are certain kinds of iron that, after being magnetized, will retain their magnetism for much longer periods than the soft iron filings which we used. This subject is treated under "Retentivity."

CONDITIONS IN A NON-MAGNETIZED IRON BAR. The energy contained in a magnet that enables it to perform work is stored up in the molecules of the substance, as we have previously explained. A single glance at the drawing in Figure 10 shows that every molecule (molecules are merely suggested by the rectangles) is a magnet in itself having its own "N" and "S" poles. Also, the dotted lines denoting the forces are seen to reach out through the void spaces between adjacent molecules thereby linking them together to form numerous closed and irregularly shaped groupings.

The extreme ends of each molecule are called "poles," and by convention they are known as "north" and "south" poles, respectively. The "N" pole ends of the molecules are indicated in the sketch by solid black squares and the "S" pole ends by white outlined squares.

Observe how there is a natural attraction between neighboring molecules which causes them to arrange themselves in a somewhat irregular order with their north and south poles practically together. When an iron mass is in this condition, that is, with its magnetic forces confined in closed paths by virtue of the closed molecular groups, the iron will not display any noticeable outward magnetic effects. The iron in this condition is said to be non-magnetized or demagnetized. In other words, although magnetism is present within the bar it is not evident in the region outside and, consequently there is no magnetic field produced.

CONDITIONS IN AND AROUND A MAGNETIZED IRON BAR. If a piece of soft iron is brought near a steel magnet the iron will become magnetized as mentioned in an early part of the lesson. The molecules of soft iron, when under the exciting magnet's influence, are forcibly turned about on their axes and rearrange themselves in a manner somewhat like the diagram in Figure 11. They form parallel rows with their "N" and "S" poles lined up end to end.

When this alignment of molecules is brought about the energy in each molecule adds to that of its neighbor with the result that the "N" poles point in the same general direction toward one end of the bar and the "S" poles toward the opposite end. Thus, the magnetized iron has all of the properties of a magnet, that is, it has a north pole and south pole of its own. We have, then, a condition where the magnetic energy in the molecules now exerts its influence in the region outside the bar, setting up strain lines in this region, the strain lines being called a "magnetic field." As indicated by the lines and arrowheads the force lines about a magnet leave at the north pole and reenter the south pole.

The magnetic circuit in the diagram in Figure 11 consists of air and iron. The air path is technically known as the "space medium." However, in practice you will find that a magnetic circuit may consist of air or iron alone, or a combination of both. Magnetic flux encircling a coil when current flows is an example of a complete air path, whereas, a ring magnet, such as the one in Figure 3, is an example of an all-iron path. A ring magnet may be employed where no external field is desired for special uses in certain types of meters and transformers.

From the facts stated heretofore the student should readily grasp the idea that a magnetic force is continuous. However, to make this point positively clear let us suppose that in Figure 5 there are 100,000,000 lines of force within the bar (we have shown only several strain lines for simplicity) then we would also have 100,000,000 strain lines acting on the space medium. In other words, for each line existing in the bar the space outside is subjected to the strain of one line for the simple reason that every line is continuous; it has no beginning or end. Moreover, the space about a magnet opposes being placed under a strain and, consequently, it exerts a constant effort to recover its normal state.

It is of utmost importance that the student should think of magnetic flux acting entirely around a magnetic circuit and not that the lines start or end at any particular point.

CONDITIONS IN IRON OR STEEL WHEN SATURATED WITH MAGNETISM. The drawing in Figure 12 shows several rows of perfectly aligned molecules. It is only natural to expect that such straight rows of molecules, when exactly end to end, will exert the greatest strain or tension in regions outside the magnet. In practice, however, molecules do not as a rule form absolutely straight lines but their rearrangement is more or less imperfect. In any event the extent of molecular rearrangement is dependent upon the kind of substance being magnetized and the strength of the inducing force. Each line contributes its individual magnetizing force to the total produced by the magnet. If all of the molecules of an iron or steel bar were rearranged as perfectly as those shown in Figure 12 then no further magnetism could be induced in the bar since there is nothing more that could be done to the iron to make it "take on" or "hold" more magnetism. In this condition the iron would be said to have reached the "saturation point," known as "magnetic saturation." Therefore, its magnetic strength could not be increased beyond this limit regardless of how strong might be the magnetizing force.

EFFECT OF BREAKING A MAGNET INTO SMALLER PIECES. The sketches in Figure 13 are intended to convey the idea that magnetism is due to a certain molecular arrangement and, also, that magnetic lines form a continuous circuit; they cannot be thought of as having any beginning

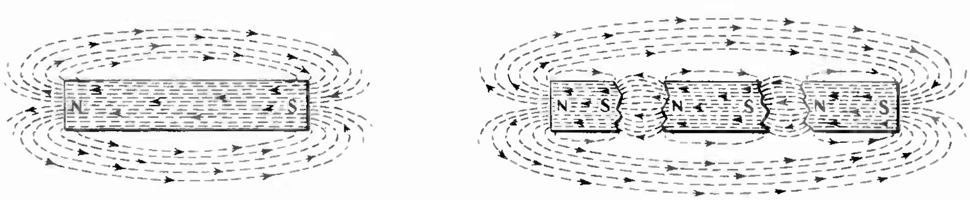


Figure 13

or end. Accordingly, if a bar magnet is broken into several pieces, as illustrated, each piece becomes a separate magnet with "N" and "S" poles of its own and with strain lines established in the surrounding space.

WHEN TWO MAGNETIC FORCES ACT SIMULTANEOUSLY IN THE SAME REGION. The purpose of showing the weather vane, in Figure 14, is to explain by a simple comparison with two air currents what would happen if two independent magnetic fields, established in the same region, acted on each other. Suppose we have the force of one air current, marked A, acting in the direction indicated by the arrows, and a second air current, marked B, acting from some other direction. If the two currents meet at a place where a weather vane is erected the vane will move about and finally come to rest pointing in a direction different from either of the oncoming air currents. The final direction assumed by the vane is a resultant effect of the two forces acting on each other. So it is with magnetic forces. If two magnetic fields are brought together in the same region the fields will be distorted and the final direction of the magnetic lines, or the resultant field, will be governed by the angle at which the fields meet and the relative strength of the forces acting.

