CHAPTER SIX

Magnetism and Electromagnets

The principles of magnetism and electricity are interrelated. Electromagnets are used in some direct-current circuits, and it is impossible to understand alternating-current theory (which will be introduced in Chapter Seven) without some basic understanding of magnetism.

The principles of magnetism go far beyond the treatment given in this chapter; but what you learn here will prepare you to study some of the material presented later in the book.

When you have finished this chapter, you will be able to:

- describe the behavior of magnetic fields;
- distinguish among natural and permanent magnets and electromagnets;
- relate electric current to its associated magnetic field;
- predict the action of a magnetic field about a current-carrying coil;
- describe the major properties of magnetic materials;
- describe the nature and operation of electromagnets; and,
- explain how magnetic shielding is accomplished.

1. A substance is said to be a magnet if it has the power to attract such substances as iron, nickel, or cobalt, known as magnetic materials. Some materials are much more magnetic than others. Aluminum, for example, is not noticeably magnetic, while steel, which is mostly iron, is very magnetic. Non-metals are not magnetic at all.

   A magnet has two magnetic poles, or points of maximum attraction. If you suspend a bar magnet from a string so that it is balanced parallel to the earth and then set it to spinning, it will eventually come to rest with one end pointing north. If you then nudge that end away, it will return to the north-pointing direction. This end of the magnet is called the south pole. Opposites attract in magnetism, too. Knowing that, what do you think the other end is called? ____________________.

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2. This principle of the north-seeking pole led to the invention of the compass. The compass needle is a magnetized strip of metal that points to the north. The end of the needle that indicates direction is the (north/south) ________________ pole.

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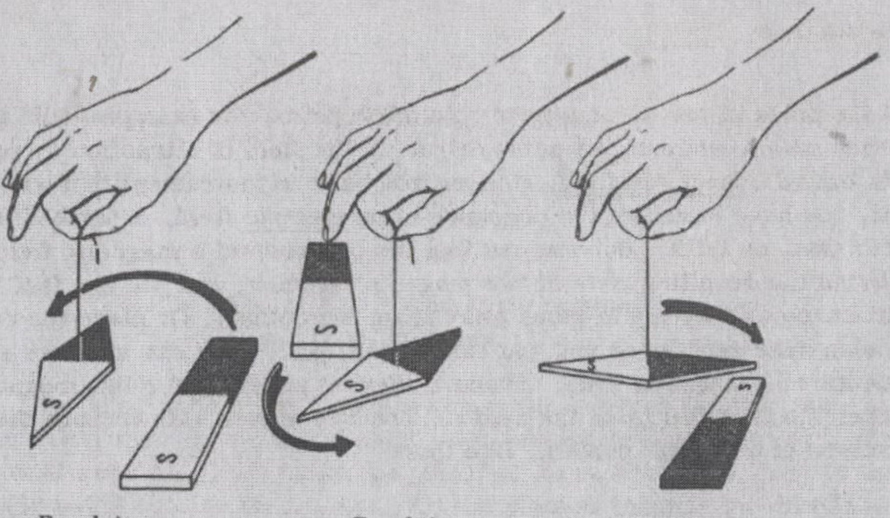

Figure 6-1. Laws of attraction and repulsion.

3. Figure 6-1 illustrates that magnets, like charged bodies, follow laws of attraction and repulsion. A north pole will (attract/repel) ____________ another north pole.

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4. What is the equivalent law about the attraction and repulsion of charged bodies? ____

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5. Can you make a similar statement about magnetic poles? ______________

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6. Two bar magnets are "stuck" end to end by magnetic force. The end of one magnet is a north pole. The end of the other is a ______________.

