

Answer to Essential Question 20.3: For loops 2 and 3, which are leaving the field, the magnetic flux into the page decreases as the fraction of the loop that is inside the field decreases. The pictorial method for loop 2 is shown in Figure 20.18. The To Oppose picture shows the field directed into the page, opposing the decrease in flux from Before to After, which requires an induced current directed clockwise. Similarly, loop 3 has a clockwise current.

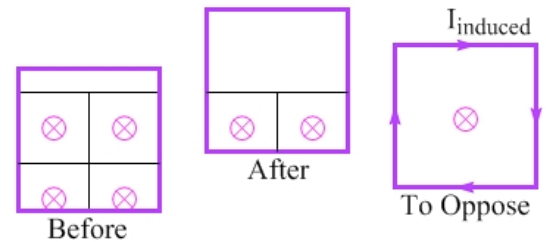


Figure 20.18: The pictorial method for loop 2, which tells us that loop 2 has an induced current that is directed clockwise.

For loops 1 and 4, which are entering the field, the Before and After pictures from Figure 20.18 switch positions. This gives a To Oppose picture with a magnetic field directed out of the page, requiring a counterclockwise current.

20-4 Motional emf

In each of the loops in Figure 20.17, the induced emf is associated with only one side of the rectangle, the side completely in the field, aligned perpendicular to the loop's velocity. Let's address this emf from another perspective.

EXPLORATION 20.4 – A metal rod moving through a magnetic field

As shown in Figure 20.19, a metal rod of length L is moving with a velocity $\vec{v}$ through a uniform magnetic field of magnitude B .

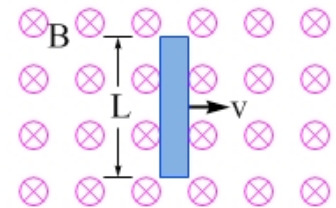


Figure 20.19: A metal rod moving through a magnetic field.

Step 1 – The rod has no net charge, but conduction electrons within the rod are free to move. First, assume that these electrons are moving through the field with the velocity of the rod. Apply the right-hand rule to determine the direction of the force these electrons experience. Hold the right hand above the page with the palm down and the fingers pointing to the right, in the direction of the velocity. When we curl the fingers they curl into the page, in the direction of the magnetic field. The thumb points up the page, showing the direction of the magnetic force on particles with positive charge. Electrons, which are negatively charged, experience a force in the opposite direction, down the page, leaving a net positive charge at the upper end of the rod. As shown in Figure 20.20, the moving rod acts like a battery.

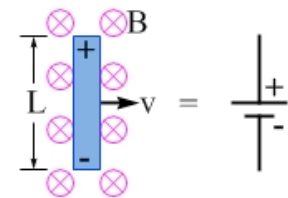
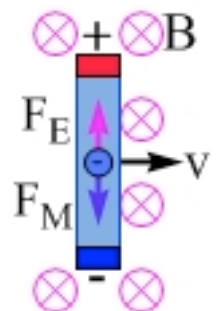


Figure 20.20: A conducting rod moving in a magnetic field acts like a battery, because of the separation of charge from the magnetic force acting on the rod's conduction electrons.

Step 2 –Determine the effective emf of the rod. As the rod becomes polarized, an electric field is set up in the rod. Show that the electric field gives rise to an electric force that is opposite to the magnetic force. Equate these two forces and, by treating the rod as a parallel-plate capacitor, determine the potential difference between the ends of the rod. The upper end of the rod is positive, so the electric field within the rod is directed down. An electron in the rod experiences an electric force that is opposite in direction to this electric field, because $\vec{F}_E = q\vec{E}$, and the charge on the electron is negative. Thus, electrons in the rod experience two forces, an electric force directed up and a magnetic force directed down. An equilibrium charge distribution is reached when these two forces balance, as shown in Figure 20.21.

Figure 20.21: Equilibrium is reached when the electric force balances the magnetic force.



The magnetic force balances the electric force, so $qvB = qE$. The factors of q cancel, leaving $vB = E$. Treating the rod as a parallel-plate capacitor, the potential difference between the ends of the rod is $\Delta V = EL$. Solving for this potential difference, which we generally call a motional emf, ε , gives:

$$\Delta V = \varepsilon = -vBL. \quad (\text{Equation 20.3: Motional emf})$$

The minus sign indicates that Lenz's law applies, and that the emf tends to produce a current that opposes any change in magnetic flux. Note that equation 20.3 applies when the rod, its velocity, and the direction of the magnetic field are all mutually perpendicular.

Key ideas for motional emf: A conductor moving with a velocity $\vec{v}$ through a magnetic field $\vec{B}$ has an induced emf across it given by $\varepsilon = -vBL$, where L is the length of the conductor that is perpendicular to both $\vec{v}$ and $\vec{B}$. The moving conductor thus acts like a battery.

Related End-of-Chapter Exercises: 9, 10, 28.

EXAMPLE 20.4 – Using a moving rod as a battery

Let's investigate what happens when we use the rod like a battery. We will connect the moving rod from Exploration 20.4 in a simple series circuit, by placing the rod on a pair of parallel conducting rails, as shown in Figure 20.22. The rod moves with negligible friction on the rails, which themselves have negligible resistance but are connected by resistor of resistance R . (a) If the rod moves to the right with a speed v in a field of magnitude B directed into the page, find an expression for the magnitude of the induced current. (b) Use the pictorial method from section 20-3 to find the direction of this current.

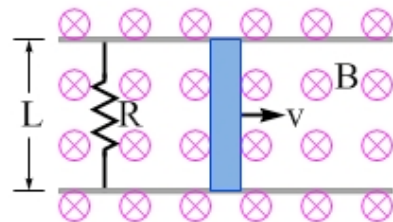


Figure 20.22: The system consisting of a conducting rod on frictionless rails. The rails are connected to one another through a resistor, and the rod moves through a magnetic field that is directed into the page.

SOLUTION

(a) In this situation we combine the equation for motional emf, $\varepsilon = -vBL$, with Ohm's law, $I = \Delta V / R$, to find that the induced current has a magnitude of:

$$I = vBL / R, \text{ matching the result from Example 20.3.}$$

(b) As the rod moves to the right, the area of the conducting loop increases. Compared to the Before picture, the After picture shows the rod farther right, with more field lines passing through because the area of the loop has increased. As seen in Figure 20.23, the To Oppose picture shows field directed out of the page, opposing the extra into-the-page field lines in the After picture. To create a field out of the page, the induced current must be directed counterclockwise around the loop.

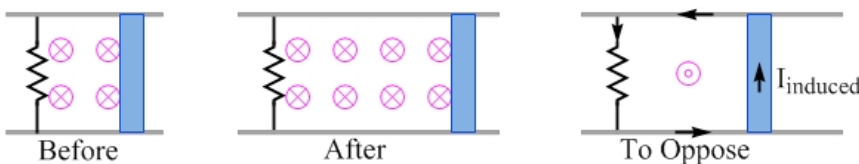


Figure 20.23: Applying the pictorial method to determine the direction of the induced current in the circuit.

Related End-of-Chapter Exercises: 29, 30, 53, and 55.

Essential Question 20.4: The moving rod in Example 20.4 experiences a magnetic force because of the interaction between the external magnetic field and the induced current passing through the rod. In what direction is this magnetic force? How is this direction consistent with Lenz's law?