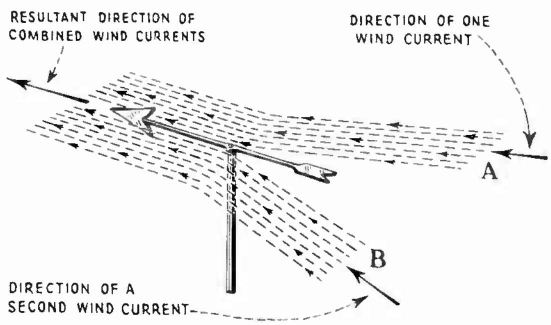


Figure 14

HYSTERESIS - MOLECULAR FRICTION. That molecules of iron actually do move and turn about on their axes when brought into the presence of a magnetic force can be proven in a practical way. If a magnetic force acting on an iron bar changes continuously in strength, or polarity, the iron molecules composing the bar will rearrange their positions in accordance with the changing force. The molecules, as they shift slightly back and forth, rub one another and in so doing they generate heat in the iron. The heat developed in the iron or steel parts of any electrical apparatus, which is built to function only when subjected to rapid changes in magnetism, represents one source of energy loss.

Therefore, if we wholly or partially magnetize and demagnetize a piece of iron steadily for a given length of time, which we can do by various means, the iron will become warm and under certain conditions it may even become very hot. The heat is said to be due to molecular friction between the iron particles, and note that all of this happens despite the fact that we can see nothing of the invisible forces that are acting. It is obvious that heat is a waste of energy when it is not desired, or when it is not put to some useful purpose.

It is more difficult and requires greater magnetic influence to alter the molecular arrangement of steel than iron, that is to say, steel naturally resists being magnetized or demagnetized to a greater extent than iron. The energy loss that occurs in iron or steel when subjected to rapid changes in their molecular arrangements is called "hysteresis."

RELUCTANCE EXPLAINED BY PLACING A BAR OF SOFT IRON BETWEEN TWO STEEL MAGNETS. The opposition which air, or iron, or any material used in a magnetic circuit presents to magnetic flux is called "reluctance." It will be recalled that in the case of an electrical circuit the opposition to current flow is spoken of as "resistance."

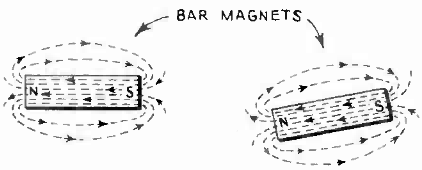


Figure 15

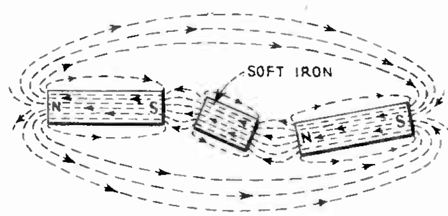


Figure 16

The reluctance of air is about a thousand times as great as the reluctance of ordinary iron. Because the reluctance of iron and steel is lower than air explains why lines of force will always take on iron or steel path in preference to an air path. Refer to Figures 15 and 16 which show that when a bar of unmagnetized soft iron is placed between two steel magnets a greater number of lines of force will be accomodated in the iron and a stronger flux will be set up in the magnetic circuit than would be the case if we simply had an air space separating the two steel magnets. The shape of the magnetic fields of the two magnets are normal when the iron bar is removed, as the drawing in Figure 15 shows. However, when the iron is inserted between the magnets, as in the drawing in Figure 16, their fields are distorted and the lines seek the path through the iron rather than through the air.

By moving the three bars closer together shorter air gaps will separate them and, of course, the reluctance of the complete magnetic circuit will be lowered accordingly with the result that more lines of force will be established. This will increase the attraction existing between the three bars and make the iron bar a stronger magnet. If, on the other hand, the three bars are moved farther apart the reluctance of the entire magnetic circuit will be increased due to the wider air gaps with the result that less lines will be established, and the iron bar will become a weaker magnet.

So long as the iron bar is kept in the presence of the steel magnets the iron will have magnetism induced in it and therefore will remain a magnet having "N" and "S" poles of its own. The polarity is due to the iron molecules being forced into alignment, a condition similar to that pictured in Figure 11. Note for one thing how the magnetic circuit in Figure 16 is formed and, also, that there is attraction between the three bars since their unlike poles are near each other.

In order to understand the reason for the results obtained in Figures 15 and 16 it is only necessary to bear in mind that air offers an infinite opposition to the setting up of magnetic lines, whereas, iron naturally offers an easier path for lines of force. This is why iron is attracted to a magnet.

The three factors governing the condition of any magnetic circuit are, namely: (a) the length of the complete magnetic path or circuit; (b) the cross-sectional area of the circuit; and (c) the permeability of the circuit, which varies according to the materials used and the length of any air gaps or spaces present through which lines of force must pass.

RETENTIVITY — PERMEABILITY. The term "retentivity" is used to denote the power of substances to retain or hold the greater part of magnetism imparted to them. The term retentivity should not be confused with permeability. The term "permeability" expresses the quality of a material that permits it to become strongly magnetized, or, in other words it indicates the ease with which a magnetic substance can be magnetized irrespective of how long the substance may retain magnetic properties afterwards.

A piece of hardened steel resists being magnetized, but after magnetism is once induced in the steel it will hold or retain this property for comparatively long periods. It requires a great magnetizing force (called coercive force) to completely demagnetize a steel magnet, that is to say, to return its molecules to such a position or arrangement that the steel will no longer show magnetic properties. So we find that molecules of steel are not easily moved out of their aligned positions after they once assume a certain arrangement. For this reason, steel is used in the manufacture of permanent magnets. A permanent magnet should always be handled with care; if dropped or subjected to shocks, jars, or heat, it is likely to lose a considerable part of its magnetism due to the breaking up of the molecular alignment.

On the other hand, soft iron is used where a temporary magnet is required because the molecules of this material will arrange and rearrange themselves with comparative ease when placed in and out of the influence of an outside magnetic force. It should now be apparent that soft iron acts as a magnet only at such times as when a magnetizing force is present.