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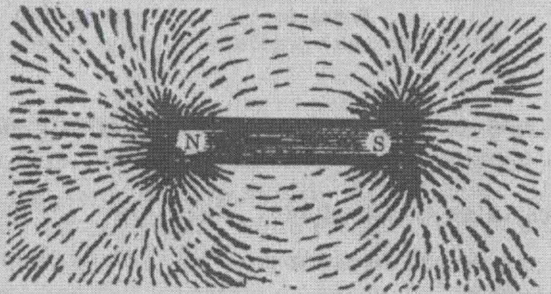
7. Like poles of two bar magnets (two north poles, for example) will repel each other, while unlike poles attract. The field of attraction or repulsion is called a magnetic field. Unless you have an instrument that will sense it, you have to accept the presence of an electric field, described in Chapter One, on faith. But you can feel the presence of a magnetic field. Bring the repelling ends of two magnets together, and you can feel the resistance as they try to move away from each other. Or place the unlike poles near each other and you can feel the pull. You can also see evidence of a magnetic field. Place a sheet of paper over a bar magnet and sprinkle iron filings on the paper. The bits of iron will arrange themselves in a distinct pattern, like this:



This patterned scattering of iron filings presents a visible "map" of the ______________________.

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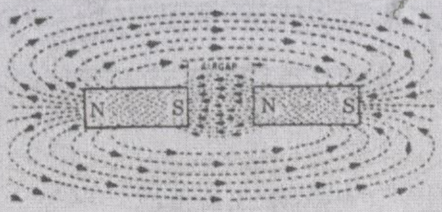
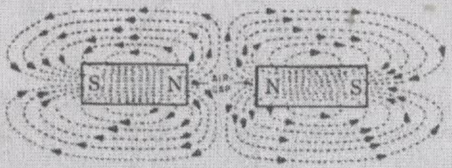
8. The magnetic field can be thought of as the lines, known as flux lines, or magnetic flux, along which a magnetic force acts. By convention, we say the lines emanate from the north pole of the magnet and re-enter through the south pole, returning to the north pole through the magnet itself. Figure 6-2 on the next page illustrates the travel of the flux lines outside the

magnet and also shows how these lines of force behave when they are attracted or repelled by another magnet.



(A) Unlike Poles Attract



Lines of Force

(B) Like Poles Repel

Figure 6-2. Flux lines between like and unlike poles.

The outer ends of the magnets are areas in which the flux lines are not acted upon by another magnet. On a separate sheet of paper, draw a single bar magnet. Label the poles and draw some flux lines to indicate their paths outside the magnet. Use arrows to indicate the direction of the flux lines.

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9. If a bar magnet is dipped into iron filings, many of the filings are attracted to the ends of the magnet, but none are attracted to the center. Explain why. ______________________________

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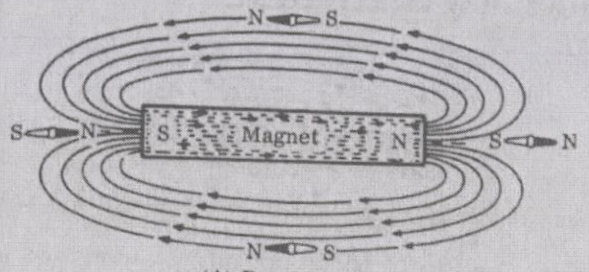
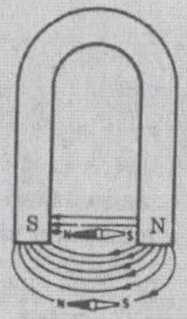


(A) Bar Magnet



(B) Horseshoe Magnet

Figure 6-3. Magnetic lines of force.

10. By using a compass, you can observe the presence of the magnetic lines of force (flux lines) at various points near the magnet. Figure 6-3 shows the position of the compass needle in various locations.

As the compass is moved around the magnet, what happens to the compass needle? ______________________________

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11. Magnets may be conveniently divided into three groups: natural magnets, permanent magnets, and electromagnets. You can probably distinguish among the three groups from the following descriptions. Fill in the blank following each description with one word: "natural," "permanent," or "electromagnet."

