24 Magnetism

Fred Myers, first photo in the chapter opener, has pioneered conceptual physics in the ninth grade since the late 1970s. He has instilled more love of physics in youngsters than any of my friends. Photo 2 is researcher and instructor Ken Ganezer of California State University at Dominquez Hills, a mutual friend of Charlie Spiegel (Figure 26.9) who was a contributor to Conceptual Physics before he died in 1995. Ken's passion for physics is evident in an e-mail to me in which he says, "Magnetism is the epitome of physics and of science in general—mysterious, beautiful, compelling, extremely practical, and a jumping off point for relativity (at least it was for Einstein) and an anomaly of our inertial frame." Not surprisingly, Ken has achieved numerous awards for dedicated teaching and improving undergraduate physics labs and curriculum, received NSF and NIH grants for research on neutrinos, grand unification, biomedical physics, and gravitational waves with LIGO. Photo 3 is Fred Cauthen, new to the CCSF physics faculty. Photo 4 is the son of friends Alan and Fe Davis. I first met Alan when visiting the island of Chuuk in Micronesia in the 1990s. They now live in the San Francisco Bay area.

The profile is on Nicola Tesla, an electric engineer rather than a physicist. What he did with physics was extraordinary and commendable.

This chapter, in the spirit of others, links the subject matter to the environment. It concludes with a bit of paleomagnetism, and the magnetic sensors in living organisms.

Direct measurements of the Earth's inner core recently suggest that it rotates faster than the bulk of the planet. Seismologists depended on the woodlike grain of the inner core, which alters the speed of seismic waves passing through it, and compiled 30 years of data to find a change of a few tenths of a second in wave travel times. Indications are that the inner core gains a full turn on the rest of the planet only every 400 years.

Magnetism is a major source of energy in galaxies, where twisting and turning of material creates a dynamo effect that amplifies the magnetic fields. The explosive release of magnetic energy from space storms that interact with Earth's magnetosphere can damage spacecraft, sicken astronauts and even disrupt power communication on the ground.

Bob Roemer reports his fascination with a compass on subways (*The Physics Teacher*, Feb. 1993). Rather than simply pointing north, the compass dances erratically in response to the strong dc that varies as the cars maneuver. Magnetic fields some 20 times larger than the Earth's are produced by dc in the wires, and the 600-V third rail that often carries currents in excess of 5000 A. Changes in field direction are noted when the cars brake by using motors as generators, supplying energy back into the third rail. If your student rides subway or other electric cars, urge them to note the effects of the currents on small hand-held compasses!

A new radiation belt was discovered back in 1993, a toroid of anomalous cosmic rays making up a third radiation belt within the inner belt of protons. The outer belt is made up of electrons.

Make iron-filing permanent displays by spraying water on iron filings on a paper atop a magnet. The rust stains will leave a permanent impression of the magnetic field. (This idea is from Matt Keller.)

A long helically wound coil of insulated wire is called a *solenoid*.

The material in this chapter is prerequisite to the next chapter.

Practicing Physics Book:
• Magnetic Fundamentals.

Problem Solving Book:
There are ample problems on magnetism

Laboratory Manual:
• Seeing Magnetic Fields *Patterns of Attraction and Repulsion* (Activity)
• Electric Magnetism *Electric Currents and Magnetic Fields* (Activity)
• Motor Madness Simple DC Motors (Activity)

Next-Time Questions:
• Magnet and Tack
• Bar and Magnet
• Wire in Magnet

Hewitt-Drew-It! Screencast: •*Magnetism*

SUGGESTED LECTURE PRESENTATION

Magnetic Force: Begin by holding a magnet above some nails or paper clips on your lecture table. State that the nails or clips are flat on the table because every particle of matter in the whole world is gravitationally pulling them against the table. Then show that your magnet out pulls the whole world and lifts the nails or clips off the table.

