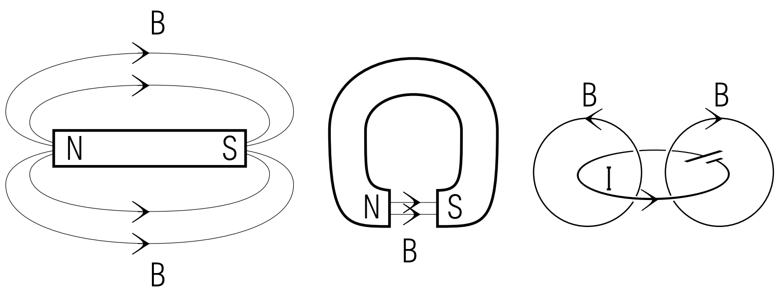
MISN-0-366

MAGNETS



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MAGNETS

by

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Title: **Magnets**

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Input Skills:

1. Describe the rotation of a current loop in a magnetic field (MISN-0-426).
2. Draw the magnetic field lines for a current-carrying coil (MISN-0-427).

Output Skills (Knowledge):

K1. State the way in which a magnetized object is equivalent to a current-carrying coil.

K2. State the atomic explanation for magnetic materials.

Output Skills (Problem Solving):

S1. Use the equivalence between magnetized objects and current-carrying coils to describe qualitatively the magnetic field produced by a magnetized object.

S2. Use the equivalence between magnetized objects and current-carrying coils to describe qualitatively the magnetic forces on a magnetized object (and its resulting tendency to rotate) in a uniform magnetic field.

S3. Use the equivalence between magnetized objects and current-carrying coils to describe qualitatively the interaction between two magnetized objects.

MISN-0-366

MAGNETS

Abstract:
Magnetic materials are those materials that can produce a magnetic field without the application of an electric current. One can "magnetize" such materials by aligning the spinning charges of electron groups, called "domains", within the materials. This is analagous to aligning a very large number of very small loops of current so that their magnetic fields add. Such magnetized material includes the common magnets used on refrigerators and bulletin boards.

SECT.

A MAGNETIC MATERIALS

► *Atomic-magnetic moments*

In text section F of Unit 426 we pointed out that atoms (or molecules) can produce magnetic effects similar to those of current loops because of the motion of the electrons in these atoms. In particular, such atoms can then have magnetic moments, both because the electrons in these atoms move in orbits and because they spin around their own axes.

► *Magnetic atoms in solids*

The magnetic moments of atoms may be preserved even if these atoms are bound together so as to form a solid. This is especially true in those cases where the magnetic moments of the atoms are due to electrons deep inside these atoms (since the motion of these electrons is not much affected by the chemical binding which is due predominantly to the outer valence electrons). Examples of such atoms with magnetic effects due to inner electrons are atoms of the "iron group" elements (e.g., iron, nickel, cobalt, . . .) and atoms of the "rare earth" elements (e.g., gadolinium, cerium, . . .).

► *Ferromagnets*

In some cases, neighboring atoms of this kind interact so that their magnetic moments tend to become aligned along the same direction. *

> * For reasons deeply rooted in "quantum mechanics" (the laws of mechanics which describe the motion of atomic particles), this interaction is basically due to the electric coulomb interaction, but depends on the sense of rotation of the spinning electrons.

If such atoms in a solid are sufficiently close to each other, the magnetic moments of all the atoms in entire macroscopic regions (called "domains") may become aligned in the same direction. Such a solid is then called "ferromagnetic."

► *Permanent magnets*

Some ferromagnetic solids (e.g., certain kinds of steel) are called "magnetically hard" or "permanent magnets." The distinguishing characteristic of these solids is that the magnetic moments in all the domains of these solids can be aligned so that all of these magnetic moments point permanently in the same direction *relative to the solid* (irrespective of how the solid itself may be rotated.)

► *Magnetically soft materials*

By contrast, other solids (e.g., iron) are called "magnetically soft." The distinguishing characteristic of these solids is that the magnetic moments in the various domains of these solids point in random directions in the absence of an externally produced magnetic field. But, when such a solid is placed in an external magnetic field, this field tends to orient the magnetic moments of all these domains along the direction of the magnetic field (just as a magnetic field tends to orient the magnetic moment of a current loop, as described in text section F of Unit 426). Hence the magnetic moments of all the domains tend to become aligned *along the external magnetic field* if this field is large enough.

SECT.

