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EDUCATIONAL COURSE

PAMPHLET E-3

ELEMENTARY ELECTRICITY

MAGNETISM

OFFICE OF
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ELEMENTARY ELECTRICITY

MAGNETISM

SECOND EDITION.

Figures 3 to 6, inclusive, are taken from "Elements of Electrical Engineering" by Dr. W. S. Franklin and Wm. Esty, who kindly furnished the cuts from which they are made.

MAGNETISM

No study of electrical engineering could be complete without a thorough study of magnetism, since much electrical apparatus is dependent upon magnetism for its action. In this pamphlet magnetism only will be discussed, reserving for other instruction papers the very closely related subjects of (1) "Magnetic Effects of the Electric Current," and (2) "Electrical Effects of Magnetism."

1. NATURAL AND ARTIFICIAL MAGNETS.—Magnets are substances which have the property of attracting iron, and the term *magnetism* is applied to the cause of this attraction and the resulting phenomena.

Magnetism was known to the ancient world. It sometimes exists naturally in pieces of an ore of iron, which is known to chemists as magnetic oxide of iron, or *magnetite*. This ore was first found at Magnesia, in Asia Minor, hence the name magnet. *Lodestone*, or "leading stone," is another name applied to a *natural magnet*.

When a bar of steel is stroked with a magnet, the bar itself becomes a magnet. Such bars are called *artificial magnets*. Magnets may also be made by means of the electric current. A bar of iron or steel may be wound with a coil of insulated wire, and will become a magnet when a direct current of electricity is passed through the coil. Very strong magnets may be made in this way. If a soft iron bar is magnetized by this method, it will be found that after the current is switched off from the coil the bar is no longer magnetic, or at best shows only very slight magnetism. A hard steel bar, however, will remain a magnet after being taken from the coil, and is, therefore, called a *permanent magnet*.

2. POLES OF A MAGNET.—When a bar magnet is suspended by a thread about its center, so that it swings freely in a horizontal plane, it will turn to such a position that one end points north and the other end south. The end which points north is known as the "north-seeking" or *north pole* of the magnet, while the end which turns south is termed the "south-seeking" or *south pole*. The north pole is also often called the *positive pole* and designated simply by a plus sign (+), or "N," and the south pole is called the *negative pole* of the magnet, and designated by a minus sign (—), or "S." When the bar magnet is rolled in iron filings, the filings are attracted by the ends or *poles* and adhere to them, but few, if any, particles are picked up by the center of the magnet.

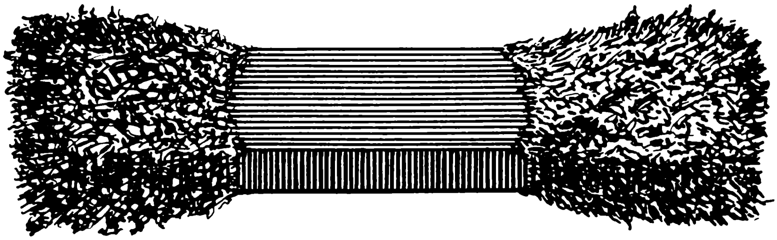


Fig. 1.

It is evident from this experiment that the greater part of the magnetic attraction is concentrated at the poles of the magnet.

3. MAGNETIC AND NON-MAGNETIC SUBSTANCES.—A magnetic substance, or, technically speaking, a *paramagnetic* substance, is one which is attracted by a magnet, or which can be magnetized. Iron and its alloy, steel, are the chief magnetic substances, though nickel and cobalt (other metals) can be magnetized to a slight extent. Certain other metals, such as bismuth, antimony, zinc and lead, are slightly repelled by a magnet, and are, therefore, termed *diamagnetic* substances. Practically all other substances are not appreciably affected by magnets, and can, therefore, be called *non-magnetic* substances.