> CHECK QUESTION: What is the net force on the magnetic needle of a compass? [Zero. When it's not aligned with the magnetic field, the net force is still zero although the net torque is not zero.]

Show that iron is not the only ferromagnetic substance. Certain Canadian nickels and quarters (1968 to 1981 which are pure nickel) are easily attracted to a magnet. The U.S. 5 cent piece is no longer pure nickel, is 75% copper, and won't respond to a magnet.

Magnetic Poles: Show how a bar magnet affects a large lecture compass and discuss magnetic poles. Similar to the fundamental rule of electricity, *like poles repel and opposite poles attract.*

Magnetic Fields: Show field configurations about bar magnets with the use of an overhead projector and iron filings. Simply lay a magnet on the glass surface of the projector and cover it with a sheet of plastic, and sprinkle iron filings over the plastic. Acknowledge the alignment of **magnetic domains** in the magnet material.

Magnetic Induction: Explain magnetic induction, and show how bringing a nonmagnetized nail near a magnet induces it to become a magnet and be attracted. Then contrast this with an aluminum rod—discuss unpaired electron spins and magnetic domains. Compare magnetic induction to the electric induction shown in Figures 22.12 and 22.13 back in Chapter 22. Stress the similarities of electrically inducing charge polarization and magnetically inducing the alignment of magnetic domains.

Electric Currents and Magnetic Fields: Discuss the source of magnetism—the *motion* of charges. All magnetism starts with a moving electric charge: in the spin of the electron about its own axis (like a top), in the revolution about the nuclear axis, and as it drifts as part of an electric current.

> DEMONSTRATION: Place a compass near a wire and show the deflection of the compass needle when current is passed through the wire.

It should be enough to simply acknowledge that the magnetic field is a relativistic "side effect" or "distortion" in the electric field of a moving charge. (Unless you've already treated special relativity, the relativistic explanation may be too involved to be effective.)

Side point: When the magnetic field about a current-carrying wire is undesirable, double wires are used, with the return wire adjacent to the wire. Then the net current for the double wire is zero, and no magnetic field surrounds it. Wires are often braided to combat slight fields where the cancellation is not perfect.

Electromagnets:
Call attention to the circular shape of the magnetic field about a current-carrying wire (Figure 24.8 and the photos of field lines of Figure 24.9). It's easy to see how the magnetic field is bunched up in a loop of current-carrying wire, and then in a coil of many loops. Then place a piece of iron in the coil and the added effect of aligned domains in the iron produces an electromagnet.

> DEMONSTRATION: Make a simple electromagnet in front of your class. Simply wind wire around a spike and pick up paper clips when you put a current through the wire. Mimic the operation of a junkyard magnet, where the clips are dropped when the current is turned off.

> DEMONSTRATION: Show your department's goodies; electromagnets and superconducting electromagnets!

> DEMONSTRATION: Do as Wai Tsan Lee (Lillian's dad) does in Figure 24.6 and show how nails or paper clips become induced magnets. This is more effective if done with an electromagnet. When the current is turned off, the nails or paper clips drop. What of those that don't? [Residual magnetism!]

If you have an electromagnetic levitator, discuss the train application when you are fascinating your students with its demonstration. The idea of a **magnetically-levitated train** was described in 1909 by Robert Goddard, an American well known for inventing the liquid-fueled rocket. Japan was the first to demonstrate maglev trains during the 1964 Olympics held in Japan, transporting spectators at speeds up to 130 mph. Although Europe and Japan now have the lead in this field, the first modern design for a maglev train comes from Americans, nuclear-engineer James R. Powell, and particle-acceleration physicist Gordon T. Danby, who were awarded a patent for their design.