B EFFECTS OF MAGNETIZED MATERIALS

► *Introduction*

A material is said to be "magnetized" along some particular direction if its atomic magnetic moments are predominantly aligned along this direction. (In particular, our preceding comments indicate how ferromagnetic materials can be magnetized, either permanently or as a result of an externally produced magnetic field.) What then are the observable properties of such a magnetized material?

► *Equivalent coil*

Figure B-1 shows a rod, oriented perpendicular to the plane of the paper and magnetized so that its atomic magnetic moments point out of the plane of the paper. Each of its many atoms is then equivalent to some atomic current I flowing around a loop of atomic size in the *same* sense (counterclockwise in Fig. B-1a, where each atomic magnetic moment is out of the paper). What then is the net effect of all these many miniature current loops?

Note that, at any point P *inside* the rod, the currents from two adjacent current loops always flow in opposite senses. Since each of these

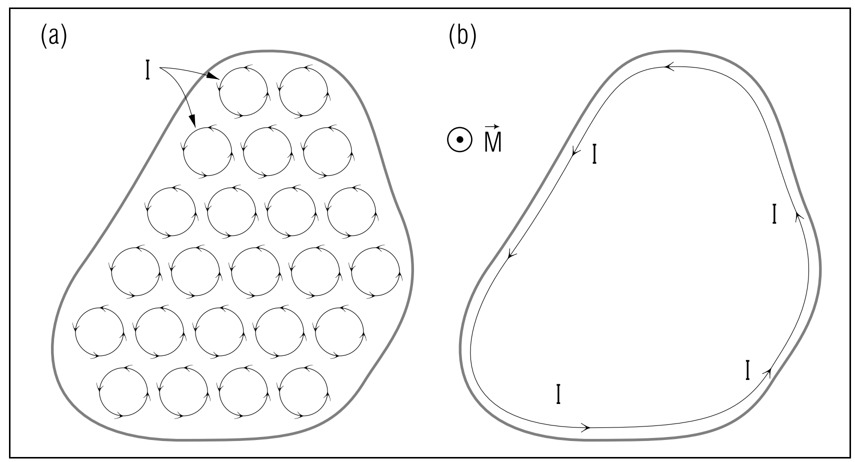


Fig. B-1: End-on view of a magnetized rod. (a) Atomic current loops. (b) Equivalent current around the periphery of the rod.

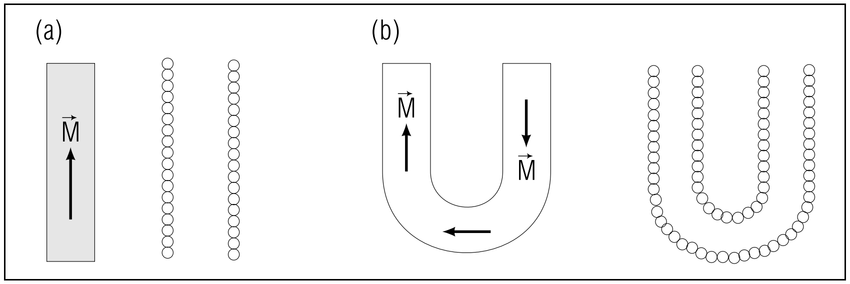


Fig. B-2.

currents has the same magnitude I, the effects of these currents then cancel, i.e., the situation is the same as if there were no current at the point P. This cancellation occurs at all points inside the rod. Only at the periphery of the rod are the atomic current loops not adjacent to other current loops. Hence the atomic currents at the periphery do not cancel and give rise to a net current I flowing in the counter-clockwise sense around the entire periphery of the rod. (See Fig. B-1b.)

Thus the electronic currents responsible for the aligned magnetic moments of the individual atoms in a rod are simply equivalent to a single current flowing around the periphery of the rod. Hence we arrive at this conclusion:

The magnetic properties of a magnetized object are completely equivalent to those of a coil with current I flowing around the periphery of the object.	(B-1)

In the next section we shall use this equivalence, together with our previous knowledge of the magnetic interaction between currents, to discuss various practical applications of magnetic materials.

► *Historical remark*

Historically, magnetic effects were first observed in the case of permanent magnets and were studied separately. However, we now realize that the magnetic effects of magnetized materials are just a special consequence of the magnetic effects produced by moving electrons in these materials.