4. INSULATORS OF MAGNETISM.—When a sheet of glass is placed in front of a strong magnet it will be found that the magnet acts through the glass without any apparent difficulty. In a similar way the magnetic attraction acts through all other materials except magnetic substances. In the case of iron or steel, the magnetic attraction acts on the metal instead of passing through it. Thus it will be seen that there is no material which will serve as an insulator against magnetism, though iron or steel will, in a measure, screen objects from it. Soft iron cases are sometimes used for watches to shield the works and prevent them from becoming magnetized.

5. MUTUAL ACTION BETWEEN MAGNETS.—Either pole of a magnet will attract a piece of iron or steel. With two magnets of equal strength, it will be found that the north or "N" pole of one repels the north pole of the other, and the south or "S" pole of one repels the south pole of the other, but the north pole of either one will attract the south pole of the other. This experiment illustrates a fundamental magnetic law, namely:

Like poles repel and unlike poles attract each other. By means of a suspended magnet the polarity of any other magnet may be readily determined, for the pole of the second magnet that repels the north pole of the suspended one is also a north pole.

6. THE MAGNETIC FIELD.—The space about a magnet or magnet pole in which the magnet can exert magnetic force is termed its *magnetic field.* This field extends in all directions about the magnet. For convenience, it is customary to consider the magnetic field to be made up of *lines of magnetic force,* which leave the magnet at its north pole and return at its south pole, passing through the magnet to the north pole and completing the circuit. The field of a magnet may be explored and the direction of the lines of force determined by means of a small pocket compass. When the compass is held in the magnet's field, the compass needle will assume a position parallel or tangent to the lines of force. The distribution of the lines of force about a bar magnet is roughly shown in Figure 2, and the position of a compass needle at various points in the field is indicated.

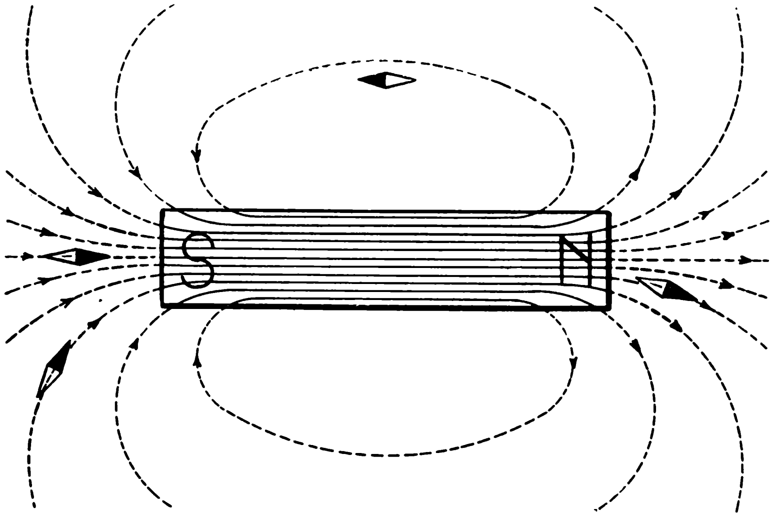


Fig. 2.

The black end of the compass needle is in every case the north pole.

7. MAGNETIC SPECTRA.—A better method of determining the distribution of the lines of force is by means of *magnetic spectra*, or diagrams. A sheet of glass or heavy paper is laid over the magnet whose field is to be reproduced, and iron filings are sifted on it. Then the glass or paper is tapped lightly and it will be found that the filings arrange themselves in tufts and lines which indicate very clearly the direction and intensity of the magnetic field. Such a *magnetic spectrum* for a bar magnet is shown in Figure 3.