Whatever the present variations in design, once the train is levitated there is no mechanical friction to contend with, so only modest force is needed to accelerate it. Fixed electromagnets along the guideway alternately pull and push by switching polarity whenever one of the train's propulsion magnets passes it. The phased switching is timed by computers under the control of the driver to accelerate or decelerate the train, or simply keep it moving. Various designs have the overall result of propelling the train like a surfboard riding a wave. Speculation by co-inventor Danby is that future travel in partially evacuated tubes will permit cross-country passage in about an hour. Maglev trains may play a large role in transportation in this century. Watch for new design features for this new technology. Also watch for Elon Musk's Hyperloop. These are technologically exciting times!

Magnetic Force on Moving Charges:
Discuss the motion of a charged particle injected into a magnetic field perpendicularly, and explain how it will follow a circle. The perpendicular push is a centripetal force that acts along the radius of its path.

Briefly discuss cyclotrons and bevatrons, with radii that range from less than a meter to more than a kilometer.

The Hand Rules:
Sorry if in the textbook I don't feature the hand rules for magnetic field, current, and force. I joke about it in the Insight at the top of page 461. It has always seemed to me that a misquided purpose of these rules was to provide material for testing. To an engineer or physicist, the rules have practical use. But for the non-science student? Although the hand rules are a tiny part of what's important in electric-magnetic phenomena, in exams, unfortunately, they can dominate. However, in the lab activity *Electric Magnetism* students see how the magnetic field surrounding a current-carrying wire reverses when the direction of current reverses. These observations lead them to developing a right-hand rule (fingers around the wire) to describe the geometry. But in the textbook? Not there, and hopefully, not on any student exams.

Magnetic Force on Current-Carrying Wires:
Simple logic tells you that if forces act on electrons that move through a magnetic field, then forces act on electrons traveling through a wire in a magnetic field. Ask your class whether they see that what's happening in Figure 24.15 is a natural consequence of what's happening in Figure 24.13. This is one of the more straight-forward connections in nature, one thing following another.

> DEMONSTRATION: Show how a wire jumps out of (or into) a magnet when current is passed through the wire (Figure 24.15). Reverse current (or turn wire around) to show both cases.

If you have a large lecture galvanometer, show your class the coil of wire that is suspended in the magnetic field of the permanent magnet (Figure 24.17). The same is found in ammeters and voltmeters. Now you are ready to extend this idea to the electric motor.

> DEMONSTRATION: Show the operation of a dc demonstration motor.

Earth's Magnetic Field:
Discuss the field configuration about Earth and how cosmic rays are deflected by the magnetic field lines. In discussing pole reversals, state that the magnetic field of the Sun undergoes reversals about every eleven years.

Biomagnetism:
Acquaint yourself with the latest findings regarding magnetic field sensing by living things. Creatures such as bacteria, bees, and pigeons are mentioned briefly in the text. Recent findings show magnetic particles in the human brain. Insects sense the world in very different ways than humans, using things we can't perceive. Birds orient flight by sunset glow and star patterns as well as by the magnetic field—a combination of approaches.

Answers and Solutions for Chapter 24

Reading Check Questions

1. Hans Christian Oersted in a high-school classroom noted how a current affects a magnet, thus relating electricity and magnetism.
2. The force depends also on the velocity of the charge.
3. Moving electrons are the source of the magnetic force.
4. Yes, in each, likes repel likes; opposites attract.
5. Magnetic poles cannot be isolated; electric charges can.
6. The closer the field lines, the stronger the magnetic field.
7. The motion of electric charges produces a magnetic field.
8. Electrons exhibit spin motion and orbital motion.
9. A magnetic domain is a cluster of aligned atoms.
10. Iron atoms are mainly aligned in a magnetized material, and un-aligned in a non-magnetic material.
11. Iron has magnetic domains, wood does not.
12. Impact jostles domains out of alignment and weakens the magnet.
13. Magnetic field takes the form of concentric circles about a current-carrying wire.
14. When current reverses, magnetic field reverses direction.
15. Inside the loop lines are more concentrated.
16. The iron's domains align with the field and add to its strength.
17. Greater electron flow produces greater magnetic field strength.
18. True! If there's no motion, there's no magnetism.
19. Force is maximum when motion is perpendicular to the field; minimum when parallel.
20. Earth's magnetic field deflects incoming charged particles and lessens their impact on Earth's surface.
21. Force is maximum when current is perpendicular to the field.
22. Electric current in its coil is deflected by a permanent magnet.
23. When calibrated for current, it is an ammeter; when calibrated for voltage, a voltmeter.
24. Current is reversed with each half turn of the armature.
25. Yes, a motor is a sophisticated galvanometer.
26. Earth's intense heat prevents alignment of atoms.
27. Magnetic pole reversals are reversals of north and south poles, common throughout Earth's history.
28. The cause of the aurora borealis is impact of charged particles with atmospheric molecules.
29. Six creatures include bacteria, pigeons, bees, butterflies, sea turtles, and fish.
30. Cosmic rays are continually penetrating your body.