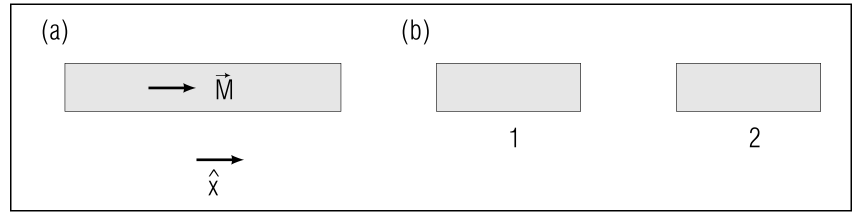


Fig. B-3.

Magnetized Objects and Equivalent Coils (Cap. 5)

B-1 *Coils equivalent to magnets:* (a) Fig. B-2a shows a permanent bar magnet (with magnetic moment in the indicated direction) and a straight coil equivalent to this magnet. In what sense does the current flow in this coil? (b) Fig. B-2b shows a permanent "horse-shoe" magnet (with magnetic moments in the indicated directions along its length) and an equivalent U-shaped coil. In what sense does the current flow in this coil? *(Answer: 3)*

B-2 *Cutting a magnet:* Suppose that a permanent bar magnet is cut into two pieces, as illustrated in Fig. B-3. By considering the equivalent coil equivalent to the original magnet, and the equivalent coils equivalent to the resulting two pieces, answer the following questions: (a) What are the directions of the magnetic moments of the two pieces? (b) Do these two pieces repel or attract each other? *(Answer: 5) (Suggestion: [s-2])*

SECT.

C APPLICATIONS OF MAGNETIC MATERIALS

► *Equivalence to coils*

According to Rule (A-1) of Unit 827, a magnetized object produces a magnetic field similar to that produced by a current-carrying coil. Furthermore, such a magnetized object located in a magnetic field experiences magnetic forces similar to those experienced by a current- carrying coil. This equivalence between magnetized objects and current-carrying coils implies that magnetized objects can often be used instead of current-carrying coils in a large variety of applications. From a practical point of view, magnetized materials are particularly convenient because their magnetic effects are due to permanently existing internal atomic currents, whereas the magnetic effects of coils can only be produced by supplying the coils with currents produced by special devices (such as batteries).

MAGNETIC FIELDS PRODUCED BY MAGNETIZED MATERIALS

► *Field for ammeters*

As described in text section F of Unit 426, an ammeter consists basically of a coil free to rotate in a magnetic field. This field is commonly provided by a permanent magnet. In this way, one does not need to supply any outside current to produce this field and can assure that the field retains a constant value at all times.

► *Field for motors*

Permanent magnets can be used (instead of current-carrying coils) to produce the magnetic field required for the functioning of an electric motor of the kind described in text section G of Unit 426. The advantage is that a current needs then only be supplied to the rotating coil in the motor, but *not* to produce the magnetic field in which this coil rotates. Such a use of permanent magnets is particularly practical in small motors (such as those used in electric shavers) which do not require large magnetic fields.

► *Field enhancement*

Current-carrying coils are very useful for producing magnetic fields which can be varied, since the magnetic field produced by such a coil is easily changed by changing the current through the coil. However, the current required to produce a desired field may often be inconveniently

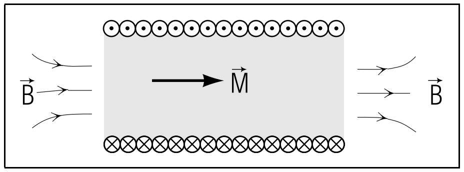


Fig. C-1: Magnetically soft iron core in a current-carrying coil.

large. To overcome this difficulty, one places inside the coil a core made of *magnetically soft* iron. The magnetic field produced by the current flowing through the coil then magnetizes this iron core so that its magnetic moment becomes oriented along the field. (See Fig. C-1.) As a result, the magnetic field outside the coil is then due *both* to the current in the coil *and* to the magnetized core (i.e., to the atomic currents of the atoms in this core). Since the magnetic field produced by this iron core is in the same direction as that produced by the current in the coil, the total magnetic field produced by a given current through the coil is thus appreciably larger than it would be without the iron core.

MAGNETIC FORCES ON MAGNETIZED MATERIALS

► *Compass needle*

A magnetized rod placed in a magnetic field acts just like a current-carrying coil (as described in text section F of Unit 426) and tends to rotate so that its magnetic moment becomes aligned along the field. For example, a "compass needle" is merely a permanently magnetized needle (or rod) suspended so as to be free to rotate in a horizontal plane. Near the surface of the earth, such a compass needle then tends to rotate so that its magnetic moment becomes aligned along the direction of the horizontal component vector of the magnetic field due to the earth (a direction which is quite close to the northern direction).

