Lecture 6

Chapter 20 Induced voltage and inductance

You may ignore

* 20.4, 20.6, and 20.7

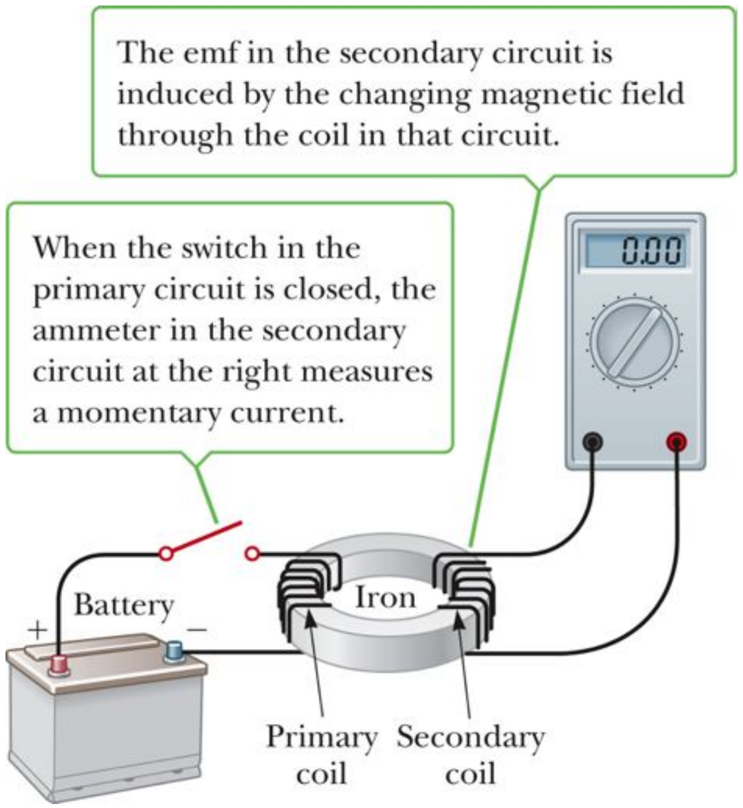
Connections Between Electricity and Magnetism

- 1819
  - Hans Christian Oersted discovered an electric current exerts a force on a magnetic compass.
  - First evidence of a link between electricity and magnetism
- 1831
  - Faraday and Henry showed a changing magnetic field could induce an electric current in a circuit.
  - Led to Faraday's Law

This will result in electricity generation and the modern world

Faraday's Experiment – Set Up

- A current can be produced by a changing magnetic field.
  - First shown in an experiment by Michael Faraday
    - A primary coil is connected to a battery.
    - A secondary coil is connected to an ammeter.



Faraday's Experiment

- There is no battery in the secondary circuit.
- When the switch is closed, the ammeter reads a current and then returns to zero.
- When the switch is opened, the ammeter reads a current in the opposite direction and then returns to zero.
- When there is a steady current in the primary circuit, the ammeter reads zero.

Faraday's Conclusions

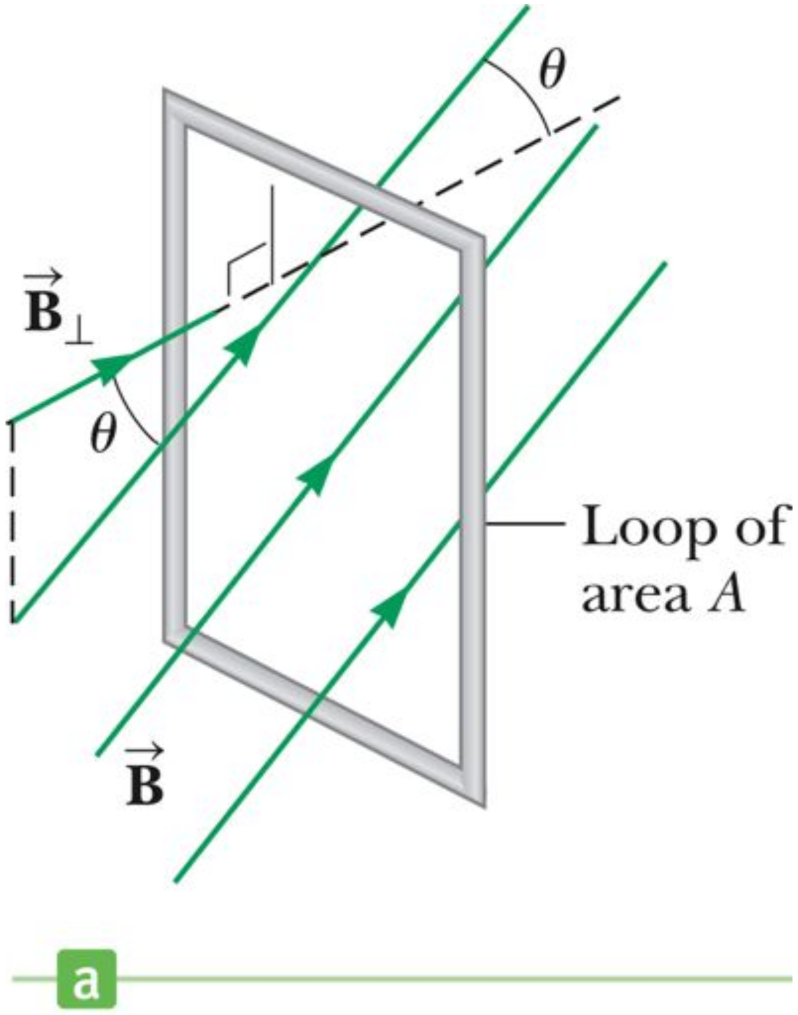
- An electrical current is produced by a *changing* magnetic field.
- The secondary circuit acts as if a source of emf were connected to it for a short time.
- It is customary to say that *an induced emf is produced in the secondary circuit by the changing magnetic field.*