DENSITY. It stands to reason that far more parallel rows of molecules can be packed into a given mass of iron when molecules form exactly straight lines and the lines are very close together as in Figure 12, than in the case where the molecules are more or less haphazard and partly in alignment as in Figure 11.

The number of lines that can be crowded into a given magnet determines its magnetic strength; the number of lines per unit area being known as the density. The strain at any point near a magnet is indicated by the density of the lines at that point. It then follows that a magnetic field of high density possesses great strength and is capable of doing considerable work while a field of lower density will be comparatively weaker.

Figure 17 shows how the density of a magnetic field varies with the distance from the source. The rectangle R is cut by many lines of force whereas the area designated as P is seen to have fewer lines traversing its boundaries. The exact relationship between distance and magnetic field intensity is expressed in the formula,

$$H \propto \frac{m}{d^2}$$

where: H = magnetic field intensity
m = the strength of the isolated magnetic pole
d = the distance from the pole

the symbol $\propto$ stands for the phrase "varies as."

From this relationship we can see that if 8 lines pass through R only one fourth of that number or 2 will pass through P or we can say that the magnetic field intensity varies inversely as the square of the distance from the pole. This is true providing P is twice as far from the end of the bar as R.

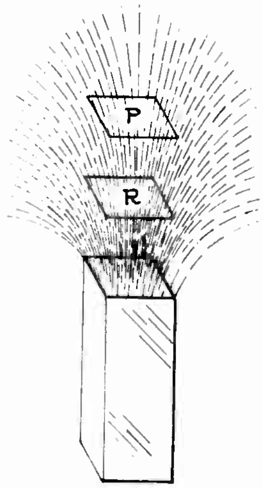


Figure 17

The magnetizing force H is the number of gilberts per cm.; a gilbert being the unit of magnetomotive force $\mathcal{F}$. The gilbert is numerically expressed in the relation,

$$\mathcal{F} = 0.4\pi NI$$

where: N = number of turns
I = current in amperes,

and the magnetizing force(H) is this result divided by the length of the magnetic path(l) or gilberts per centimeter,

$$\text{or, } H = \frac{0.4\pi NI}{l}$$

The number of lines of force in a unit area is called the flux density or field intensity. When one line passes through one square centimeter the field strength is said to be one gauss.

$$B = \frac{\Phi}{S}$$

where: B = flux density in gausses
Φ = total flux
S = total area in square centimeters

The total number of lines or flux in any given area is the product of the field strength and the area.

Due to the fact that magnetic lines of force are set up in iron much more easily than they are in air, the ratio of the number of lines that exist in iron to the number existing in air gives us a relationship known as permeability. Thus, if a single line passes through one square inch of air and one hundred lines pass through the same area of iron the iron is said to have a permeability of 100 divided by 1, or 100.

Figure 18 shows a number of lines of force passing through a unit area of air space; in this case 1 inch.

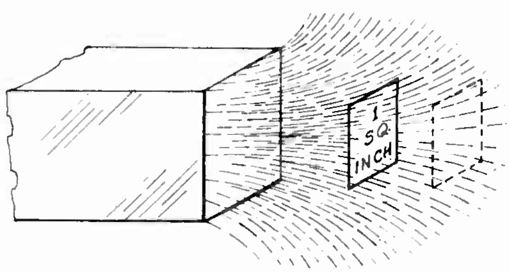


Figure 18

The ratio of the flux density (B) to the magnetizing force (H) likewise represents magnetic permeability (μ)

$$\mu = \frac{B}{H}$$

where: B = flux density in gausses
H = magnetizing force in gilberts per centimeter

If iron takes the place of air as a medium for magnetic lines of force the flux density B is increased. All kinds of iron, however, do not have the same flux density. Various specimens of iron and steel have been tested for use in magnetic circuits as well as for use in electrical machinery, and it has been found that the flux density or number of gausses set up by different magnetizing forces vary greatly. In order to show the relationship between the magnetizing force, (H), and the resultant flux (B), curves are plotted for all types of iron and steel. These curves are known as magnetization-saturation, or more commonly as B-H curves.

Figure 19 is a set of standard curves for several different materials used for magnetizing purposes. They represent the average for materials used by large commercial organizations.

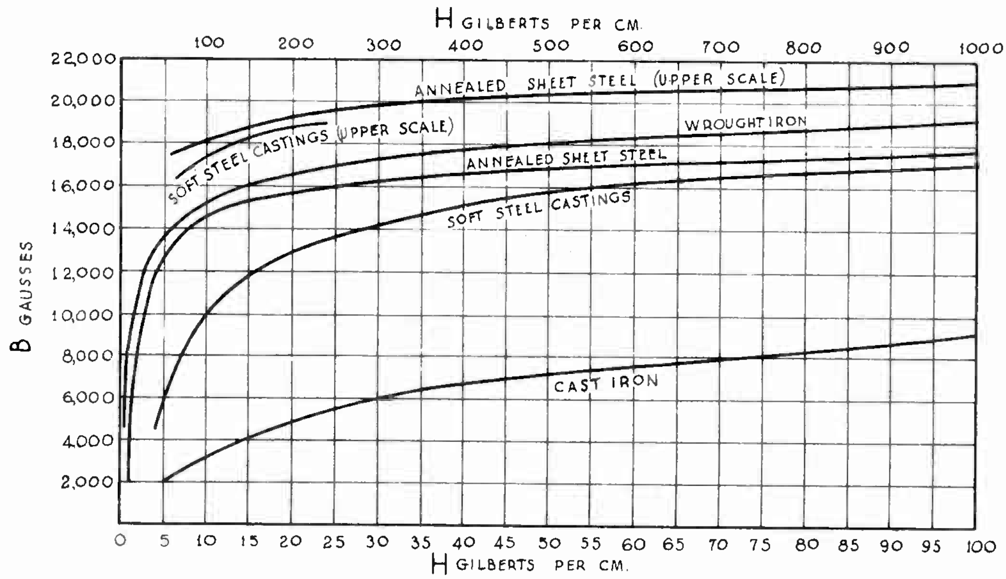


Figure 19

Now that we understand that permeability is the ability of a material to conduct magnetic lines of force we can expect that a unit representing the ability of a substance to oppose magnetic flux will be useful. The resistance to magnetic lines of force is called reluctance $\mathcal{R}$, the unit of which is known as the oersted. The difficulty with which a substance is magnetized is called its reluctivity and, as has been explained, reluctance is inversely proportional to permeability. This is the same as saying that if the permeability increases the reluctance decreases proportionally and if the reluctance is increased the permeability is decreased a corresponding amount.

