Figure 20.29: The pictorial method applied to the region that is leaving the magnetic field.

Answer to Essential Question 20.5: For the region that is moving out of the field, the After picture shows fewer field lines passing through the region than the Before picture does (see Figure 20.29). The To Oppose picture shows a field line directed into the page, opposing the change in flux. By the right-hand rule, the induced eddy currents in this region must swirl clockwise to create a field into the page.

Figure 20.30 shows a magnified view of the clockwise current interacting with the field. The left-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 right-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. Note that no matter which region we consider, one entering the field or one leaving the field, the torque always acts to slow the wheel.
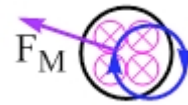

Figure 20.30: The magnetic force acting on the eddy current in the region leaving the field produces a torque that acts to slow down the wheel.

20-6 Electric Generators

Faraday's Law, and the induced emf and induced current associated with it, is one of the most practical ideas in physics — it lies at the heart of most devices that generate electricity. The basic components that make up an electric generator are quite simple. All we need is a conducting loop exposed to a changing magnetic flux.

In section 19-6, we spent some time investigating a DC motor, which is a conducting loop in a magnetic field. When current is sent through the loop, the magnetic field exerts a torque on the loop that makes the loop spin, transforming electrical energy into mechanical energy. An electric generator does exactly the opposite, transforming mechanical energy into electrical energy. We can use the same device, a loop in a magnetic field, as a motor or a generator.
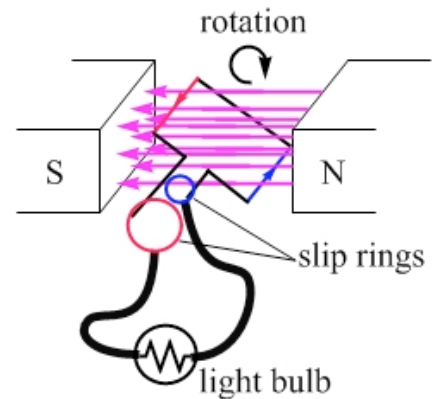
As the loop in Figure 20.31 rotates, the magnetic flux through the loop changes, giving rise to an induced emf. If we completed the circuit by connecting the ends of the loop directly to an electrical device, like a light bulb, the induced emf gives rise to an induced current that lights the bulb, but the wires would twist, either stopping the loop or breaking the wires. One solution to this problem is to have the wires coming from each side of the loop rub against the inside of fixed slip rings, which are then connected to the bulb. Each wire maintains electrical contact with one slip ring as the loop rotates.

Figure 20.31: The basic components of an electric generator are a conducting loop and a magnetic field. Rotating the loop changes the magnetic flux through the loop, giving rise to an induced emf.

Another solution to this problem, which is used in some electricity generating plants, is to keep the loop fixed and spin the magnets around the loop. This has the same effect as spinning the loop through the magnetic field.

EXPLORATION 20.6 – The form of the electric signal from a generator
Step 1 – *The loop in Figure 20.31 rotates at a constant angular speed* ω*. Plot graphs of the flux through the loop, and the corresponding induced emf, as a function of time. Define the positive direction such that the flux at t = 0 is positive. Plot a second set of graphs to show what happens when the rotation rate doubles.* As the loop rotates, the magnetic flux oscillates. We can understand the cosine dependence of the flux graph, shown at the top in Figure 20.32, by starting with the equation for magnetic flux, $\Phi = BA\cos\theta$. *B*, the magnetic field, and *A*, the area of the loop, are constant, but θ changes. Using a relationship from rotational kinematics, the angle between the field and the loop's area vector is given by $\theta = \omega t$. This gives the flux equation a form which shows the time dependence, and the cosine nature, explicitly: $\Phi(t) = BA\cos(\omega t)$.

The induced emf is proportional to the negative of the slope of the flux versus time graph. Thus, the emf is zero when the flux graph reaches a positive or negative peak. When the flux is decreasing, the flux graph has a negative slope, so the induced emf is positive. The emf peaks when the flux passes through zero, and the flux graph has a large slope.

If the rotation rate increases, the maximum flux does not change but the flux changes in half the time, doubling the slope on the flux graph. This produces a corresponding doubling in the peak emf. Thus, the peak emf is proportional to the angular speed of the magnets.
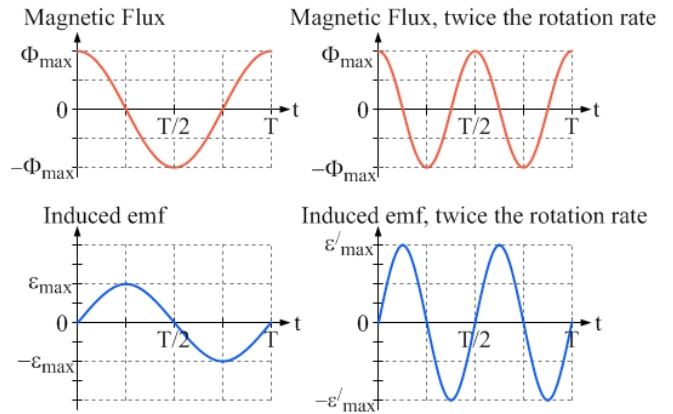
Figure 20.32: For the magnetic flux and induced emf graphs on the right, the rotation rate is twice as large as in the graphs on the left.

Step 2 – *Combine Faraday's Law with results from step 1 to find an expression for the emf induced in the loop as a function of time.* If the loop has *N* turns, applying Faraday's Law gives:

$\varepsilon = -N\dfrac{\Delta\Phi}{\Delta t} = -N\dfrac{\Delta\big[BA\cos(\omega t)\big]}{\Delta t}$, where we have used the flux expression from step 1.

The field and area are constants, so they can be moved out front: $\varepsilon = -NBA\dfrac{\Delta\big[\cos(\omega t)\big]}{\Delta t}$.

Simplifying, we get: $\varepsilon = \omega NBA\,\sin(\omega t)$. This last step is easy to show using calculus. However, we saw both the sine dependence, and the fact that the induced emf is proportional to the angular speed, in step 1, so we can be confident in the result even without using calculus.

Key idea: As a function of time, the emf of an electric generator, in which either the loop or the magnetic field spins at a constant angular velocity $\bar{\omega}$, oscillates sinusoidally. In other words, the electric generator puts out alternating current. Expressed as an equation, the emf is:
   $\varepsilon = \omega NBA\sin(\omega t) = \varepsilon_{max}\sin(\omega t)$.   (Equation 20.4: **emf from an electric generator**)

The peak voltage, ε_{max}, is the product of ω, *N* (the number of turns in the loop), *B* (the strength of the magnetic field), and *A* (the loop area).   **Related End-of-Chapter Exercises: 31 – 34.**

Essential Question 20.6: For generators in North America, which provide 60 Hz AC for a standard wall socket, what is ω , the magnitude of the angular velocity of the rotation?