► *Magnetic poles*

Largely for historical reasons, the two ends of a magnetized rod are called its "poles." Thus the "south pole" and the "north pole" are such that the magnetic moment of the rod points from its south to its north pole. (See Fig. C-2.) The reasons for this terminology is that the north pole of a rod then points toward the northern direction at the surface of the earth.

► *Force on magnetized rod*

As discussed in Example E-1 of Unit 426, a net magnetic force acts on a current-carrying coil placed in a non-uniform magnetic field. Since

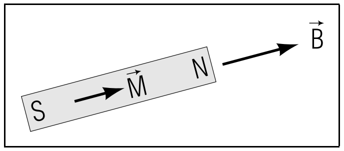


Fig. C-2: Magnetic moment $\vec{M}$ of a magnetized rod aligned along an external magnetic field $\vec{B}$. (The north and south poles of the rod are indicated by N and S.)

a magnetized rod is equivalent to a current-carrying coil, a net magnetic force acts then also on a magnetized rod placed in a non-uniform field. Such a force acts even if the rod is *not* permanently magnetized. Indeed, if the rod consists of a magnetically soft material, the magnetic field first magnetizes the rod (by aligning the atomic magnetic moments in the rod) and then produces a magnetic force on this magnetized rod.

► *Interaction of permanent magnets*

In text section D of Unit 427 we discussed the interaction between two current-carrying coils. Since magnetized rods are equivalent to such coils, the conclusions of that section are equally applicable to the interaction between magnetized rods. For example, Item (D-1) of Unit 427 implies that two permanently magnetized rods, aligned along the same axis, attract each other if their magnetic moments have the same direction, but repel each other if their magnetic moments have opposite directions. (See Fig. C-3.)

► *Attraction of "soft" iron*

Suppose that one end of a permanently magnetized rod is brought close to a coaxial rod made of magnetically soft iron. (See Fig. C-4) Then the magnetic field of the permanent magnet magnetizes the iron rod so that its magnetic moment has the same direction as the magnetic field produced by the permanent magnet, i.e., the same direction as that of the magnetic moment of the permanent magnet. By Item (D-1) of Unit 427, the permanent magnet then exerts an *attractive* force on the iron rod.

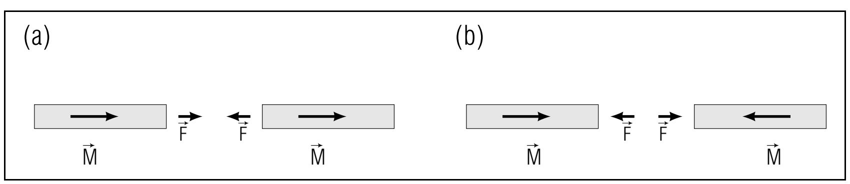


Fig. C-3: Attractive and repulsive forces exerted on one permanent magnet by another.

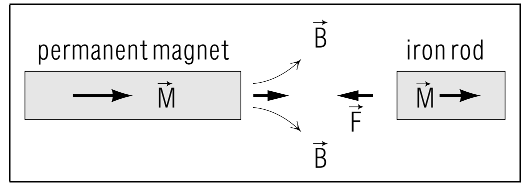


Fig. C-4: Permanent magnet attracting an originally unmagnetized rod of soft iron.

LONG-DISTANCE COMMUNICATION

The magnetic field produced by a current in a coil can be used to exert magnetic forces and thus to move permanent magnets. But the current in such a coil can be produced by connecting the coil through a very long wire to an emf source very far away. Thus we arrive at the basic idea of all telecommunication. For example, in the telegraph or teletype, currents are sent over long distances to move magnets attached to type bars used for printing a message. Similarly, in the telephone, currents are sent over long distances to move magnetically a diaphragm whose vibrations produce the sound waves constituting a spoken message.