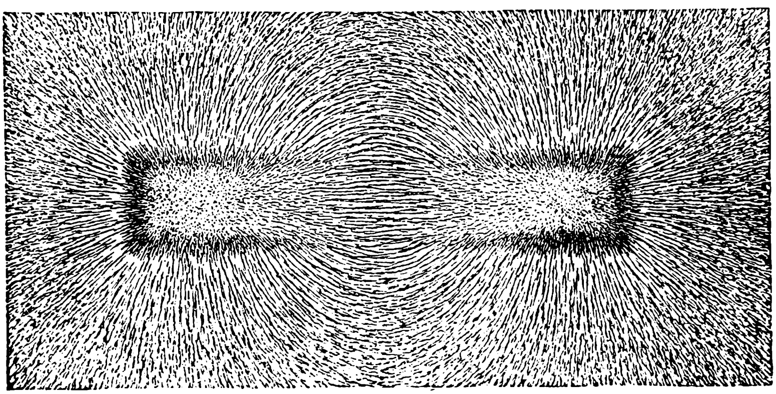
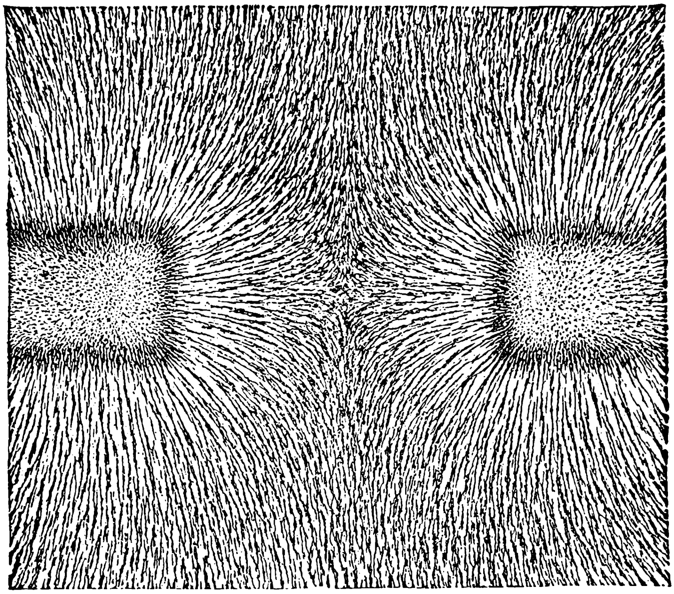


Fig. 3.

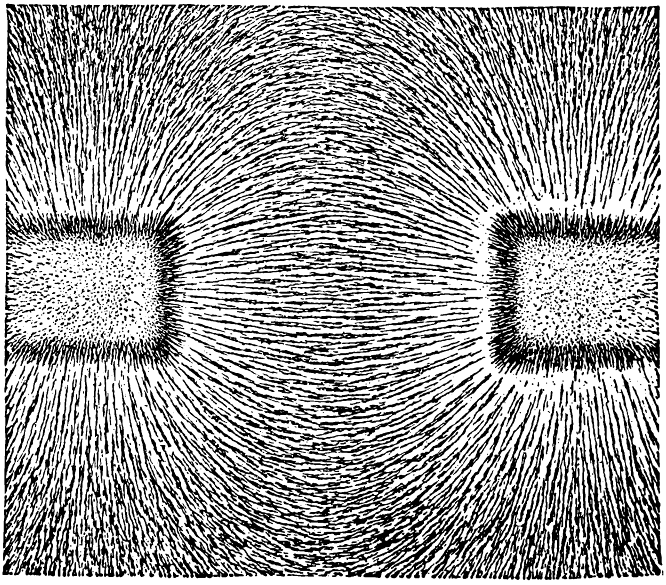
8. STUDY OF MAGNETIC SPECTRA.—By a study of magnetic spectra many of the phenomena of magnetism are made clear. In Figure 3 it will be seen that the lines of force are concentrated at the edges of the magnet poles, and spread out over the field, their intensity growing less the farther they are away. If the diagram were large enough, and could show the actual lines of force instead of filings influenced by the force, it would be found that all lines leaving one pole ultimately curve around and enter the other pole. Each line of force constantly tends to shorten itself, and is repelled by the other lines beside it, so that the resulting curves are obtained. Another peculiarity attributed to lines of force is that they never cross each other.