Think and Do

31. A worthwhile activity.

32. Make your own magnet!

Think Explain

33. Separation is easy with a magnet (try it and be amazed!)

34. All magnetism originates in moving electric charges. For an electron there is magnetism associated with its spin about its own axis, with its motion about the nucleus, and with its motion as part of an electric current. In this sense, all magnets are electromagnets.

35. How the charge moves dictates the direction of its magnetic field. (A magnetic field is a vector quantity.) Magnetic fields cancel, more in some materials than others.

36. Beating on the nail shakes up the domains, allowing them to realign themselves with the Earth's magnetic field. The result is a net alignment of domains along the length of the nail. (Note that if you hit an already magnetized piece of iron that is not aligned with the Earth's field, the result can be to weaken, not strengthen, the magnet.)

37. Attraction will occur because the magnet induces opposite polarity in a nearby piece of iron. North will induce south, and south will induce north. This is similar to charge induction, where a balloon will stick to a wall whether the balloon is negative or positive.

38. Yes, the poles, being of opposite polarity, attract each other. If the magnet is bent so that the poles get closer, the force between them increases.

39. The poles of the magnet attract each other and will cause the magnet to bend, even enough for the poles to touch if the material is flexible enough.

40. An electric field surrounds a stationary electric charge. An electric field and a magnetic field surround a moving electric charge. (And a gravitational field also surrounds both).

41. Refrigerator magnets have narrow strips of alternating north and south poles. These magnets are strong enough to hold sheets of paper against a refrigerator door, but have a very short range because the north and south poles cancel a short distance from the magnetic surface.

42. Apply a small magnet to the door. If it sticks, your friend is wrong because aluminum is not magnetic. If it doesn't stick, your friend might be right (but not necessarily—there are lots of nonmagnetic materials).

43. A magnet will induce the magnetic domains of a nail or paper clip into alignment. Opposite poles in the magnet and the iron object are then closest to each other and attraction results (this is similar to a charged comb attracting bits of electrically neutral paper—Figure 22.13). A wooden pencil, on the other hand, does not have magnetic domains that will interact with a magnet.

44. Over time, domains are knocked out of alignment.

45. Domains in the paper clip are induced into alignment in a manner similar to the electrical charge polarization in an insulator when a charged object is brought nearby. Either pole of a magnet will induce alignment of domains in the paper clip: Attraction results because the pole of the aligned domains closest to the magnet's pole is always the opposite pole, resulting in attraction.

46. The needle is not pulled toward the north side of the bowl because the south pole of the magnet is equally attracted southward. The net force on the needle is zero. (The net torque, on the other hand, will be zero only when the needle is aligned with the Earth's magnetic field.)

47. The mechanism of alignment involves two factors: First, each filing is turned into a tiny magnet by the magnetic field of the bar magnet, which induces domain alignment in the filing. Second, a pair of equal and opposite torques act on each filing whenever it is not parallel to the magnetic field lines. These torques rotate the filings into alignment with the field lines like little compass needles.