Magnetized Objects and Equivalent Coils (Cap. 5)

C-1 *Field near bar magnet:* Fig. C-5 shows a permanent bar magnet having a magnetic moment in the indicated direction along $\hat{x}$. What is the direction of the magnetic field produced by this magnet at the points P_1, P_2, and P_3? *(Answer: 2) (Suggestion: [s-4])*

C-2 *Orientation of compass needle:* Fig. C-6 shows a long wire in which there flows a current I into the paper. (a) What is the direction of the magnetic field produced by this current at the points P_1, P_2, P_3, and P_4? (b) A compass needle is pivoted so as to be free to rotate in a horizontal plane. What is the orientation of this compass needle (i.e., what is the direction of its magnetic moment) when it is placed at the points P_1, P_2, P_3, or P_4 in Fig. C-6? (c) What would be the orientation of this compass needle if it is placed at the points P_1, P_2, or P_3 near the permanent bar magnet in Fig. C-5? *(Answer: 4) (Suggestion: [s-1])*

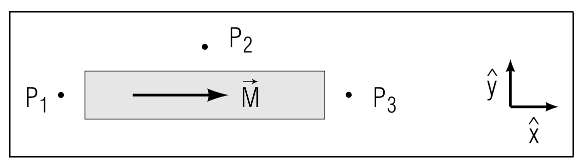


Fig. C-5.

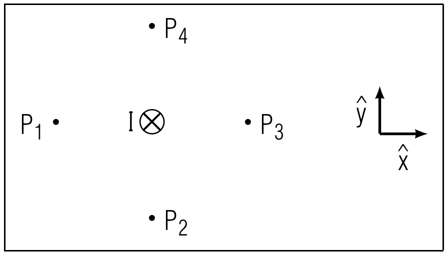


Fig. C-6.

C-3 *Force between magnets:* Fig. C-7 shows a large permanent bar magnet and a small permanent bar magnet placed near the large magnet at the three positions, 1, 2, and 3. (a) Suppose that the small bar magnet is always oriented so that its magnetic moment is along the same direction as that of the large magnet. At the positions 1, 2, and 3, is the small bar magnet repelled by, or attracted to, the large magnet? Why? (b) Suppose that the small bar magnet were oriented so that its magnetic moment is opposite to that of the large magnet. At the positions 1, 2, and 3, would the small magnet then be repelled or attracted? *(Answer: 1) (Suggestion: [s-3])*

C-4 *Force on soft iron:* Fig. C-8 shows a coil (with current flowing in such a sense that the magnetic moment of the coil is directed to the right) and a small piece of magnetically soft iron near this coil. (a) Is there a magnetic force on the piece of iron? If so, is the piece of iron repelled from, or attracted to, the coil? (b) Suppose that the current were flowing in the coil in the opposite sense (so that its magnetic moment had the opposite direction). What then would be the answers to the preceding questions? (c) An "ophthalmological magnet" consists of a small coil through which a large current can be made to flow for a short time (to prevent overheating the coil) to produce a large magnetic field near this coil. Explain why this magnet, brought close to a patient's eye, is useful to remove small iron fragments from the eye without touching the eye. *(Answer: 6) (Suggestion: [s-5]) (Practice: [p-1]), [p-2]*

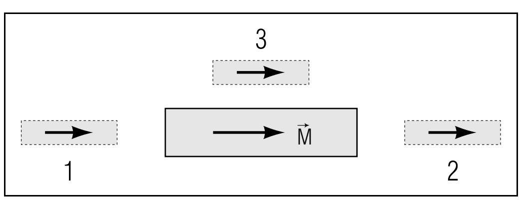


Fig. C-7.

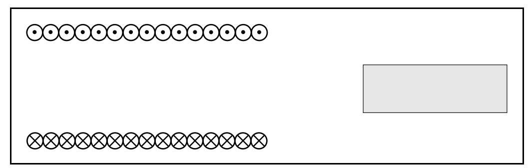


Fig. C-8.

SECT.
D SUMMARY

IMPORTANT RESULTS

Equivalence of magnetized object to coil: Rule (B-1)

Object is equivalent to coil with current flowing around periphery.

USEFUL KNOWLEDGE

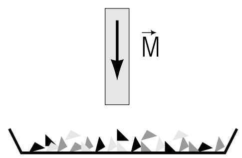
Magnetic materials (Sec. A)

NEW CAPABILITIES

(1) Use the equivalence between magnetized objects and current-carrying coils to describe qualitatively the magnetic field produced by a magnetized object, the magnetic forces on a magnetized object (and its resulting tendency to rotate), and the interaction between two magnetized objects. (Sects. B and C, [p-1], [p-2])