In Figure 4, which shows the magnetic field between two like poles, the bending over of the lines from the poles as they meet is clearly shown, and the repulsion between the two poles can readily be imagined.



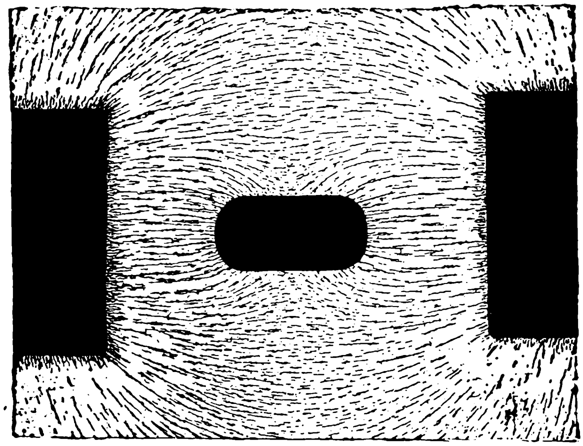
MAGNETIC POLES N AND N OR S AND S.
Fig. 4.

Figure 5 shows the field between two unlike poles, and it will be seen that many of the lines from one pole continue to the other. Since the tendency of these lines is to shorten, the reason for the pull or attraction between the two can be seen.



MAGNETIC POLES N AND S.
Fig. 5.

Figure 6 shows the field between unlike poles, but with a piece of iron placed beween the two magnets. The distribution of the lines of force is considerably altered. The iron is a better conductor of the lines of force than the air space, and there is a convergence or bending in of the lines to it.



MAGNETIC SPECTRUM WITH IRON IN IT.
Fig. 6.

9. INDUCED MAGNETISM.—The iron filings used in obtaining magnetic spectra do not touch the magnets whose fields they represent, yet they attract each other and form into tufts and lines under the influence of the magnetic field. In reality each one of the filings has been *magnetized by induction,* and while in the magnetic field produced by the large magnet, is a magnet itself. In a similar way, the piece of iron between the magnet poles in Figure 6 is magnetized by induction.

10. DISTRIBUTED, CONCENTRATED, AND ISOLATED POLES.—It will be seen that, in the short bar shown in Figure 3, the lines of force leave and enter the magnet over a large area at the ends, extending well down to the center. Such a magnet is said to have *distributed poles.* If the length of the magnet is great compared with its cross-section, magnetic force will be appreciable only at the poles over a comparatively small area. Such a magnet is said to have *concentrated poles.* If the poles of the magnet are so far apart that their effect on each other is negligible, each pole may be considered separately as an *isolated pole.*

11. FORMS OF MAGNETS.—A bar magnet, such as is mentioned in the preceding paragraphs, can be bent so that both of its poles point in the same direction, as shown in Figure 7, which also shows approximately the distribution of the magnetic field or lines of force. A magnet of this form is called a *horseshoe magnet.*

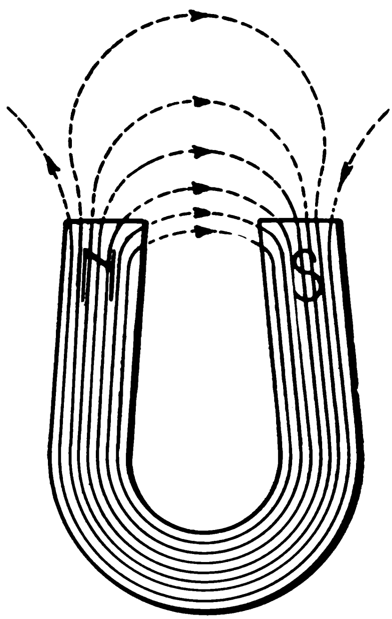


Fig. 7.

