Answer to Essential Question 19.7: To get a net magnetic field of zero, the two fields must point in opposite directions. This happens only along the straight line that passes through the wires, in between the wires. The current in wire 1 is three times larger than that in wire 2, so the point where the net magnetic field is zero is three times farther from wire 1 than from wire 2. This point is 30 cm to the right of wire 1 and 10 cm to the left of wire 2.

19-8 Magnetic Field from Loops and Coils

The Magnetic Field from a Current Loop

Let's take a straight current-carrying wire and bend it into a complete circle. As shown in Figure 19.27, the field lines pass through the loop in one direction and wrap around outside the loop so the lines are continuous. The field is strongest near the wire. For a loop of radius R and current I, the magnetic field in the exact center of the loop has a magnitude of

$$B = \frac{\mu_0 I}{2R} .$$ (Equation 19.11: **The magnetic field at the center of a current loop**)

The direction of the loop's magnetic field can be found by the same right-hand rule we used for the long straight wire. Point the thumb of your right hand in the direction of the current flow along a particular segment of the loop. When you curl your fingers, they curl the way the magnetic field lines curl near that segment. The roles of the fingers and thumb can be reversed: if you curl the fingers on your right hand in the way the current goes around the loop, your thumb, when you stick it out, shows the way the field line points inside the loop.

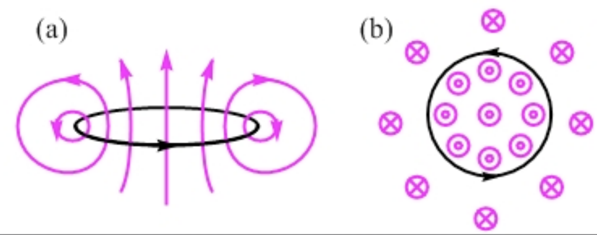

Figure 19.27: (a) A side view of the magnetic field from a current loop. (b) An overhead view of the same loop, showing the field in the plane of the loop.

The magnetic field from a current loop is similar to from a thin disk magnet that you might find on your fridge (as long as the north and south poles of the disk magnet are on opposite faces of the disk, which is generally the case). This similarity between the fields is no coincidence. The disk magnet is made from **ferromagnetic** material – ferromagnetic means having magnetic properties similar to that of iron. In any material, each electron in an atom has an associated angular momentum. In many materials these angular momenta either cancel out or are randomly aligned, giving rise to little or no magnetic field. In ferromagnetic materials, however, the angular momenta of neighboring atoms line up, producing a substantial magnetic field.

A model of a ferromagnetic material is shown in Figure 19.28. Each atom acts like a tiny current loop, with the loops carrying currents that circulate in the same direction. In the inner part of the magnet, nearby currents point in opposite directions and cancel one another out. Around the edge of the magnet, however, there is no cancellation, and the net effect of the currents at the outside is like that of a single current that goes all the way around the outer edge of the disk.

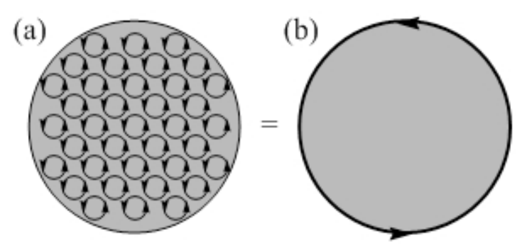

Figure 19.28: A model of a ferromagnetic material. Each atom acts like a tiny current loop, with neighboring current loops aligned with one another. Except around the outer edge of the magnet, nearby currents are directed in opposite directions, and cancel one another. The net effect is that the disk magnet produces a magnetic field similar to that from a current loop of the same radius as the disk.