PRACTICE PROBLEMS

p-1 *MAGNETIZED OBJECTS AND EQUIVALENT COILS (CAP. 1): Magnetic separation:* The diagram shows a permanent magnet, with magnetic moment in the downward direction, placed above a container filled with small iron, brass, and aluminum filings collected from the floor of a machine shop. (a) Is there a magnetic force on any of these filings? If so, on which filings? Are these filings repelled by, or attracted to, the magnet? What filings remain then preferentially in the container? (b) What would be the answers to the preceding questions if the magnetic moment of the permanent magnet were in the opposite direction? *(Answer: 7) (Suggestion: [s-6] and review text problem C-4.)*



p-2 *MAGNETIC OBJECTS AND EQUIVALENT COILS (CAP. 1): Magnetic stirrer:* A magnetic field, rotating in a horizontal plane, can be produced in the region near the bottom of a beaker by rotating a permanent magnet below the beaker (or, more conveniently, by suitably varying currents set up in coils below the beaker). Suppose then that a permanent bar magnet is placed at the bottom of the beaker. What is the effect of the rotating magnetic field on this bar magnet? Why? Explain why this device is useful for stirring solutions in the beaker. *(Answer: 8) (Suggestion: Review text problem C-2.)*

SUGGESTIONS

s-1 *(Text problem C-2):* The compass needle is equivalent to a coil with the same magnetic moment. As discussed in text section F of Unit 426, such a coil tends to rotate so that its magnetic moment becomes aligned along the magnetic field.

s-2 *(Text problem B-2):* Does cutting the magnet affect the sense of the current in any part of the original equivalent coil? The force acting on one coil due to another was already discussed in text section D of Unit 427. This discussion is directly applicable here.

s-3 *(Text problem C-3):* The force on one permanent magnet due to another is the same as the force on one equivalent current-carrying coil due to another. The forces are thus exactly the same as those already discussed in text problem (D-1) of Unit 427 for the coils illustrated in Fig. D-2 there.

s-4 *(Text problem C-1):* The bar magnet is equivalent to the coil illustrated in Figure (B-3) of Unit 427. Hence the magnetic field lines outside the magnet are the same as those for that coil.

s-5 *(Text problem C-4):* Part (a): See the discussion in Sec. C of the text. Part (b): If the sense of the current is reversed, the magnetic field produced by the coil is reversed. Hence the iron piece becomes magnetized so that its magnetic moment has the opposite direction. Thus there are *two* sign reversals (a magnetic moment of *opposite* direction in a magnetic field of *opposite* direction). Hence the magnetic force on the iron piece remains unchanged.

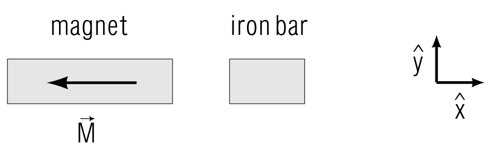
s-6 *(Practice problem [p-1]):* Of these materials, only iron is ferromagnetic and can acquire an appreciable magnetic moment in the presence of the magnetic field. The magnetic moments of the other materials are utterly negligible.

ANSWERS TO PROBLEMS

1. a. attracted, attracted, repelled
   b. repelled, repelled, attracted
2. along $\hat{x}$, opposite $\hat{x}$, along $\hat{x}$
3. a. into paper on R side, out of paper on L side.
   b. into paper inside of U, out of paper outside of U.
4. a. $\hat{y}$, $-\hat{x}$, $-\hat{y}$, $\hat{x}$
   b. $\hat{y}$, $-\hat{x}$, $-\hat{y}$, $\hat{x}$
   c. $\hat{x}$, $-\hat{x}$, $\hat{x}$
5. a. both along $\hat{x}$
   b. attract
6. a. yes, attracted
   b. yes, attracted
   c. attractive magnetic force pulls iron fragment out.
7. a. Magnetic force on iron filings; attracted; brass and aluminum remain
   b. same answers
8. Magnet rotates because its magnetic moment tends to remain aligned along the magnetic field

MODEL EXAM

1. See Output Skills K1-K2 in this unit's *ID Sheet*. One or both of these skills, or neither, may be on the actual exam.
2. A bar magnet and an unmagnetized iron bar lie in the relative positions shown in the diagram.
   a. What is the direction of the magnetic field produced by the bar magnet along the axis of the iron bar?
   b. What is the direction of the force exerted on the iron bar by the bar magnet?



Brief Answers:

1. See module text.
2. a. $-\hat{x}$ (or opposite to $\hat{x}$)
   b. $-\hat{x}$ (or opposite to $\hat{x}$)