(a) An iron compound called magnetite, found in nature, has been known for centuries to attract iron. ______________

(b) When an electric current is passed through a coil around an iron core, a magnet is produced as long as current flows. ________

(c) Commercial magnets are made by a special process that magnetizes certain steels or other alloys which then retain their magnetic properties almost indefinitely. __________________

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[redacted]

12. "Loadstones" (or "lodestones"), for centuries the only kind of magnet known, are __________________ magnets.

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[redacted]

13. The magnet in your telephone receiver is produced by a special process that gives the metal long-lasting magnetic properties. It is called a __________________ magnet.

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[redacted]

14. An electromagnet is a (permanent/temporary) __________________ magnet.

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[redacted]

15. The nature of a magnetic field, which is made up of all the magnetic lines of force, is important because it has many applications in electricity. One might think of the lines of force, which form closed loops in space and through the magnet, as a magnetic circuit. All the lines of force together are called magnetic flux. Flux in a magnetic circuit compares to what in an electric circuit? __________________________

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16. Some magnetic fields are, of course, stronger than others. The strength of the field is related to <u>flux density</u>. The number of lines of force per unit area is directly porportional to this field strength, or flux density. If the current flowing through an electromagnet is increased to make the magnet stronger, what happens to the flux density? __________________

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[redacted]

17. Let's review some terminology:

(a) The space surrounding a magnet, in which the magnetic force acts, is called the ______________________.

(b) The entire quantity of magnetic lines of force surrounding a magnet is called ______________________.

(c) The number of lines of force per unit area is called ______________________.

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[redacted]

Electromagnetism

18. You have learned that magnets are divided into three categories: natural magnets, permanent magnets, and electromagnets. Electromagnetism is important to the study of electricity because many devices, such as circuit breakers and relays, make use of electromagnets.

Electromagnetism includes two closely related areas: magnetism as it is affected by electric current flow, and electricity as it is affected by magnetism. You have probably noticed that your automobile radio is affected when you drive under high-tension power lines. This is an example of electricity (the performance of your radio) affected by the magnetic field around the power lines. If your home uses circuit breakers instead of fuses, they operate when there is an overload of current because the current produces magnetism to "trip" the circuit breaker. Both these phenomena are examples of ______________________.

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19. Magnetism and electricity are so closely related that one cannot be studied at length without involving the other. It is important to remember one general relationship between magnetism and electricity: Electric current flow will always produce some form of magnetism. You can produce a weak magnetic field around a flashlight, for example, simply by doing what? ______________________

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20. Electric current flow will (sometimes/always/never) ________________ produce some form of magnetism.

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Magnetic Field Around a Current-Carrying Conductor

21. A definite relation between magnetism and electricity was discovered in 1819 when a Danish physicist, Hans Christian Oersted, established that an electric current is accompanied by certain magnetic effects and that these effects obey definite laws. If a compass is placed in the vicinity of a current-carrying conductor, the needle aligns itself at right angles to the conductor, thus indicating the presence of a ____________________.

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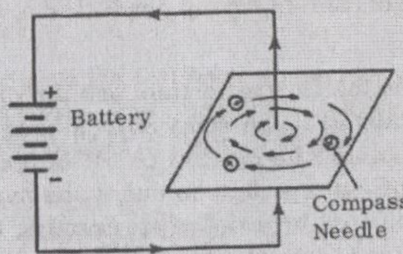

Figure 6-4. Magnetic field around a current-carrying conductor.

22. The presence of a magnetic force can be demonstrated by passing an electric current through a vertical conductor which passes through a horizontal piece of cardboard, as illustrated in Figure 6-4. The presence of a magnetic force is indicated by the positioning of a compass at various points on the cardboard and noting the deflection of the needle. In Figure 6-4, the direction of the magnetic field, as you view the cardboard from above, is (clockwise/counterclockwise) ____________________.

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23. The magnetic field is at right angles to the conductor, and there is a definite relation between the direction of the current flow and the direction of the associated magnetic field—if one is reversed, so is the other. If the direction of current flow, as shown in Figure 6-4, is reversed, the

direction of the magnetic field will be (clockwise/counterclockwise) ________________________ (as viewed from the top).