Both of its poles can be brought to bear on the same object, and horseshoe magnets will therefore lift heavier weights than bar magnets of similar proportions. Another characteristic of horseshoe magnets is that they retain their strength better than bar magnets. This appears to be due to the fact that the *air gap*, or distance the magnetic lines of force must pass through air between the poles, is shorter. Magnets of the horseshoe type are very often used in electrical measuring instruments, such as direct current voltmeters and ammeters.

The ordinary horseshoe magnet is usually provided with an armature or keeper, which helps to preserve the strength of the magnet.

12. RESIDUAL MAGNETISM—RETENTIVITY.—Any piece of magnetic material brought in contact with a magnet, or within a magnetic field, becomes a magnet itself. Suppose that three bars of the same size are prepared, one of soft iron, one of soft steel, and one of hard steel, and that one end of each bar is dipped into iron filings while a strong magnet is brought in contact with the other end. When the bars are withdrawn and the magnet removed, the most filings will adhere to the hard steel, less to the soft steel and very few to the soft iron. The filings are held by the *residual magnetism* of the bars, and the ability to retain magnetism is called *retentivity*. This would indicate that hard steel has greater retentivity than either soft iron or steel.

13. AGEING.—In order that magnets used for certain purposes may be satisfactory, it is important that their strength remain constant. After magnetization it is found that the strength of even the hardest steel magnets decreases for some time, especially if they are subject to severe changes of temperature or to mechanical vibration or shock. However, a point is finally reached where the residual magnetism is really permanent, and the strength of the magnet does not diminish. In order that this point of permanent strength may be reached quickly, magnets are often put through a process called *ageing*. This process consists in subjecting the magnets to repeated changes of temperature and mechanical jars and shocks, until tests show that their strength has fallen to a constant value. Well aged magnets of the best magnet steel will remain practically constant indefinitely.

14. THE EARTH'S MAGNETISM.—Everyone knows that a compass needle is a magnet, and that it takes a definite position when free to swing, pointing nearly north and south. From preceding paragraphs it is evident that the compass needle must be acted upon by a magnet whose lines of force run north and south. This magnet is the earth itself. If a bar magnet, about half the length of the earth's diameter, were thrust through the earth's centre, making an angle of about twenty degrees with its axis, it would account for many of the phenomena of *terrestrial magnetism*.

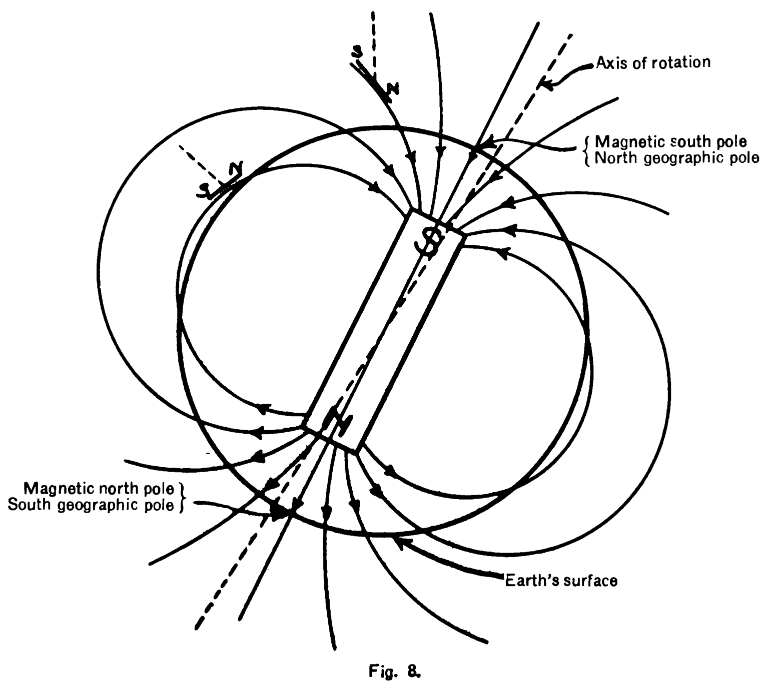


Fig. 8.