Magnetic Flux

- The emf is actually induced by a change in the quantity called the *magnetic flux* rather than simply by a change in the magnetic field.
- Magnetic flux is defined in a manner similar to that of electrical flux.
- Magnetic flux is proportional to both the strength of the magnetic field passing through the plane of a loop of wire and the area of the loop.

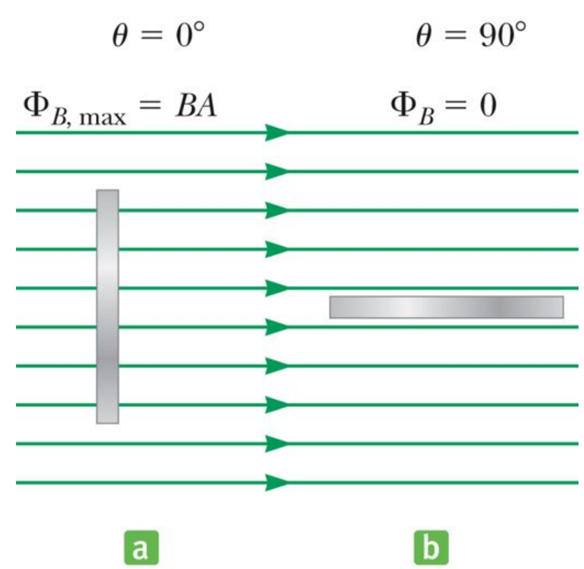
Magnetic Flux, 2

- You are given a loop of wire.
- The wire is in a uniform magnetic field.
- The loop has an area A.
- The flux is defined as
  - $\Phi_B = B_\perp A = B\ A \cos\theta$
    - θ is the angle between B and the normal to the plan
- SI unit: weber (Wb)
  - $Wb = T \cdot m^2$



Section 20.1

Magnetic Flux, 3



- When the field is perpendicular to the plane of the loop, as in a, θ = 0 and $\Phi_B = \Phi_{B,\,max} = BA$
- When the field is parallel to the plane of the loop, as in b, θ = 90° and $\Phi_B = 0$
  - The flux can be negative, for example if θ = 180°

Section 20.1

HW #2

Magnetic Flux, Final

- The flux can be visualized with respect to magnetic field lines.
  - **The value of the magnetic flux is proportional to the total number of lines passing through the loop.**
- When the area is perpendicular to the lines, the maximum number of lines pass through the area and the flux is a maximum.
- When the area is parallel to the lines, no lines pass through the area and the flux is 0.

A uniform 4.5-T magnetic field passes perpendicularly through the plane of a wire loop 0.10 m^2 in area. What flux passes through the loop?

a.5.0 Tm^2

b.0.45 Tm^2

c.0.25 Tm^2

d.0.135 Tm^2

Nature abhors a change in flux

* A changing flux will generate a current in a conductor which in turn generates a magnetic field which opposes the change in flux

