

**Figure 23.2** Physics, like this butterfly, has inherent symmetries. (credit: Thomas Bresson)

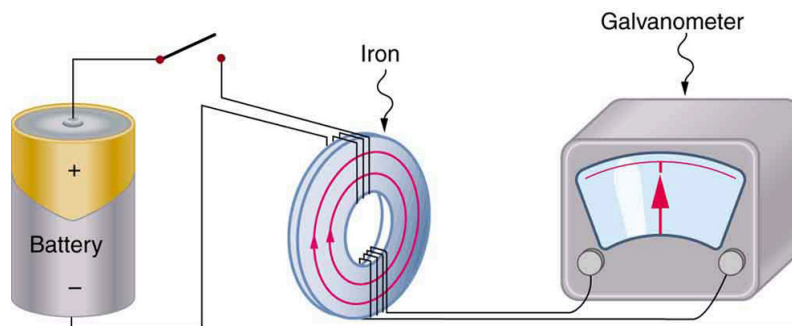
The hint of symmetry between electricity and magnetism found in the preceding chapter will be elaborated upon in this chapter. Specifically, we know that a current creates a magnetic field. If nature is symmetric here, then perhaps a magnetic field can create a current. The Hall effect is a voltage caused by a magnetic force. That voltage could drive a current. Historically, it was very shortly after Oersted discovered currents cause magnetic fields that other scientists asked the following question: Can magnetic fields cause currents? The answer was soon found by experiment to be yes. In 1831, some 12 years after Oersted's discovery, the English scientist Michael Faraday (1791–1862) and the American scientist Joseph Henry (1797–1878) independently demonstrated that magnetic fields can produce currents. The basic process of generating emfs (electromotive force) and, hence, currents with magnetic fields is known as **induction**; this process is also called magnetic induction to distinguish it from charging by induction, which utilizes the Coulomb force.

Today, currents induced by magnetic fields are essential to our technological society. The ubiquitous generator—found in automobiles, on bicycles, in nuclear power plants, and so on—uses magnetism to generate current. Other devices that use magnetism to induce currents include pickup coils in electric guitars, transformers of every size, certain microphones, airport security gates, and damping mechanisms on sensitive chemical balances. Not so familiar perhaps, but important nevertheless, is that the behavior of AC circuits depends strongly on the effect of magnetic fields on currents.

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## 23.1 Induced Emf and Magnetic Flux

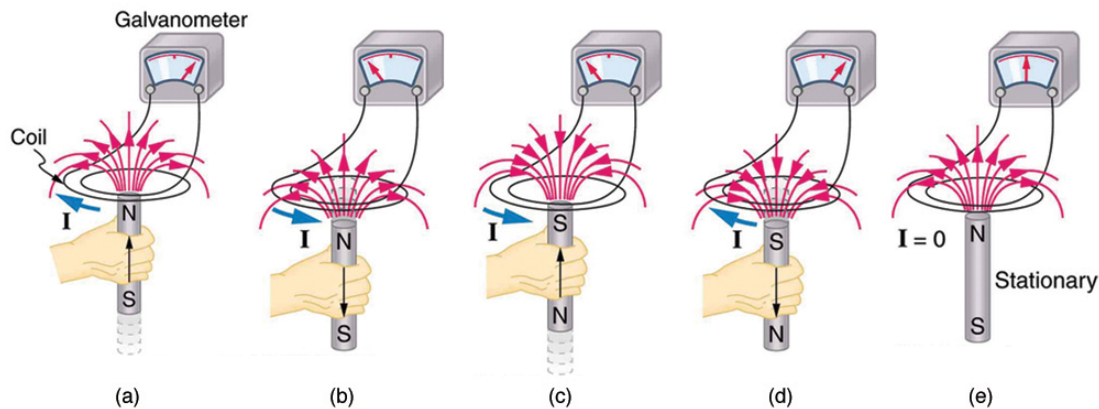
The apparatus used by Faraday to demonstrate that magnetic fields can create currents is illustrated in [Figure 23.3](#). When the switch is closed, a magnetic field is produced in the coil on the top part of the iron ring and transmitted to the coil on the bottom part of the ring. The galvanometer is used to detect any current induced in the coil on the bottom. It was found that each time the switch is closed, the galvanometer detects a current in one direction in the coil on the bottom. (You can also observe this in a physics lab.) Each time the switch is opened, the galvanometer detects a current in the opposite direction. Interestingly, if the switch remains closed or open for any length of time, there is no current through the galvanometer. *Closing and opening the switch* induces the current. It is the *change* in magnetic field that creates the current. More basic than the current that flows is the *emf* that causes it. The current is a result of an *emf induced by a changing magnetic field*, whether or not there is a path for current to flow.



**Figure 23.3** Faraday's apparatus for demonstrating that a magnetic field can produce a current. A change in the field produced by the top coil induces an emf and, hence, a current in the bottom coil. When the switch is opened and closed, the galvanometer registers currents in opposite directions. No current flows through the galvanometer when the switch remains closed or open.