48. The north and south poles of a magnet are so named because they are "north-seeking" and "south-seeking." So magnetically speaking, Earth's pole in the Northern Hemisphere is a south pole. Earth's pole in the Southern Hemisphere is a north pole.

49. Yes, for the compass aligns with the Earth's magnetic field, which extends from the magnetic pole in the Southern Hemisphere to the magnetic pole in the Northern Hemisphere.

50. Rotation is not produced when the axis of the loop is aligned with the field.

51. Back to Newton's 3rd law! Both A and B are equally pulling on each other. If A pulls on B with 50 newtons, then B also pulls on A with 50 newtons. Period!

52. Yes, it does. Since the magnet exerts a force on the wire, the wire, according to Newton's third law, must exert a force on the magnet.

53. Newton's 3rd law again: Yes, the paper clip, as part of the interaction, certainly does exert a force on the magnet—just as much as the magnet pulls on it. The magnet and paper clip pull equally on each other to comprise the single interaction between them.

54. The needle points perpendicular to the wire (east or west). (See Figure 24.8.)

55. Both the vibrations in the coil and the speaker cone have identical frequencies at any instant.

56. Less power because of reduced electrical resistance means less heat loss.

57. Just as a nail is magnetized by beating on it, an iron ship is beat upon in its manufacture, making it a permanent magnet. Its initial magnetic field orientation, which is a factor in subsequent magnetic measurements, is in effect recorded on the brass plaque.

58. The beam must be traveling along or parallel to the magnetic field.

59. An electron must be moving across magnetic field lines in order to feel a magnetic force. So an electron at rest in a stationary magnetic field will feel no force to set it in motion. In an electric field, however, an electron will be accelerated whether or not it is already moving. (A combination of magnetic and electric fields is used in particle accelerators such as cyclotrons. The electric field accelerates the charged particle in its direction, and the magnetic field accelerates it perpendicular to its direction.)

60. The diameter decreases as the proton is pulled in a tighter circle.

61. If the particles enter the field moving in the same direction and are deflected in opposite directions (say one left and one right), the charges must be of opposite sign.

62. When we write *work* = *force* × *distance*, we really mean the component of force in the direction of motion multiplied by the distance moved (Chapter 7). Since the magnetic force that acts on a beam of electrons is always perpendicular to the beam, there is no component of magnetic force along the instantaneous direction of motion. Therefore a magnetic field can do no work on a charged particle. (Indirectly, however, a *time-varying magnetic field* can induce an electric field that *can* do work on a charged particle.)

63. If the field interacts with a stationary bar magnet it is magnetic; if with a stationary charge, it is electric. If an electric current is generated in a rotating loop of wire, the field is magnetic. If a force acts only on a moving charge, the field is magnetic. So any of the classes of experiments that deal with electric charge at rest and electric charge in motion could be used to determine the nature of the field in the room.

64. Charged particles moving through a magnetic field are deflected most when they move at right angles to the field lines, and least when they move parallel to the field lines. If we consider cosmic rays heading toward the Earth from all directions and from great distances, those descending toward northern Canada will be moving nearly parallel to the magnetic field lines of the Earth. They will not be deflected very much, and secondary particles they create high in the atmosphere will also stream downward with little deflection. Over regions closer to the equator like Mexico, the incoming cosmic rays move more nearly at right angles to the Earth's magnetic field, and many of them are deflected back out into space before they reach the atmosphere. The secondary particles they create are less intense at the Earth's surface. (This "latitude effect" provided the first evidence that cosmic rays from outer space consist of charged particles—mostly protons, as we now know.)

65. The Van Allen radiation belts are filled with swarms of high-energy charged particles that can damage living tissue. Astronauts, therefore, make an effort to keep below these belts.

66. Cosmic ray intensity at the Earth's surface would be greater when the Earth's magnetic field passed through a zero phase. Fossil evidence suggests the periods of no protective magnetic field may have been as effective in changing life forms as x-rays have been in the famous heredity studies of fruit flies.

