

**Answer to Essential Question 20.4:** The induced current is directed up through the rod, while the external magnetic field is directed into the page. Make sure you look at the external magnetic field, and not the field from the induced current! Applying the right-hand rule that goes with the expression for magnetic force,  $F_M = ILB \sin\theta$ , we find that the rod experiences a magnetic force directed to the left. Because the velocity of the rod is directed to the right, the magnetic force tends to slow the rod down, decreasing the time rate of change of flux. The tendency of the induced current to oppose the change in flux is completely consistent with Lenz's law.

## 20-5 Eddy Currents

Thus far, in this chapter, we have discussed induced currents set up in conducting loops and coils, and in moving rods connected in a circuit, in response to a changing magnetic flux. Something similar happens in solid pieces of conductor, in which a changing magnetic flux gives rise to what are called eddy currents. The meaning of the word “eddy” in this case is the same as its meaning when you refer to an eddy in a river, which is a swirl of water.

**Eddy currents** are swirling currents that are set up in conductors that are exposed to a changing magnetic flux. Consistent with Lenz's law, these swirling currents create their own magnetic field that tends to oppose the original change in flux.

Eddy currents can arise when there is relative motion between a conductor and a magnet. The relative motion tends to change the flux in the conductor, so by Lenz's law the eddy currents produce a magnetic field that acts to slow the motion. Magnetic interactions in ferromagnetic materials (like iron or steel) are often dominated by the strong attraction between the magnet and the ferromagnetic material. The effects of eddy currents are generally easier to observe in non-ferromagnetic materials like aluminum and copper. Such materials interact weakly with magnets that are at rest with respect to them, but the effects of eddy currents in such materials, which involve a changing magnetic flux, often produced by relative motion, can be dramatic.

Some examples of eddy currents include:

- **Train brakes.** Turning on an electromagnet to create a magnetic field that passes through part of a train wheel causes the wheel, and the train, to slow as different areas of the wheel move into and out of the field (see Exploration 20.5).
- **Magnetic damping on a balance.** Like the system in Figure 20.24, many triple-beam balances have an aluminum plate located near a magnet, to damp out (steadily reduce) the oscillations of the balance so it settles down quickly for a reading.
- **Dropping a magnet down an aluminum or copper tube.** Try this if you can. It is fascinating to look down the tube and see the magnet fall, almost in slow motion, as the eddy currents in the tube wall slow the magnet's fall.

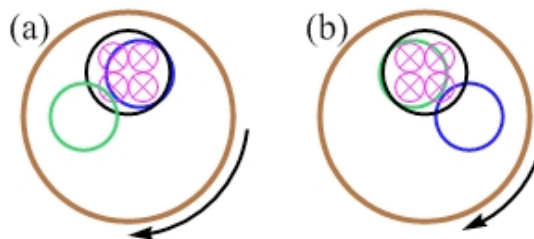


### EXPLORATION 20.5 – Using eddy currents to stop a train

Figure 20.25 shows the wheel of a train. When the driver of the train applies the brakes, an electromagnet sets up a magnetic field, directed into the page, which passes through a circular region (in black) at the top of the wheel. Eddy currents are set up in a part of the wheel (in green) that is entering the field, as well as in a part of the wheel (in blue) that is leaving the field.

**Figure 20.24:** A photograph of the two magnets (dark cylinders) used to damp out the oscillations of the aluminum plate that is part of an apparatus used in a Coulomb's law experiment. Photo credit: A. Duffy.

**Figure 20.25:** Two views of a train wheel exposed to a magnetic field at the top. The wheel is rotating clockwise. View (b) is at a later time than view (a), so the wheel is moving slower in (b).



**Step 1 – Apply the pictorial method to the region of the wheel moving into the field, to determine the direction of the eddy currents induced in this region by the changing flux.** This region is moving into the field, so the After picture shows more field lines passing through the region than the Before picture does (see Figure 20.26). The To Oppose picture shows a field line directed out of the page, opposing the change in flux. By the right-hand rule, the induced eddy currents in this region must swirl counterclockwise to create a field out of the page.



**Figure 20.26:** The pictorial method applied to the region that is entering the magnetic field.

**Step 2 – Consider the interaction between the eddy currents in the region moving into the field and the external magnetic field. Does this interaction give rise to a torque on the wheel? If so, in what direction is the torque?** Figure 20.27 shows a magnified view of the counterclockwise current interacting with the field. The right-hand part of the swirling current, directed up, is in the magnetic field. Applying the right-hand rule shows that there is a force directed to the left on this upward current. The left-hand part of the eddy current is outside the field, so there is no force on that part. The force to the left produces a counterclockwise torque on the wheel, relative to an axis through the wheel's center, acting to slow the wheel's clockwise motion.



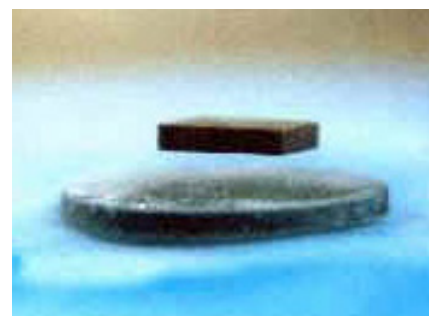
**Figure 20.27:** The magnetic force acting on the eddy current in the region moving into the field produces a torque that acts to slow down the wheel.

Note that we will consider the region moving out of the field in Essential Question 20.5.

**Key idea:** Eddy currents can give rise to forces or torques that tend to slow relative motion between a conductor and a magnet. **Related End-of-Chapter Exercises: 56 and 57.**

### Superconductors and the Meissner effect

One application of eddy currents is the levitation of a magnet above a superconductor, which is a material that has no electrical resistance. Superconductors generally exhibit zero resistance only at very low temperatures. The black disk at the bottom of Figure 20.28 is known as a high-temperature superconductor, because it has no resistance when it is cooled by liquid nitrogen, at a relatively high temperature (at least for superconductors!) of about 77 K (−196°C). When the magnet is brought close to the superconductor, the changing flux gives rise to eddy currents in the superconductor. The eddy currents, which can flow forever because there is no resistance, set up a magnetic field that exactly cancels the field from the magnet (this exclusion of magnetic field from the superconductor is known as the Meissner effect). The magnetic field from the eddy currents in the superconductor can support the magnet without the magnet and the superconductor being in contact.



**Figure 20.28:** A magnet being levitated by the magnetic field produced by eddy currents in a superconducting disk, which is cooled by liquid nitrogen. Photograph from <http://www.lbl.gov>

**Essential Question 20.5:** Repeat steps 1 and 2 of Exploration 20.5 for the region of the wheel (see Figure 20.25) that is leaving the region of magnetic field.