$$\mathcal{R} = \frac{l}{\mu S}$$

where: l = length of magnetic circuit in centimeters
μ = permeability
S = cross section area in centimeters

RESIDUAL MAGNETISM. If an iron mass, after being subjected to a magnetizing influence, is removed from the exciting force and the iron then holds a perceptible amount of magnetism, the remaining magnetism is known as "residual magnetism." It simply means that the molecules do not all move back in the original positions they occupied before magnetization took place, but a certain number remain permanently fixed in more or less irregular lines which produces a weak magnetism. "Remanance" is a term used when comparing the total number of lines of force of residual magnetism remaining in different kinds of iron and steel after the removal of the magnetizing force.

MAGNETIC SHIELD — AIR AND SPACE MEDIUM. We do not really consider air as the space medium in which magnetic lines are established around a magnet although the term air is frequently used to denote this region. Just what the medium is has never been ascertained, but it is known that it is something other than air. For instance, suppose we exhaust the air from a sealed glass chamber and suppose a compass occupies a position in the very center of the vacuous space. It would be found that if a steel magnet was brought near the chamber the magnetic lines emanating from the magnet would penetrate through both the glass wall and the vacuum and cause the compass needle to deflect.

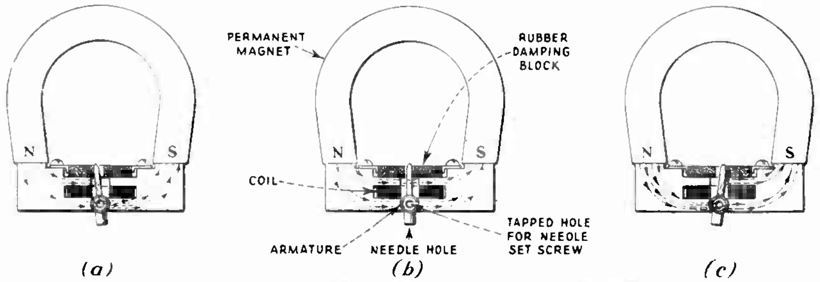
It is interesting to note from this test that neither glass nor a vacuum will act as a shield to block magnetism. Iron is used in practically all cases where a magnetic shield is desired. The principle of an iron shield is as follows: Magnetic lines from some source will not pass directly through and out on the opposite side of an iron shield, but rather the force of the lines act on the iron molecules tending to rearrange them and make the shield itself a magnet. What happens is this: the shield takes up the magnetism and in this way shunts the magnetic forces around the region which is to be protected or isolated from magnetic effects. Thus, when a shield is employed, magnetic lines cannot spread outward indefinitely into space, as the lines naturally would do otherwise. The principle explained here is one of magnetic induction, and it holds true in the case of any magnetic force acting on iron which tends to make the iron a magnet.

In a future lesson you will study a type of magnetism known as electromagnetism which produces effects similar to those studied in this lesson. Many electrical devices are operated on electro-magnetic principles and many depend on ordinary magnets for their action. Perhaps you are familiar with the difference between the two forces or perhaps you have learned the difference from the foregoing sentences. An ordinary magnet retains its magnetism at all times whereas an electromagnet is magnetic only in the presence of a current flow.

COMMERCIAL APPLICATIONS. Figure 20 shows various stages in the operation of a magnetic pickup device which is used to change the mechanical vibrations of a phonograph needle into electrical impulses, which can be increased by the amplifiers of a radio receiver or sound picture machine. This pickup contains a permanent magnet of the horseshoe type between the poles of which a light coil of wire is suspended. The needle is permanently connected to this coil and the wires of the coil are connected to the amplifier.

The coil of wire is located midway between the N and S poles of the permanent magnet as is shown in the illustration. The arrows indicate the path of the flux from the N to the S pole. If the coil moves through this flux due to mechanical vibration from the needle the flux will be affected or will be cut by the coil or conductor. When we study the subject of electromagnetism we will learn how this action produces an electrical current.

Permanent magnets are employed in a similar role in the magnetic type of loudspeaker and in ear phones or receivers. Instead of producing or generating a current, however, as does the pickup these sound producing devices receive electrical energy and change it to mechanical motion, which is the reverse action. The principle, however, is similar.



Operation of the magnetic pickup

Figure 20

Figure 21 illustrates a common type of magnetic speaker used whenever a medium amount of sound is desired such as is in the home or in the sound projection room of a theatre. When greater volume of sound is required a dynamic type of speaker must be employed. The magnetic

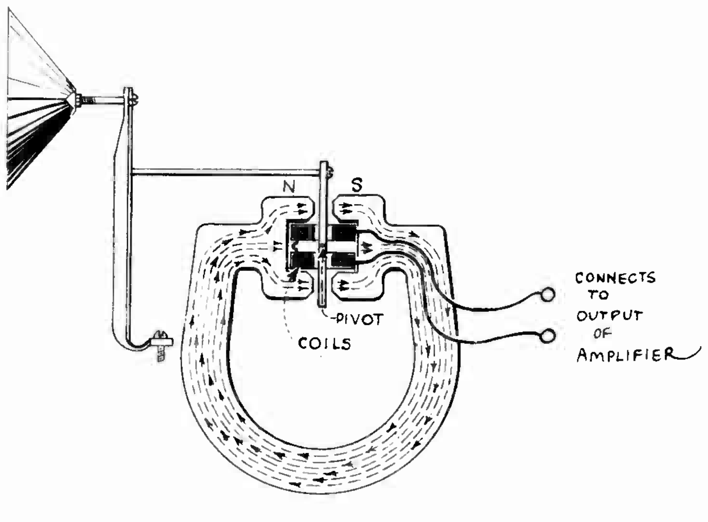


Figure 21

speaker contains a large permanent magnet and a coil of wire is located between its poles as shown. The arrows indicate the path of the magnetic flux.