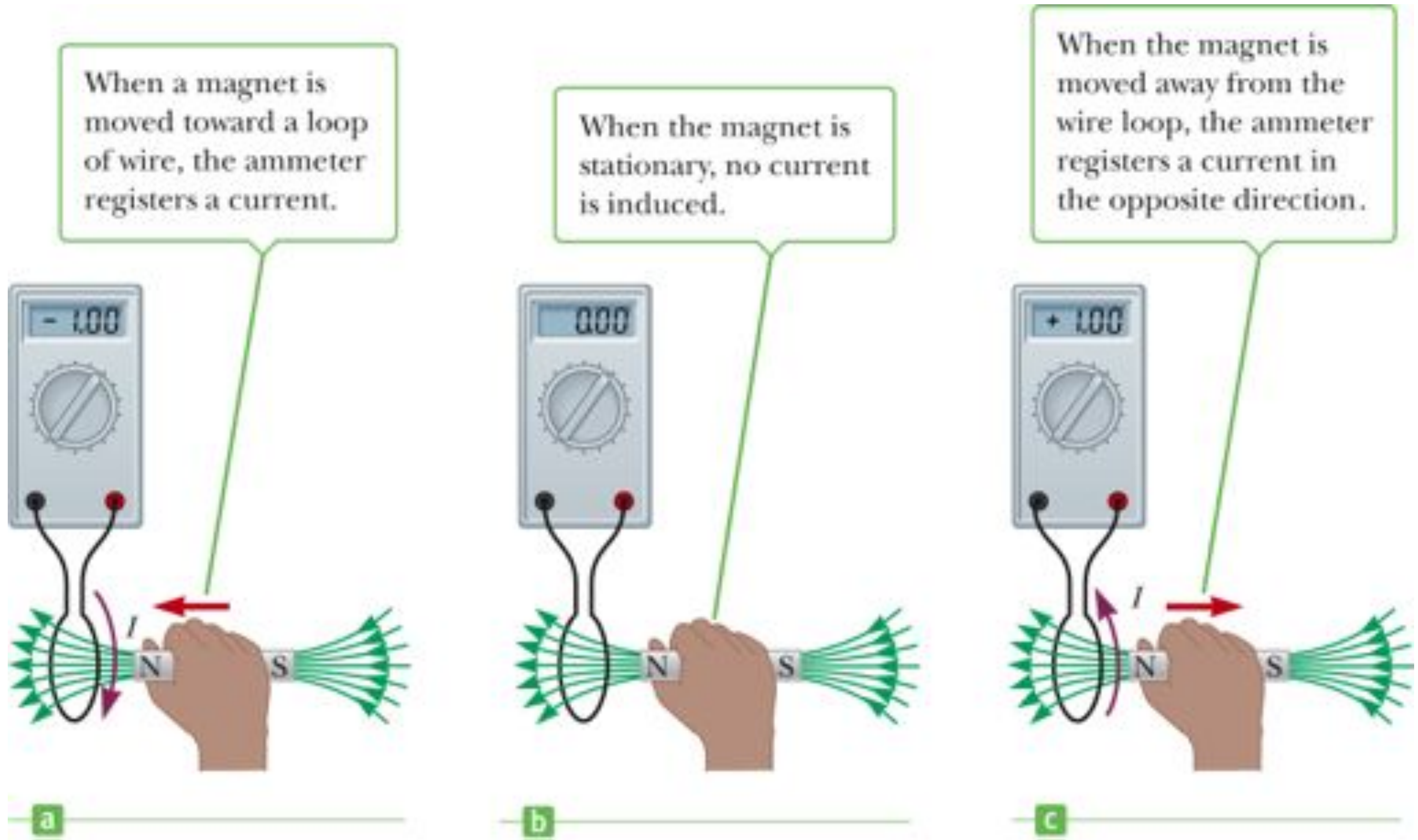


Fig. 20-4, p. 692

In A you are increasing the flux, in C you are decreasing it

Electromagnetic Induction – Results of the Experiment

- A current is set up in the circuit as long as there is *relative motion* between the magnet and the loop.
  - The same experimental results are found whether the loop moves or the magnet moves.
- The current is called an *induced current* because is it produced by an induced emf.

Faraday's Law and Electromagnetic Induction

- The instantaneous emf induced in a circuit equals the negative time rate of change of magnetic flux through the circuit.
- If a circuit contains N tightly wound loops and the flux changes by $\Delta\Phi_B$ during a time interval Δt, the average emf induced is given by *Faraday's Law:*

$$\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$$

Section 20.2

A sensitive ammeter is connected to a wire loop and placed within the magnetic field of a strong horseshoe magnet. The ammeter shows a deflection when:
a.the wire is moved parallel to the field.
b.the wire is moved perpendicularly to the field.
c.neither wire nor magnet is moving.
d.The wire's axis is parallel to the field.