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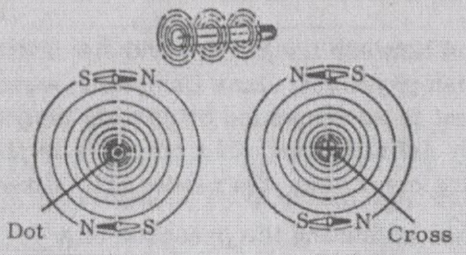

(A) Current Flowing Out

(B) Current Flowing In

Figure 6-5. Cross-section of a current-carrying conductor.

24. The relation between the magnetic field and the direction of current flow is more easily visualized if the conductor is shown in cross-section with the current thought of as flowing into or out of the paper. In Figure 6-5, when the direction of current flow is out of the page (toward the reader), this direction is indicated by a dot, representing the point of an arrow. When the current flow is into the page (away from the reader), the cross, representing the tail of an arrow, is used. Place your <u>left</u> hand over View A so that your thumb is pointing up and your fingers are curved around the cross-sectional view of the conductor. The curvature of your fingers is (clockwise/counterclockwise) ________________________.

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25. Now rest the tip of your <u>left</u> thumb on the cross in View B so that your fingers are curved around the cross-sectional view of the conductor. The curvature of your fingers is ________________________.

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[redacted]

26. You have just demonstrated the <u>Left-Hand Rule for a Conductor</u>. This rule is used to determine the relation between the direction of the magnetic lines of force around a conductor and the direction of current flow along the conductor. If the conductor is grasped in the left hand with the thumb extended in the direction of electron flow (negative to positive), the fingers will be curved in the direction of the magnetic lines of force. (If the conductor is not insulated, do this <u>mentally</u>!) Figure 6-5 also illustrates the deflection of a compass needle in a magnetic field about a conductor. Which pole of the compass needle points in the direction of the magnetic lines of force? ______________________.

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27. How would you determine the direction of the magnetic lines of force about a current-carrying conductor if the direction of current is known?

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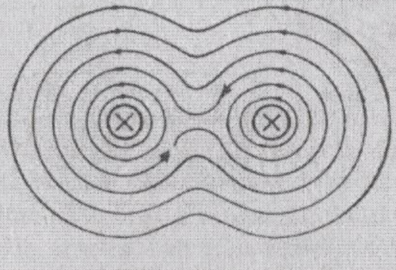
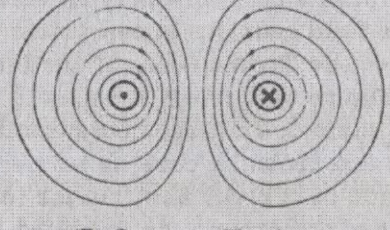


(A) Currents Flowing in the Same Direction



(B) Currents Flowing in Opposite Directions

Figure 6-6. Magnetic field around two parallel conductors.

28. In View A of Figure 6-6, current in both conductors is flowing into the page. When two parallel conductors carry current in the same direction, the magnetic fields tend to encircle both conductors, drawing them together with a force of attraction. When two parallel conductors carry current in opposite directions, as in View B, the magnetic fields

(attract/repel) _______________________.

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29. In View B, what is the physical effect of the magnetic fields on the conductors? ____

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Magnetic Field of a Coil

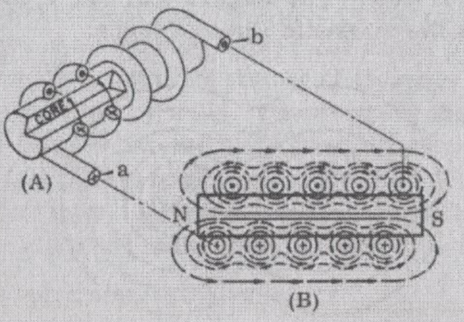

Figure 6-7. Magnetic field produced by a current-carrying coil.