The various parts which comprise a magnetic speaker are shown in Figgure 22. The student should recognize that the main component parts are the permanent magnet and the coil or winding previously described.

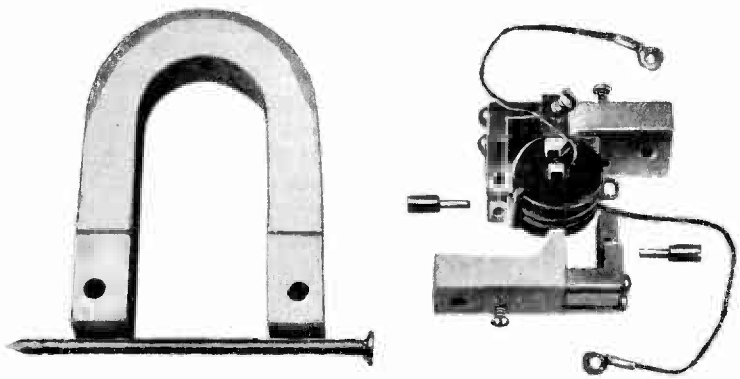


Figure 22

INCLINATION AND DECLINATION. The following terms do not have a direct bearing on our study of radio or sound pictures although many students will find them interesting and useful as magnetic disturbances often affect radio communication and navigation.

We mentioned in the first part of this lesson that a magnetic compass points towards the magnetic poles and that these poles do not coincide with the geographical poles of the earth. The angular deviation of the magnetic compass from the geographical north pole is called the angle of declination, or just declination. The first notice of this discrepancy of alignment between the magnetic and geographical north poles is accredited to Columbus who was unable to account for the phenomenon.

Lines connecting points on a map having the same declination are known as isogonic lines. The lines are very irregular due to magnetic deposits in the earth. A line connecting the geographical and magnetic north poles and running through Chicago is known as the line of zero declination as compasses located on this line point toward the true north. In northeastern Maine compasses point 20 degrees west of true north whereas in the state of Washington they point about 25 degrees east of north.

If a magnetic needle is balanced freely by means of a thread or pivot it will not lie parallel to the earth's surface but will dip towards the magnetic pole nearest to it. The angle of inclination, or dip varies from zero at the equator to a vertical position or 90 degree dip at the magnetic poles.

Navigators of both aeroplanes and ships must take these variations of the magnetic compass into consideration. A sensitive compass needle often swings back and forth three degrees on either side of its normal position when affected by a magnetic storm. Although the cause of such storms is unknown they are often accompanied by sun spots and auroral displays. Telegraph and telephone lines are inoperative during magnetic disturbances and radio signals become weak or fade out entirely.

The magnetic condition of the earth is continually undergoing changes. At the present time both the inclination and the declination are slowly increasing in the United States. Slow changes such as these are known as secular changes. That these changes have been going on for many centuries is evident from the fact that coal deposits are found in the extreme northern parts of the earth where no vegetation now grows. As coal is formed by tropical or semi-tropical vegetation the northern or arctic region of the earth must have been located in an entirely different position with respect to the sun than the present one. Such a change of the earth's position would no doubt shift the magnetic as well as the geographical poles.

SERIES AND PARALLEL MAGNETIC CIRCUITS.

Series Arrangement.

We shall see the advantage of connecting magnetic materials in series or in parallel with each other when we study electromagnetism, especially in connection with motors and generators. These machines have large magnetic cores composed of pieces of iron made in various shapes and sizes. The reluctance or opposition to lines of force offered by magnetic materials whether connected in series or in parallel depends on the length, the permeability, and the cross sectional area. This was expressed in the general formula for reluctance, namely,

$$\mathcal{R} = \frac{l}{\mu S}$$

The total reluctance offered by a series connection of magnetic circuits is equal to the sum of the individual reluctances, or

$$\mathcal{R} = R_1 + R_2 + R_3 + \text{------} \quad \text{etc.}$$

In the explanation dealing with electrical circuits resistance offered to the flow of current in an electrical circuit is handled in a similar manner.

Let us work out a typical problem in series magnetic circuits. Suppose we have a magnetic circuit composed of two pieces of iron with permeabilities and dimensions as given below and we wish to find the total reluctance of this magnetic circuit. If we compute the reluctance of each piece of iron and add the two values together the result is the desired total reluctance, or total opposition to the magnetic flux.

The first piece is 12 centimeters long, 5 square centimeters in area, and has a permeability of 400. The total reluctance is:

$$\mathcal{R} = \frac{l}{\mu S} = \frac{12}{400 \times 5} = 0.006 \text{ oersteds.}$$

The second piece is 30 centimeters long, 8 centimeters in area and has a permeability of 1000. Again we substitute and

$$\mathcal{R} = \frac{l}{\mu S} = \frac{30}{1000 \times 8} = 0.0037 \text{ oersteds.}$$

The total reluctance equals the sum of the two reluctances, or

$$0.006 + 0.0037 = 0.0097 \text{ oersteds.}$$

Parallel Arrangement.

When it is desired to find the total reluctance of several magnetic circuits placed in parallel or in shunt we employ the following relation:

$$\mathcal{R} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \text{------etc.}}$$

For example, suppose we have an iron ring with a circumference of 100 centimeters, a cross sectional area of 10 square centimeters, and a permeability of 180. Now if a ring of the same dimensions but of different material, and having a permeability of 90, is placed alongside the first ring the total reluctance is computed as follows:

Reluctance of first ring:

$$\mathcal{R} = \frac{l}{\mu S} = \frac{100}{180\text{x}10} = \frac{1}{18} \text{ or } 0.0555 \text{ oersteds}$$

Reluctance of second ring:

$$\mathcal{R} = \frac{l}{\mu S} = \frac{100}{90\text{x}10} = \frac{1}{9} \text{ or } 0.1111 \text{ oersteds}$$

The total reluctance of the two rings connected in shunt, or parallel is computed as follows:

$$\mathcal{R} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}} = \frac{1}{\frac{1}{\frac{1}{18}} + \frac{1}{\frac{1}{9}}} = \frac{1}{18 + 9} = \frac{1}{27} \text{ or } 0.037 \text{ oersteds.}$$

Using the decimal equivalents instead of fractions we arrive at the same result.

$$\mathcal{R} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}} = \frac{1}{\frac{1}{0.055} + \frac{1}{0.111}} = \frac{1}{\frac{2}{0.111} + \frac{1}{0.111}} = \frac{1}{\frac{3}{0.111}} = \frac{0.111}{3} = 0.037 \text{ oersteds.}$$

The above worked out problems are similar to those given in the examination questions.