The Magnetic Field from a Current-Carrying Coil

A cylindrical current-carrying coil, or **solenoid**, is like a stack of current loops. In the ideal case, the solenoid is infinitely long, producing a uniform magnetic field inside the solenoid and negligible field outside the solenoid. The solenoid is the magnetic equivalent of the parallel-plate capacitor – when both devices extend to infinity, the field produced (magnetic field for the solenoid, electric field for the capacitor) is uniform. Just as the electric field from the capacitor depends on the capacitor geometry, the magnetic field produced by the solenoid depends on the solenoid geometry. For a solenoid of length L, with a total of N turns (or $n = N/L$ turns per unit length), and carrying a current I, the magnitude of the magnetic field inside the solenoid is:

$$B = \frac{\mu_0 N I}{L} = \mu_0 n I \, ,$$ (Equation 19.12: **The magnetic field for an ideal solenoid**)

As shown in Figure 19.29, the magnetic field in an ideal solenoid is parallel to the axis of the solenoid. If you curl the fingers of your right hand in the direction of the current, your thumb points in the direction of the field inside the solenoid.

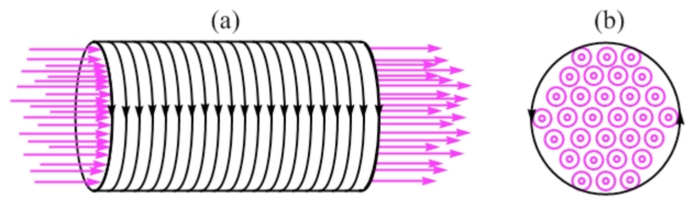

Figure 19.29: The magnetic field from an ideal (infinitely long) solenoid. A three-dimensional view is shown in (a), while (b) shows the field from the perspective of someone looking along the axis of the solenoid from the right.

Equation 19.12 applies to an ideal solenoid, of infinite length. Figure 19.30 shows that for a real solenoid, of finite length, the magnetic field is strongest in the center, and reduces in magnitude toward the ends as field lines leak out the sides of the solenoid. The field from a real solenoid has the same form as the field from a typical bar magnet. Like a disk magnet, the bar magnet can be modeled as a number of tiny current loops, all aligned, associated with the angular momentum of electrons in atoms. The net effect of these current loops is a current that circles the outside of the bar magnet, like the current in a solenoid.

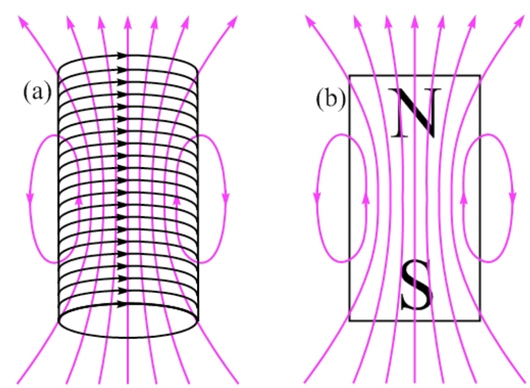

Figure 19.30: The magnetic field from a solenoid of finite length (a), has the same form as the field from a bar magnet (b).

The pictures in Figure 19.30 could be labeled (a) an electromagnet, and (b) a permanent magnet. In a permanent magnet, the magnetic field is always on. An electromagnet can be turned on or off as a current is turned on or off. An electromagnet made by connecting a coil of wire to a battery generally has a weak magnetic field. If a ferromagnetic core, like an iron nail, is placed in the coil, however, the magnetic field can be increased by a factor of several hundred. The core should consist of "soft" ferromagnetic material, as opposed to the "hard" material that permanent magnets are made from. In hard ferromagnetic materials, neighboring atoms remain aligned when an external magnetic field is removed. In soft materials, the alignment mostly disappears when the external field is removed, so the magnetic field turns off when the current turns off.

Related End-of-Chapter Exercises: 28, 29, 31, 32.

Essential Question 19.8: Starting at a point on the axis of a solenoid, which has 800 turns per meter, an electron is given an initial velocity of 500 m/s in a direction perpendicular to the axis. The electron takes 75 ns to go through a complete circle. What is the current in the solenoid?