30. The magnetic field around a current-carrying wire exists at all points along its length. The field consists of concentric circles in a plane perpendicular to the wire (see Figure 6-4). A partial cutaway view of a simple coil is shown in Figure 6-7, View A. View B is a complete cross-sectional view of the same coil. Each cross-section of conductor (actually a single conductor wound around a core) is labeled with a dot or a cross to indicate the direction of current flow. In the top portion of the coil, the current is flowing out of the paper. As indicated in Frame 28, when two parallel conductors carry current in the same direction, the magnetic fields tend to draw the conductors together. The same is true of any number of parallel conductors. In a coil, there is actually only one conductor,

but the turns are, in effect, parallel conductors. In the coil shown in Figure 6-7, the "parallel conductors" on the bottom half carry current in a direction that is (the same as/opposite to) ______________________ that of the conductors in the top half.

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31. There are two magnetic fields around the turns of wire that make up the coil in Figure 6-7. The two fields (repel/attract) ______________ each other.

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32. When current is passed through the coiled conductor in Figure 6-7 the magnetic field of each turn of wire links with the fields of adjacent turns. The combined influence of all the turns produces a two-pole field similar to that of a simple bar magnet. As in all magnets, it has a north pole and a south pole. The north pole of the magnet produced by the current flow in the coil is, as in all magnets, the pole at which the flux lines (enter/leave) _______________ the magnet.

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33. In Figure 6-5, it was shown that the direction of the magnetic field around a straight conductor depends on the direction of current flow through that conductor. Thus, a reversal of current flow through a conductor causes a reversal in the direction of the magnetic field that is produced. Reversal of current flow through a coil also causes a reversal of its two-pole field. In Figure 6-7, if the current flow through the coil is reversed, the left end of the coil will become a (north/south) _______________ pole.

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34. There is also a left-hand rule for coils, which is illustrated in Figure 6-8 on the next page. If you grasp a coil in the left hand, with the fingers "wrapped around" the coil in the direction of current flow, the thumb will point toward one of the poles.

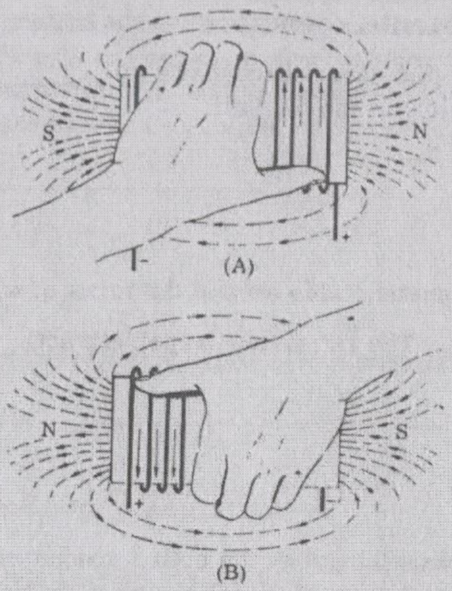

Figure 6-8. The left-hand rule for coil polarity.

The thumb is pointing toward the (north/south) ______________ pole.

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35. If a simple coil is grasped in the left hand so that the thumb points toward the north pole, the fingers will curve in a direction that is (the same as/opposite to) ______________________ the direction of current flow.

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36. The left-hand rule for coils is used to determine the ______________ of a coil.

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37. The strength, or intensity, of the magnetic field of a coil depends on a number of factors.

    - As the <u>number of turns</u> of a conductor about a coil is increased, the field strength also increases.

- As current flow through the coil increases, field strength increases.
- Field strength depends on the type of material in the core. The better the core material can conduct magnetic lines of force (soft iron is an excellent conductor), the greater the field strength. (The measure of magnetic conduction is called "permeability," which will be discussed later.)