67. Singly-charged ions traveling with the same speed through the same magnetic field will experience the same magnetic force. The extent of their deflections will then depend on their accelerations, which in turn depend on their respective masses. The least massive ions will be deflected the most and the most massive ions will be deflected least. (See Figure 34.14, further in the book, for a diagram of a mass spectrograph.)

68. A habitat in space could be shielded from cosmic radiation if a magnetic field were set up about the habitat, just as the magnetic field of the Earth shields us from much of the cosmic radiation that would otherwise strike the Earth. (As to the idea of a blanket, some have proposed that a thick layer of slag from mining operations on planets or asteroids could be placed around the habitat.)

69. To determine only by their interactions with each other which of two bars is a magnet, place the end of the bar #1 at the midpoint of bar #2 (like making a "T"). If there is an attraction, then bar #1 is the magnet. If there isn't, then bar #2 is the magnet.

70. Magnetic levitation will reduce surface friction to near zero. Then only air friction will remain. It can be made relatively small by aerodynamic design, but there is no way to eliminate it (short of sending vehicles through evacuated tunnels). Air friction gets rapidly larger as speed increases.

71. Yes, each will experience a force because each is in the magnetic field generated by the other. Interestingly, currents in the same direction attract, and currents in opposite directions repel.

72. The magnetic fields of each cancel at some distance from the wires.

73. Currents will be induced in metals by the changing magnetic field of the MRI device.

Think and Discuss

74. An electron always experiences a force in an electric field because that force depends on nothing more than the field strength and the charge. But the force an electron experiences in a magnetic field depends on an added factor: velocity. If there is no motion of the electron through the magnetic field in which it is located, no magnetic force acts. Furthermore, if motion is along the magnetic field direction, and not at some angle to it, then also no magnetic force acts. Magnetic force, unlike electric force, depends on the velocity of the charge. (Interestingly, due to electron spin it experiences a torque that tends to align its magnetic field with the external magnetic field.)

75. The dip needle will point most nearly vertically near the Earth's magnetic poles, where the field points toward or away from the poles (which are buried deep beneath the surface). It will point most nearly horizontally when near the equator (see Figure 24.20).

76. At the Earth's North magnetic pole the needle would point downward.

77. The net force on a compass needle is zero because its north and south poles are pulled in opposite directions with equal forces in the Earth's magnetic field. When the needle is not aligned with the magnetic field of the Earth, then a pair of torques (relative to the center of the compass) is produced (Figure 24.3). This pair of equal-strength torques, called a "couple," rotates the needle into alignment with the Earth's magnetic field.

78. Tell your first friend that the magnetic field of the Earth is continuous from pole to pole, and certainly doesn't make a turnaround at the Earth's equator; so a compass needle that is aligned with the Earth's field likewise does not turn around at the equator. Your other friend could correctly argue that compass needles point southward in the Southern Hemisphere (but the same pole points southward in the Northern Hemisphere). A compass does not turn around when crossing the equator.

79. The electric field in a cyclotron or any charged particle accelerator forces the particles to higher speeds, while the magnetic field forces the particles into curved paths. A magnetic force can only change the direction (not the speed) of a charged particle because the force is always perpendicular to the particle's instantaneous velocity. (Interestingly enough, in an accelerator called a betatron, the electric field is produced by a changing magnetic field.)

80. Speed or KE doesn't increase because the force is perpendicular to the velocity, doing no work on the particle.

81. Associated with every moving charged particle, electrons, protons, or whatever, is a magnetic field. Since a magnetic field is not unique to moving electrons, there is a magnetic field about moving protons as well. However, it differs in direction. The field lines about the proton beam circle in one way, the field lines about an electron beam in the opposite way. (Physicists use a "right-hand rule." If the right thumb points in the direction of motion of a positive particle, the curved fingers of that hand show the direction of the magnetic field. For negative particles, the left hand can be used.)

82. Each coil is magnetically attracted to its electromagnetic neighbor.