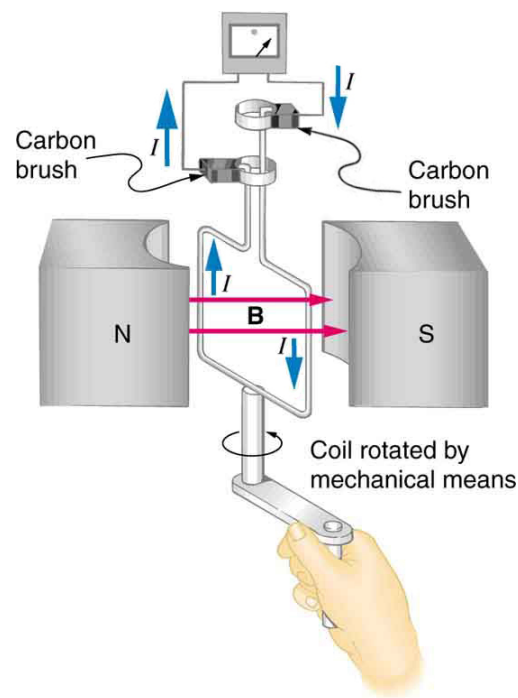
An experiment easily performed and often done in physics labs is illustrated in [Figure 23.4](#). An emf is induced in the coil when a

bar magnet is pushed in and out of it. Emfs of opposite signs are produced by motion in opposite directions, and the emfs are also reversed by reversing poles. The same results are produced if the coil is moved rather than the magnet—it is the relative motion that is important. The faster the motion, the greater the emf, and there is no emf when the magnet is stationary relative to the coil.



**Figure 23.4** Movement of a magnet relative to a coil produces emfs as shown. The same emfs are produced if the coil is moved relative to the magnet. The greater the speed, the greater the magnitude of the emf, and the emf is zero when there is no motion.

The method of inducing an emf used in most electric generators is shown in [Figure 23.5](#). A coil is rotated in a magnetic field, producing an alternating current emf, which depends on rotation rate and other factors that will be explored in later sections. Note that the generator is remarkably similar in construction to a motor (another symmetry).



**Figure 23.5** Rotation of a coil in a magnetic field produces an emf. This is the basic construction of a generator, where work done to turn the coil is converted to electric energy. Note the generator is very similar in construction to a motor.

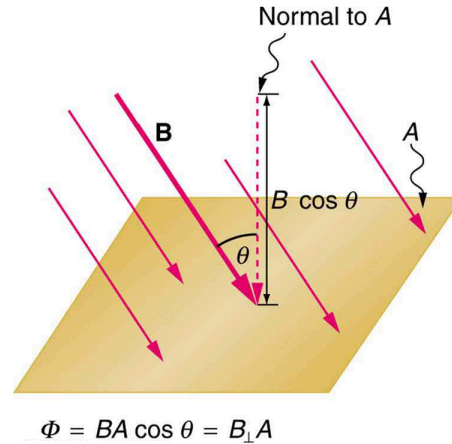
So we see that changing the magnitude or direction of a magnetic field produces an emf. Experiments revealed that there is a crucial quantity called the **magnetic flux**,  $\Phi$ , given by

$$\Phi = BA \cos \theta,$$

23.1

where  $B$  is the magnetic field strength over an area  $A$ , at an angle  $\theta$  with the perpendicular to the area as shown in [Figure 23.6](#). **Any change in magnetic flux  $\Phi$  induces an emf.** This process is defined to be **electromagnetic induction**. Units of magnetic flux  $\Phi$  are  $\text{T} \cdot \text{m}^2$ . As seen in [Figure 23.6](#),  $B \cos \theta = B_{\perp}$ , which is the component of  $B$  perpendicular to the area  $A$ . Thus magnetic

flux is  $\Phi = B_{\perp}A$ , the product of the area and the component of the magnetic field perpendicular to it.



**Figure 23.6** Magnetic flux  $\Phi$  is related to the magnetic field and the area over which it exists. The flux  $\Phi = BA \cos \theta$  is related to induction; any change in  $\Phi$  induces an emf.

All induction, including the examples given so far, arises from some change in magnetic flux  $\Phi$ . For example, Faraday changed  $B$  and hence  $\Phi$  when opening and closing the switch in his apparatus (shown in [Figure 23.3](#)). This is also true for the bar magnet and coil shown in [Figure 23.4](#). When rotating the coil of a generator, the angle  $\theta$  and, hence,  $\Phi$  is changed. Just how great an emf and what direction it takes depend on the change in  $\Phi$  and how rapidly the change is made, as examined in the next section.

## 23.2 Faraday's Law of Induction: Lenz's Law

### Faraday's and Lenz's Law

Faraday's experiments showed that the emf induced by a change in magnetic flux depends on only a few factors. First, emf is directly proportional to the change in flux  $\Delta\Phi$ . Second, emf is greatest when the change in time  $\Delta t$  is smallest—that is, emf is inversely proportional to  $\Delta t$ . Finally, if a coil has  $N$  turns, an emf will be produced that is  $N$  times greater than for a single coil, so that emf is directly proportional to  $N$ . The equation for the emf induced by a change in magnetic flux is

$$\text{emf} = -N \frac{\Delta\Phi}{\Delta t}. \quad \boxed{23.2}$$

This relationship is known as **Faraday's law of induction**. The units for emf are volts, as is usual.

The minus sign in Faraday's law of induction is very important. The minus means that *the emf creates a current  $I$  and magnetic field  $B$  that oppose the change in flux  $\Delta\Phi$* —this is known as *Lenz's law*. The direction (given by the minus sign) of the emf is so important that it is called **Lenz's law** after the Russian Heinrich Lenz (1804–1865), who, like Faraday and Henry, independently investigated aspects of induction. Faraday was aware of the direction, but Lenz stated it so clearly that he is credited for its discovery. (See [Figure 23.7](#).)