The south pole of the magnet would be at the end under the northern portion of the earth's surface. The lines of the earth's magnetic force are only parallel with the earth's surface at certain places near the equator, as can be seen by reference to Figure 8. In the northern hemisphere the compass needle tends to dip its "N" pole downward, in order to parallel the lines of magnetic force, while in the southern hemisphere the "S" pole has a similar tendency. Directly over the *magnetic poles* of the earth, the compass needle, if free to turn in all directions, would point directly downward.

15. DECLINATION.—Owing to the fact that the magnetic poles do not coincide with the geographic poles of the earth, the compass needle does not point true north at most places on the earth's surface. The angle between the magnetic north and south line or meridian, and the geographic north and south line or meridian, at any point, is the *declination* of the earth's magnetic field at that place.

16. INCLINATION.—Paragraph 14 and Figure 8 show that the earth's lines of force are not horizontal at most places on the surface. A compass needle mounted to swing vertically (on a horizontal axle) is called a *dipping needle*. When set to swing in a magnetic north and south line, the needle will assume a position parallel to the earth's magnetic field. The angle which the needle makes with a horizontal surface is the *inclination* of the earth's field.

At the present time (1913), the declination at Philadelphia is about seven degrees west, and the inclination about seventy degrees. In other words, the compass needle points seven degrees west of true geographical north, and the dipping needle has its north pole downward, and makes an angle of seventy degrees with the horizontal.

17. THEORY OF MAGNETISM.—There have been a number of theories advanced to account for magnetic phenomena, but the one commonly accepted at the present time is the *molecular theory*. All the forms of material are considered to be made up of very small particles which are called *molecules*. It is supposed that each particle or molecule of iron or steel (magnetic materials) is naturally a magnet, with a north and south pole. In an unmagnetized bar the poles of molecules are turned in all directions, so that the fields of force of the different molecules neutralize each other, and the bar as a whole shows no magnetic qualities. In paragraph 6 it was stated that a magnet, when placed in a magnetic field, tends to turn until it is parallel to the lines of force. Therefore, if the bar under consideration is placed in the field of a magnet, the molecules all try to turn parallel to the lines of the field. When the molecules are turned in the same direction their magnetic fields act together, and the bar, as a whole, becomes a magnet.

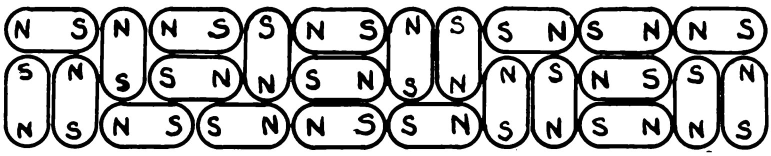


Fig. 9a.

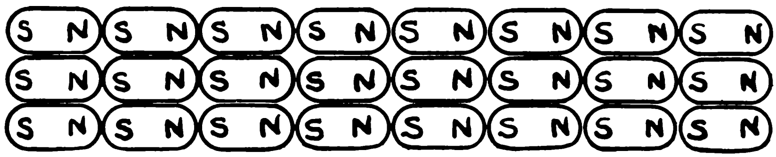


Fig. 9b.

The condition of the molecules of the unmagnetized bar is represented by Figure 9*a*, and the condition of the magnetized bar by Figure 9*b*. In this figure the very minute particles or molecules which form the magnet are shown rather large and are marked on their ends "N" and "S." In reality a molecule cannot be seen by the naked eye, as it is too small, but can be seen with the aid of powerful microscopes.

The properties and behavior of magnets are more readily understood through a study of this molecular theory.