PRACTICAL APPLICATIONS OF MAGNETS.

The photograph in Figure 23 shows the most recent type of dynamic loudspeaker which uses a large magnet to supply the permanent field in which the voice coil of the speaker is located. The mechanical design is clearly shown in this rear view photograph. The magnet

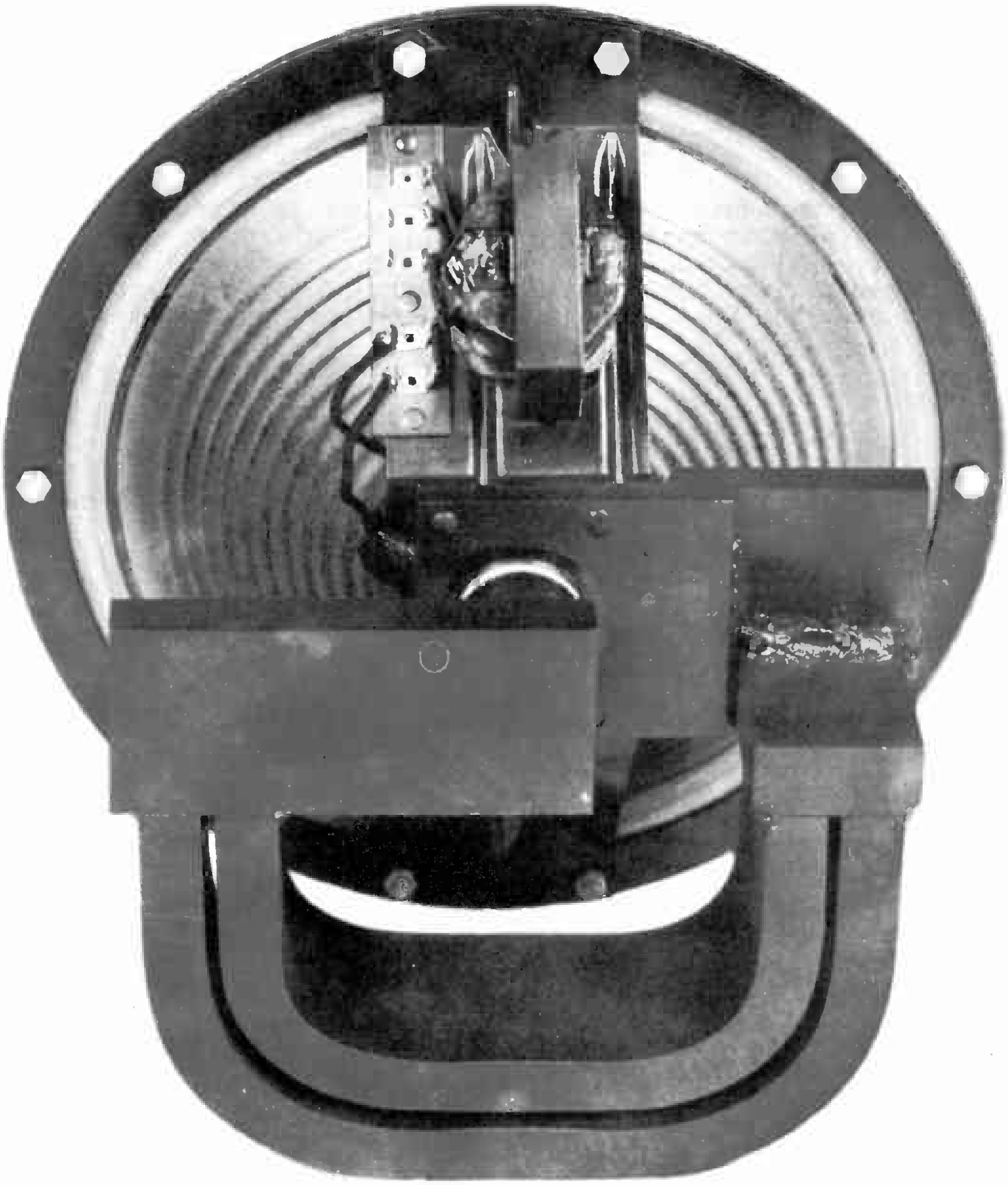


Figure 23

structure is formed from a high grade magnet steel or chromium steel which affords practically indefinite life or permanent magnetic strength unless the magnet is mistreated, such as by the application of demagnetizing fields, by severe mechanical shocks, by undue heating, or by improper contact with other magnetic materials. The yoke consists of two horseshoe type magnets which support all remaining portions of the assembly. One pole piece is formed from a solid cylindrical unit extending forward within a circular hole in the head or second pole piece to which both sections of the cone

