? The immense cylinder in this photograph is a current-carrying coil, or solenoid, that generates a uniform magnetic field in its interior as part of an experiment at CERN, the European Organization for Nuclear Research. If two such solenoids were joined end to end, the magnetic field along their common axis would (i) become four times stronger; (ii) double in strength; (iii) become $\sqrt{2}$ times stronger; (iv) not change; (v) weaken.

# 28 Sources of Magnetic Field

**LEARNING OUTCOMES**

***In this chapter, you'll learn...***

**28.1** The nature of the magnetic field produced by a single moving charged particle.
**28.2** How to describe the magnetic field produced by an element of a current-carrying conductor.
**28.3** How to calculate the magnetic field produced by a long, straight, current-carrying wire.
**28.4** Why wires carrying current in the same direction attract, while wires carrying opposing currents repel.
**28.5** How to calculate the magnetic field produced by a current-carrying wire bent into a circle.
**28.6** What Ampere's law is, and what it tells us about magnetic fields.
**28.7** How to use Ampere's law to calculate the magnetic field of symmetric current distributions.
**28.8** How microscopic currents within materials give them their magnetic properties.

***You'll need to review...***

**10.5** Angular momentum of a particle.
**21.3–21.5** Coulomb's law and electric-field calculations.
**22.4** Solving problems with Gauss's law.
**27.2–27.9** Magnetic field and magnetic force.

In Chapter 27 we studied the forces exerted on moving charges and on current-carrying conductors in a magnetic field. We didn't worry about how the magnetic field got there; we simply took its existence as a given fact. But how are magnetic fields *created*? We know that both permanent magnets and electric currents in electromagnets create magnetic fields. In this chapter we'll study these sources of magnetic field in detail.

We've learned that a charge creates an electric field and that an electric field exerts a force on a charge. But a *magnetic* field exerts a force on only a *moving* charge. Similarly, we'll see that only *moving* charges *create* magnetic fields. We'll begin our analysis with the magnetic field created by a single moving point charge. We can use this analysis to determine the field created by a small segment of a current-carrying conductor. Once we can do that, we can in principle find the magnetic field produced by *any* shape of conductor.

Then we'll introduce Ampere's law, which plays a role in magnetism analogous to the role of Gauss's law in electrostatics. Ampere's law lets us exploit symmetry properties in relating magnetic fields to their sources.

Moving charged particles within atoms respond to magnetic fields and can also act as sources of magnetic field. We'll use these ideas to understand how certain magnetic materials can be used to intensify magnetic fields as well as why some materials such as iron act as permanent magnets.

## 28.1 MAGNETIC FIELD OF A MOVING CHARGE

Let's start with the basics, the magnetic field of a single point charge $q$ moving with a constant velocity $\vec{v}$. In practical applications, such as the solenoid shown in the photo that opens this chapter, magnetic fields are produced by tremendous numbers of charged particles moving together in a current. But once we understand how to calculate the magnetic field due to a single point charge, it's a small leap to calculate the field due to a current-carrying wire or collection of wires.

As we did for electric fields, we call the location of the moving charge at a given instant the **source point** and the point $P$ where we want to find the field the **field point.** In Section 21.4 we found that at a field point a distance $r$ from a point charge $q$, the magnitude of the