Coil A and Coil B are the same size and have the same type of core material. Each has the same type of wire wound about it, and each has the same amount of current flowing through the wire. Coil A, however, has 20 turns of wire, while Coil B has 30. Which coil has the greater magnetic field strength? ____________________

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[redacted]

38. A relay is a type of electromagnet that is used to open or close one or more connections in a circuit. A certain relay's coil does not have sufficient field strength to operate its contacts, and the only thing that can be changed in the circuit is the source voltage. To make the relay work, would you increase or decrease the source voltage? ____________________

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[redacted]

39. If a core of soft iron is inserted in an air-core coil, will the magnetic field become stronger or weaker? ____________________ Why? ______

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[redacted]

There are equations for the precise determination of magnetic fields, but it is not necessary to study them now. We have seen that the core material affects the strength of a magnetic field. Now let us examine some of the properties of magnetic materials.

Properties of Magnetic Materials

40. When an annealed sheet steel core is used in an electromagnet it produces a stronger magnet than if a cast iron core is used. This is true because annealed sheet steel is more readily acted upon by the magnetizing force

of the coil than is hard cast iron. In other words, soft sheet steel is said to have greater permeability because of the greater ease with which magnetic lines are established in it. Permeability is the relative ease with which a substance conducts magnetic lines of force. The permeability of air is arbitrarily set at 1. The permeability of other substances is the ratio of their ability to conduct magnetic lines compared to that of air; the figure is often much greater than 1. Here are the relative permeability figures for three magnetic materials: wrought iron, 1,500; sheet steel, 2,310; cast iron, 600. (These figures are not constant but depend on other factors beyond the scope of this book.) Which of the three materials has the greatest ability to conduct magnetic lines of force?

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sheet steel

41. The permeability of magnetic materials varies with the degree of magnetization and with the type of material. A highly magnetized material (one in which the flux density is great) cannot readily conduct magnetic lines of force because it is already near saturation. That is, it has a great concentration of lines of force already. Since its ability to conduct lines of force is reduced, it has a lower permeability than the same material when it is not so highly magnetized. Permeability of a magnetic material that has not been magnetized is a certain figure that depends on the type of material. When it begins to be magnetized, its permeability decreases as its concentration of lines of force, or flux density, increases. Therefore, permeability depends on what two factors? ________________

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the type of material and the flux density (degree of magnetization)

42. Hysteresis is another property of magnetic materials that should be considered when the core material of a coil is selected. Any magnetic material becomes magnetized to some degree when magnetic lines of force pass through it. In the case of a coil, the flow of current through the coil produces a magnetic field which results in the whole coil's becoming magnetic with a north pole and a south pole. When the current is reversed, the polarity of the coil is also reversed.

When current flows through the coil, a magnetic polarity is established. If the coil has a core of some magnetic material, such as iron, the core material will become magnetized and will show evidence of being magnetized even when the current is shut off. For reasons that are beyond the scope of this book, there is a lag in the reversal of magnetic polarity when the current is reversed. This property that causes the magnetization to lag is called hysteresis. The lag is caused by molecular friction, and where there is friction of any kind, energy is dissipated. Energy dissipated through molecular friction is called hysteresis loss. Hysteresis loss, then, is a dissipation of energy that results from the tendency of magnetization to lag behind the force that produces it. The more easily a material can be magnetized, the shorter the lag will be. Would hysteresis loss be greater in a material that is hard to magnetize, or in one that is easy to magnetize? ________________________________

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[redacted]

43. If the magnetization is reversed slowly, the energy loss may be negligible. But in the case of alternating current, the direction of current flow changes rapidly, as you will see later in the book. Therefore, hysteresis losses could be significant. It happens that some substances retain their magnetization more easily than others. Hard steel, for example, retains its magnetism better than cast iron. If current through a coil with a hard steel core is reversed, the core does not readily reverse its polarity (compared to cast iron). Its lag, in other words, is greater. Is hysteresis loss greater in hard steel or in cast iron? ________________

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[redacted]

44. The properties of permeability and hysteresis are both important in electricity, because they must be considered in designing an electrical circuit. It is important to keep energy losses to a minimum, and hysteresis loss is a type of energy loss. The type of magnet of most interest to us in the study of electricity is the electromagnet, which we will study in the next section. When possible, the core material selected for the coil of an electromagnet should be a substance that has (high/low) ____________ hysteresis.