18. STRENGTH OF MAGNETS.—It is well known that all magnets of the same size and shape are not of the same strength. It can readily be seen that the greater the number of molecules turned to act together magnetically the stronger will be the magnet.

19. PERMEABILITY.—A bar of soft iron subjected to magnetic force will become a stronger magnet than a similar bar of hardened steel subjected to the same force. This is because the molecules of the iron bar offer less resistance to turning than those of the steel bar, and therefore, more of them are "lined up" by the magnetizing force. This difference is expressed by saying that the *permeability* of the iron is greater than that of the steel.

In paragraph 12, *retentivity* was illustrated and defined. Evidently, if the molecules of a material are difficult to turn in magnetizing a bar, these same molecules will tend to remain in the magnetized position after the force is withdrawn, so that a material which has low permeability, or which is difficult to magnetize, will have high retentivity or will retain its magnetism well.

20. DEMAGNETIZATION.—Any magnet heated to a red heat loses its magnetism, and does not regain it when cooled off again. Iron and steel at high temperatures are non-magnetic, and cannot be magnetized or attracted by a magnet. It is believed that the action of high temperatures sets the molecules of the metal in vibration and thus breaks up magnetic combinations that exist and prevents others from forming. Another method of *demagnetization* is to place the object to be demagnetized in a strong magnetic field, which is then reversed in direction many times and at the same time gradually reduced to zero strength.

21. SATURATION.—If the magnetizing force acting on a bar is great enough, it is reasonable to suppose that all the molecules will be turned in one direction, and that the bar will be fully magnetized. In this case the bar is said to have reached *magnetic saturation*. No increase in the magnetizing force, however great, will increase the magnetic strength of the bar after this saturation point is reached.

22. EQUALITY OF NORTH AND SOUTH POLARITY MAGNETISM.—Each molecule of magnetic material is supposed to be a magnet with north and south poles of equal strength. Therefore, when the material is magnetized, and the molecular magnets are turned to act together, the number of north poles acting together will be the same as the number of south poles combining forces and the total positive and total negative magnetism produced will be equal.

23. MAGNETIC CIRCUIT.—The equality of north and south polarity magnetism may be stated in another way, by considering that the lines of force form a *magnetic circuit*, as briefly stated in paragraph 6. In any magnetic circuit the total number of lines of force issuing from the north poles is the same as the number of lines entering at the associated south poles.

24. DIVIDED MAGNETS.—If a bar magnet is broken in two pieces, each piece will be a magnet. A consideration of Figure 9*b*, will show why this is the case. Since each of the smallest particles is a magnet, it is evident that every combination of these particles is also a magnet, as long as the molecules are turned in the same direction.

25. CONSEQUENT POLES.—If two bar magnets be placed end to end, with their south poles together, the field produced will be like that of one magnet with a north pole at each end and a south pole of twice the strength at the centre. By proper application of the magnetizing force, a single bar may be so treated that it will have poles at other points in addition to those at the ends. These intermediate poles are termed *consequent poles*. The arrangement of the molecules in a magnet with consequent poles may be imagined to be similar to that shown in Figure 10.

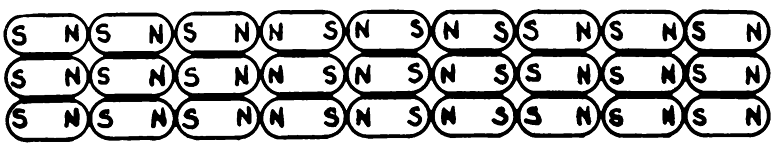


Fig. 10.

26. ACTION BETWEEN MAGNETS.—*The force of attraction or repulsion between two magnet poles is inversely proportional to the square of the distance between them.* This relation may be expressed in the following formula:

$$\frac{F}{F_1} = \frac{r_1^2}{r^2}, \text{ or } F : F_1 :: r_1^2 : r^2 \qquad \text{eq. (1).}$$

in which F is the force attraction at a distance r between the poles and F_1 is the force attraction of the same two magnet poles at the distance r_1 between them. From eq. (1), the product of the force and the square of their distance apart is the same for any distance between the poles.