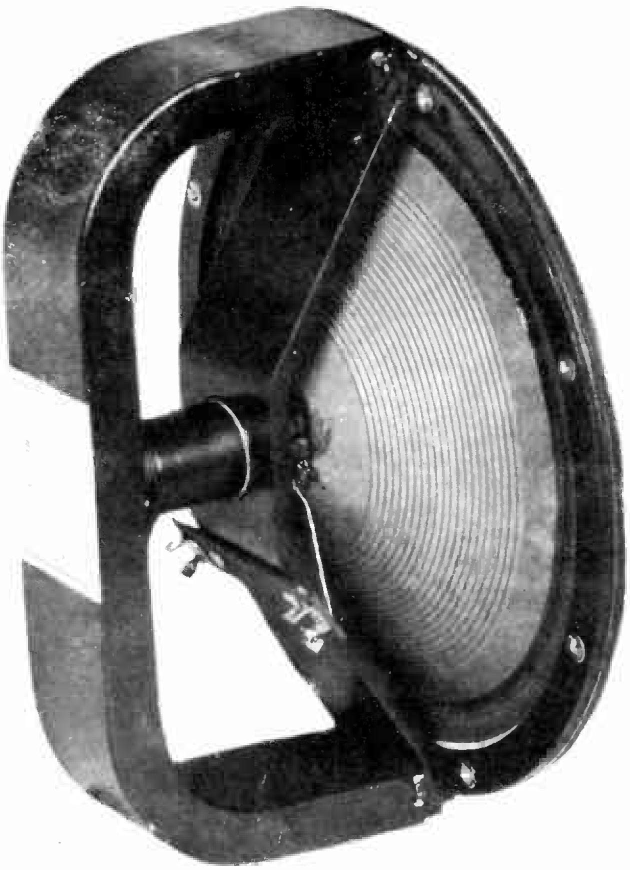


Figure 24

support are rivited. All joints between the various pole piece units and the magnet faces are electrically welded. This construction provides an annular air-gap in assembly within which the cone coil is suspended, the cone support being of non-magnetic material. In brief the action of the loudspeaker depends upon the magnetic lines set up around the cone coil when voice currents flow through it reacting on the magnetic lines of the permanent magnet. This reaction between the two magnetic fields causes the cone to move since the coil is mounted on the apex of the cone. The main feature in utilizing the permanent magnet for a dynamic type loudspeaker is for applications wherein either insufficient or no field supply power is available. The sound radiating surface is a paper cone which is corrugated to improve the reproduction.

There are many useful applications of a permanent magnet to be found in the electrical field such as in meters of various descriptions, in telephone receivers or headsets as they are often called, in devices used in connection with the visual indicating method employed in the reception of airplane beacon signals, in the pickup units used with self recording apparatus, and in the sound-on-disc system employed in sound picture equipment and so on.

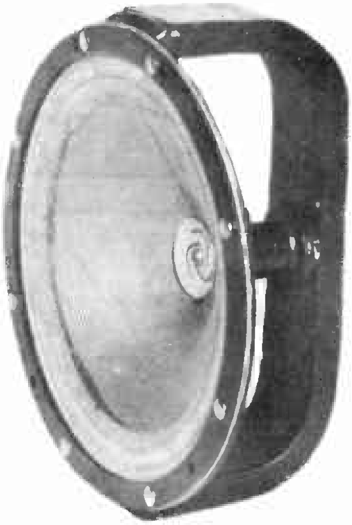


Figure 25

Among the widely varied applications of a permanent magnet are the instrument relays designed for complex automatic testing devices incorporating vacuum tubes and photoelectric cells. The Jewell relay in Figure 26-A shows the horseshoe magnet, the moving coil and the contacts.

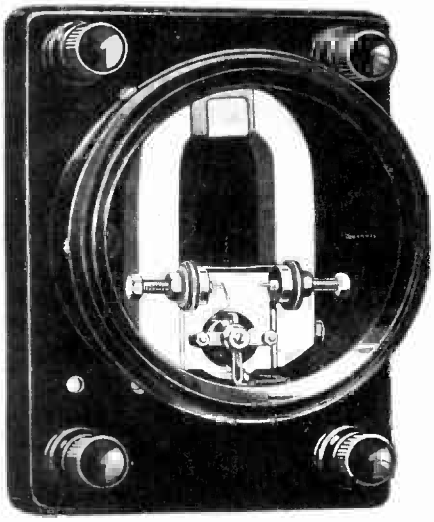


Figure 26-A

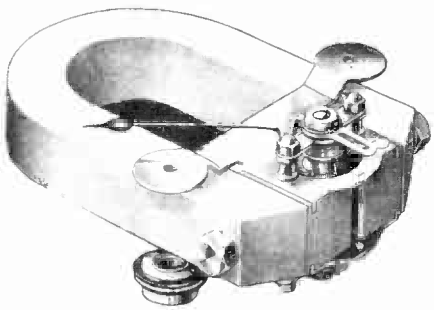


Figure 26-B

The permanent magnets used in direct-current instruments are of conventional shape as shown by the horseshoe magnet in Figure 26-B which is used in the d-c movement of a Jewell instrument. These magnets are designed to have the proper ratio of length to cross section in terms of the required flux and length of air gap and are forged from alloy magnet steel and heat treated.

In Figure 27 you see a pickup unit about to be placed in the starting position on a record while the sketch in Figure 28 illustrates

Figure 27

the component parts and of particular interest at this time in our study of magnetism are the pole pieces and the magnet.

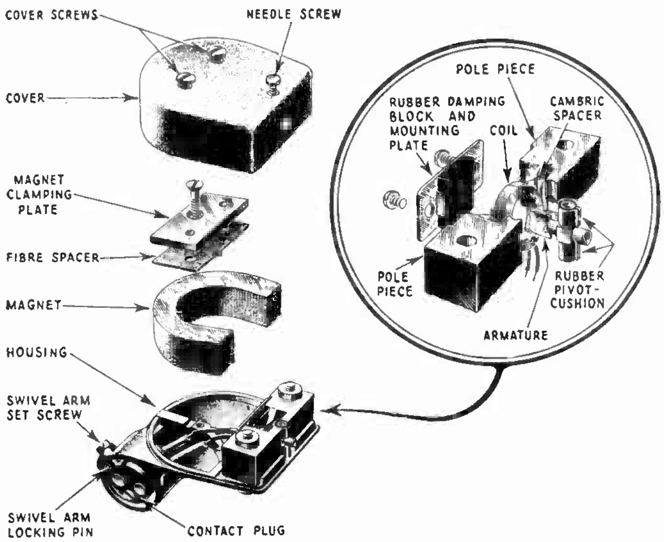


Figure 28

When the unit is assembled the pole pieces act as extentions to the poles of the magnet and hence, they carry the flux to the air gap in which the coil and armature are located.

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EXAMINATION QUESTIONS

1. What would be the best material to use in the construction of:
   (a) A permanent magnet? Explain why this is true.
   (b) A temporary magnet? Why?