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Electromagnets

45. An electromagnet is composed of a coil of wire wound around a core that is normally soft iron, because of its high permeability and low hysteresis. When direct current flows through the coil, the core will become magnetized with the same polarity that the coil would have without the core. If the current is reversed, what happens to the polarity of both the coil and the core? ________________________________

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[redacted].

46. When is an electromagnet a magnet? The other types of magnet we have mentioned — the natural magnet and the permanent magnet — are always magnets, unless something happens to destroy their magnetism. But the electromagnet is a temporary magnet. It is of great importance in electricity simply because the magnetism can be "turned on" or "turned off" at will. An example of this is the starter solenoid in your automobile. A solenoid is a current-carrying coil designed for a specific purpose. In your car, it is part of a relay that connects the battery to the induction coil, which generates the very high voltage needed to start the engine. The starter solenoid isolates this high voltage from the ignition switch. When no current flows in the coil, it is "air-core," but when the coil is energized, a movable soft-iron core does two things. First, the magnetic flux is increased because the soft-iron core is more permeable than the air core. Second, the flux is more highly concentrated. All this concentration of magnetic lines of force in the soft-iron core results in a very good magnet when current flows in the coil. But soft-iron loses its magnetism quickly when the current is shut off. The effect of the soft iron is, of course, the same whether it is movable, as in some solenoids, or permanently installed in the coil. An electromagnet, then, consists basically of a coil and a core. When is an electromagnet a magnet? ____

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47. The ability to control the action of magnetic force makes an electromagnet very useful in many circuit applications. You have probably noticed that either pole of an ordinary bar magnet will attract a magnetic material such as soft iron. The same is true of an electromagnet. The component that is to be attracted by the electromagnet is called the armature. One application of an electromagnet is illustrated in Figure 6-9, which shows a magnetic circuit breaker. Since a circuit breaker is a protective device that is designed to trip when current reaches its maximum permissible value, the adjustment of the armature is important.

Magnetic lines of force emanate from a magnet indefinitely, but the field becomes weaker as the distance from the magnet is increased. You might have noticed that a weak magnet must almost touch bits of metal before they are picked up, while a strong magnet operates over a greater distance. When an electromagnet is used as a circuit breaker, its armature (the part that unlatches the contacts) must be carefully adjusted so that it is attracted by the magnetic field, thus opening the breaker contacts, only when there is a need to protect the circuit. The magnetic field strength of an electromagnet increases as the current through its coil increases. Therefore, the armature can be adjusted so that its distance from the magnet is just great enough for it to be attracted only when the rated current of the circuit is exceeded. If it is set too close to the magnet, the circuit breaker might be tripped under normal operating conditions; while too great a distance would result in a failure to trip if the current load became too high. Let us assume that a circuit breaker is designed to be tripped when the current in the circuit exceeds 20 a. It actually trips, however, when the circuit current is only 18 a. Should the armature be set closer to or farther from the magnet? ____________

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[redacted]

48. The pair of contacts are normally latched closed by the armature, and current flows in the circuit. When the armature is pulled against the core of the electromagnet, the current in the circuit is interrupted because

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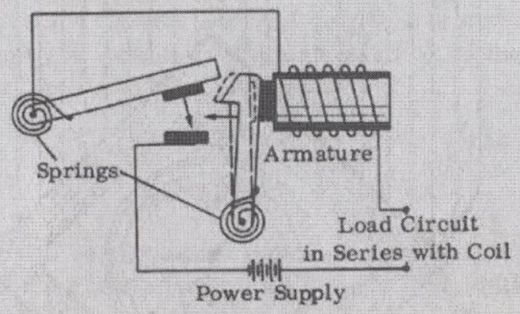

Figure 6-9. Magnetic circuit breaker.