For example, when two magnets are held one inch apart and they repel each other with a force of ten pounds, the push between them when held at a distance of two inches would be found by applying formula 1, and substituting these values : $F = 10$, $r = 1$, $r_1 = 2$; then

$$10 : F_1 :: 2^2 : 1^2$$

from which $F_1 = \frac{10 \times 1^2}{2^2} = 2.5 =$ number of pounds push at a distance of two inches. If the distance between these poles had been $\frac{1}{2}$ inch, then the repulsion would be found by this same formula as

$$10 : F_1 : : (\tfrac{1}{2})^2 : 1^2$$

from which $F_1 = \frac{10 \times 1^2}{(\frac{1}{2})^2} = \frac{10}{\frac{1}{4}} = 40$ = number of pounds push at this shorter distance.

The problems would be worked the same if the poles were unlike. The force exerted would then be a pull or force of attraction instead of a push or repulsion.

27. COMMERCIAL APPLICATIONS OF PERMANENT MAGNETS.— Perhaps the most important use of permanent magnets is in the mariner's compass, although the magnets used in these instruments are very small. Permanent magnets of various forms are also used in telephone receivers, telephone magnetos or ringing generators, magnetos for gas engine ignition, electrical measuring instruments, etc. In future pamphlets the use of magnets for most of these purposes will be explained.

PROBLEMS

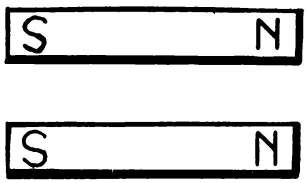
First Lesson

1.—Give two methods of magnetizing a piece of steel.

2.—A steel ball is plated with brass and enclosed in a leather case. Will it be attracted by a magnet brought near it?

3.—If you were given a bar magnet and a compass, how would you determine the north and south poles of the magnet?

4.—Two bar magnets are laid side by side as shown.



(*a*) Would they attract or repel each other?

(*b*) Make a sketch full size showing the distribution of the magnetic field about these magnets.

5.—One of the magnets in question 4 is turned around, end for end.

(*a*) What difference does this make in the force between the two magnets?

(*b*) Make a sketch showing the distribution of the magnetic field.

6.—The magnetic pole at the left side of Figure 6 is a north pole. Make a sketch showing the location and sign (whether positive or negative, north or south) of all other poles in the figure.

7.—If a magnetic compass were placed between the poles of a horseshoe magnet, how would the compass needle behave?

8.—(*a*) What shape should a magnet have to best retain its magnetism?
(*b*) Of what material should it be made?

9.—A magnet of constant strength is required for a voltmeter. How should it be treated after magnetization to obtain this quality?

10.—Why does a compass needle take up a definite position on its pivot? Explain fully.

Second Lesson

11.—What is the inclination in degrees of the earth's magnetic field at the south geographic pole? Which end of the dipping needle would point below the horizontal?

12.—Will a material having great retentivity have high permeability? Give a reason for your answer.

13.—(*a*) How would you demagnetize a bar of steel?
(*b*) How can a watch be demagnetized?

14.—Is there any limit to the strength that can be given to a magnet? Explain your answer.

15.—A bar magnet eighteen inches long is broken into three pieces six inches long. Will any of these pieces be magnets? If so, which ones?

16.—How many magnetic poles would there be in the bar in Figure 10? Make a sketch showing their location and polarity.

17.—How does the distance between two magnet poles affect the attraction or repulsion (pull or push) between them?

18.—Two magnets are held one inch apart, and the pull between them is one pound.
(*a*) What will the pull amount to when they are six inches apart?
(*b*) When they are one-eighth of an inch apart?