2. Name and illustrate three types of permanent magnets.

3. Why must great care be taken in the handling of a permanent magnet?

4. A steel magnet bar is broken into small pieces. What is characteristic of each particle?

5. What form does the magnetic spectrum of a horseshoe magnet assume? Illustrate by means of a diagram.

6. In your own words make clear the meanings of the following terms. (a) Reluctance, (b) Retentivity, (c) Permeability, (d) Magnetic saturation, (e) Hysteresis, (f) Residual magnetism.

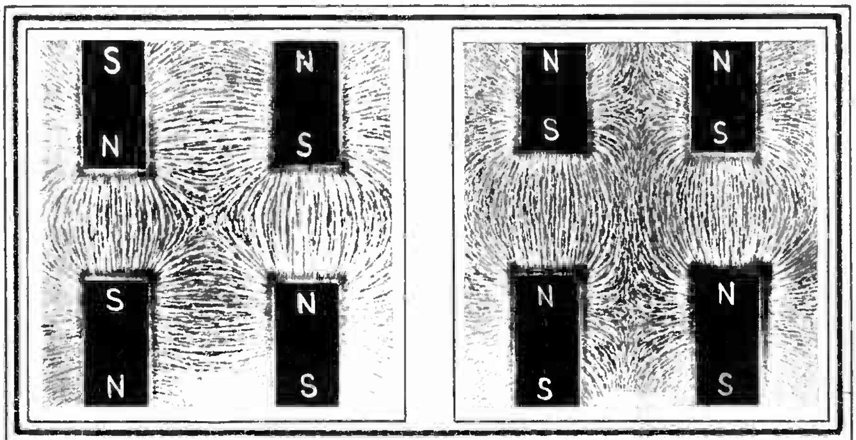
7. Give an explanation of the laws of attraction and repulsion. How would you undertake to give a simple demonstration of these laws, to someone?

8. Answer briefly but clearly:
   (a) What is a magnetic field?
   (b) What is meant when one speaks of "density?"
   (c) What is induced magnetism?
   (d) What is meant by magnetic flux?

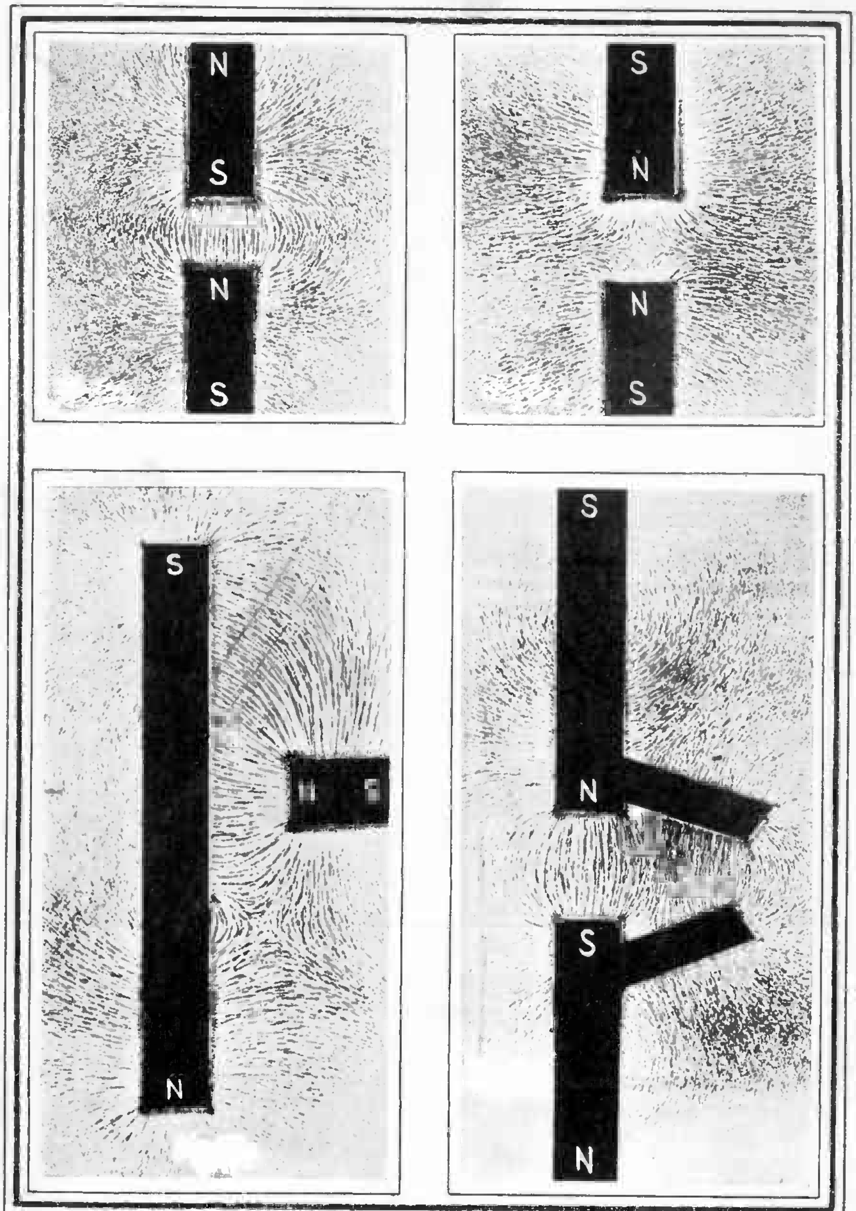
9. What are a few of the characteristics of "lines of force?"

10. What is the arrangement of molecules in an iron or steel bar (a) When magnetized? (b) When demagnetized? (c) When magnetically saturated?

11. An iron bar 10 centimeters long, 5 square centimeters in cross section, and having a permeability of 100, is connected in series with another iron bar of the same dimensions but having a permeability of 80. A third piece of iron which is 4 square centimeters in area and 20 centimeters long is clamped alongside of the first two pieces so that the ends meet. If the third iron bar has a permeability of 100 what is the total reluctance of the three bars?



THE IRON FILINGS ARRANGE THEMSELVES INTO CURVED LINES BETWEEN THE UNLIKE POLES OF MAGNETS



IRON FILINGS INDICATE ATTRACTION AND REPULSION OF VARIOUS COMBINATIONS OF BAR MAGNETS

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