Magnetic Shielding

49. In electricity, insulators are used to control voltage or restrict the flow of current. But there is no known insulator to control magnetic flux, the magnetic "equivalent" of current. Placing a nonmagnetic material in a magnetic field does little or nothing to change the flux. For example, a magnet can attract bits of iron quite well through glass, which is a good insulator for electric current. Stray magnetic fields, however, can influence the sensitive mechanism of an electric instrument and cause an error in its reading. The instrument can't be insulated against magnetic flux but it can be shielded. Shielding is the redirection of magnetic flux.

Why is it necessary to shield sensitive instruments? ______________

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[redacted]

50. A material that can be easily magnetized, such as soft iron, is useful for shielding. If a case of such a material (which is said to have high permeability) is built around a sensitive instrument, most of the magnetic flux in its vicinity will go into the case instead of into the instrument. A magnetic shield (blocks/redirects/destroys) ______________ magnetic flux.

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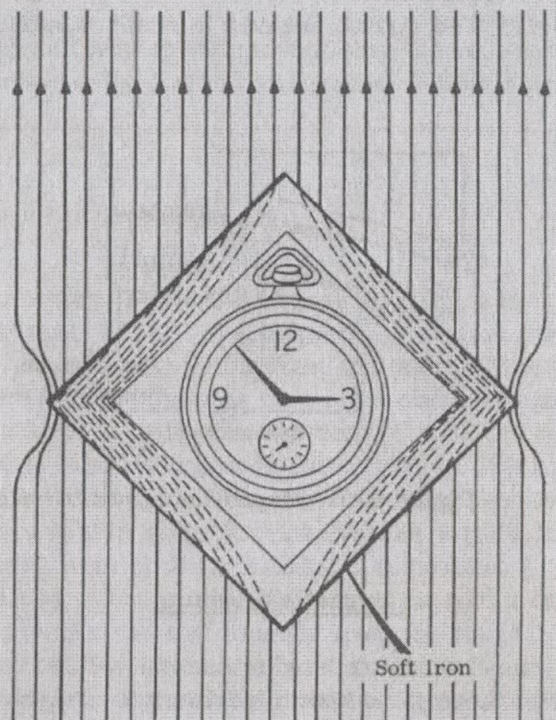

Figure 6-10. A magnetic shield.

51. Figure 6-10 on the preceding page illustrates how a magnetic shield works. How is the watch shielded from the magnetic flux? ____________

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In this chapter you have learned that, as in electricity, magnets have polarity and conform to the laws of attraction and repulsion. You have become acquainted with natural and permanent magnets and have learned the special properties of electromagnets.

You have learned that a magnetic field is always associated with electric current, and you have become acquainted with the laws governing the relationship of current to its magnetic field.

The properties of magnetic materials that are most important in electricity—permeability and hysteresis—have been described, as well as the special properties of electromagnets.

Since sensitive instruments cannot be insulated against magnetic fields, they must be shielded. You have learned how this is accomplished.

When you feel that you have a good understanding of the material covered in this chapter, go on to the Self-Test.

Self-Test

The following questions will test your understanding of Chapter Six. Write your answers on a separate sheet of paper and check them with the answers provided following the test.

1. What are the points of maximum attraction on a magnet?
2. What is the law of attraction and repulsion as it is related to magnetism?
3. What is a magnetic field?
4. What are the three general groups of magnets?
5. What is the relationship between flux density and magnetic field strength?
6. How can you determine the direction of the magnetic field about a conductor when the direction of current flow is known?
7. When the left-hand rule is applied to a coil, the thumb points to which pole?

8. Name three ways the magnetic field strength of a current-carrying coil can be increased.
9. Permeability depends on what two factors?
10. What is hysteresis?
11. When does an electromagnet actually function as a magnet?
12. When an electromagnet is used as a circuit breaker, what factor determines the amount of current flow in the coil that will cause the armature to be attracted?
13. How is a sensitive instrument shielded from stray magnetic fields?