A square coil, enclosing an area with sides 2.0 cm long, is wrapped with 2 500 turns of wire. A uniform magnetic field perpendicular to its plane is turned on and increases to 0.25 T during an interval of 1.0 s. What average voltage is induced in the coil?
a.0.25 V
b.0.12 V
c.2.0 V
d.2.5 V

A 10-turn square coil of area 0.036 m^2 and a 20-turn circular coil are both placed perpendicular to the same changing magnetic field. The voltage induced in each of the coils is the same. What is the area of the circular coil?
a.0.072 m^2
b.0.60 m^2
c.0.018 m^2
d.0.036 m^2

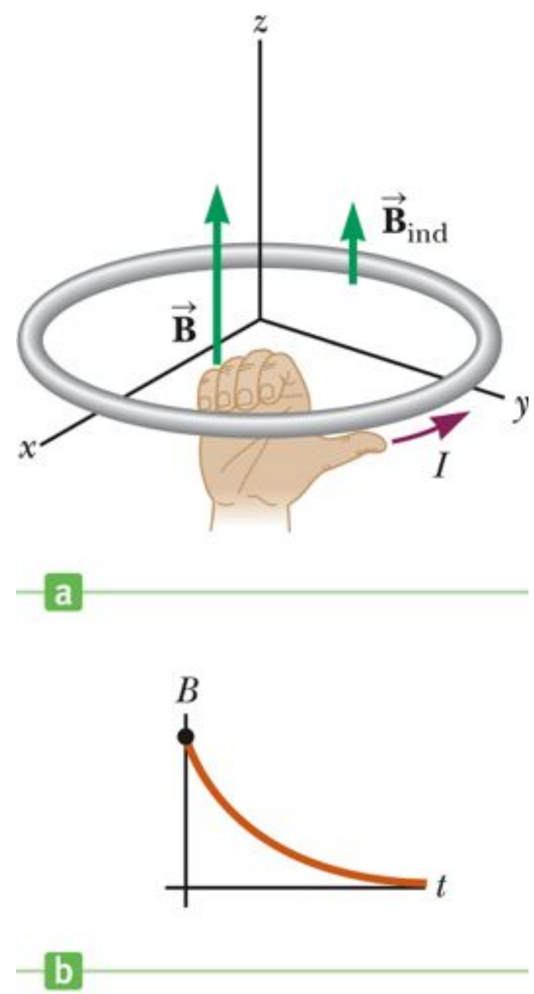
There is another way to change the flux.
What is it?

Faraday's Law and Lenz' Law

- The change in the flux, $\Delta\Phi_B$, can be produced by a change in B, A or θ
  - Since $\Phi_B = B\,A\cos\theta$
- The negative sign in Faraday's Law is included to indicate the polarity of the induced emf, which is found by *Lenz' Law.*
  - The current caused by the induced emf travels in the direction that creates a magnetic field with flux opposing the change in the original flux through the circuit.

Lenz' Law – Example

- The magnetic field, $\vec{\mathbf{B}}$, becomes smaller with time.
  - This reduces the flux.
- The induced current will produce an induced field, $\vec{\mathbf{B}}_{ind}$, in the same direction as the original field.



Section 20.2

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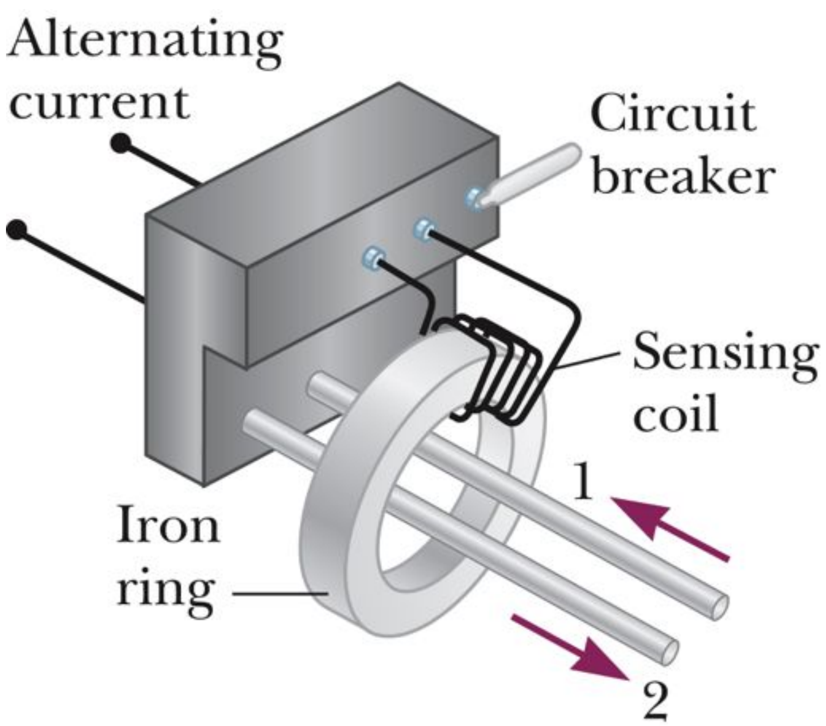
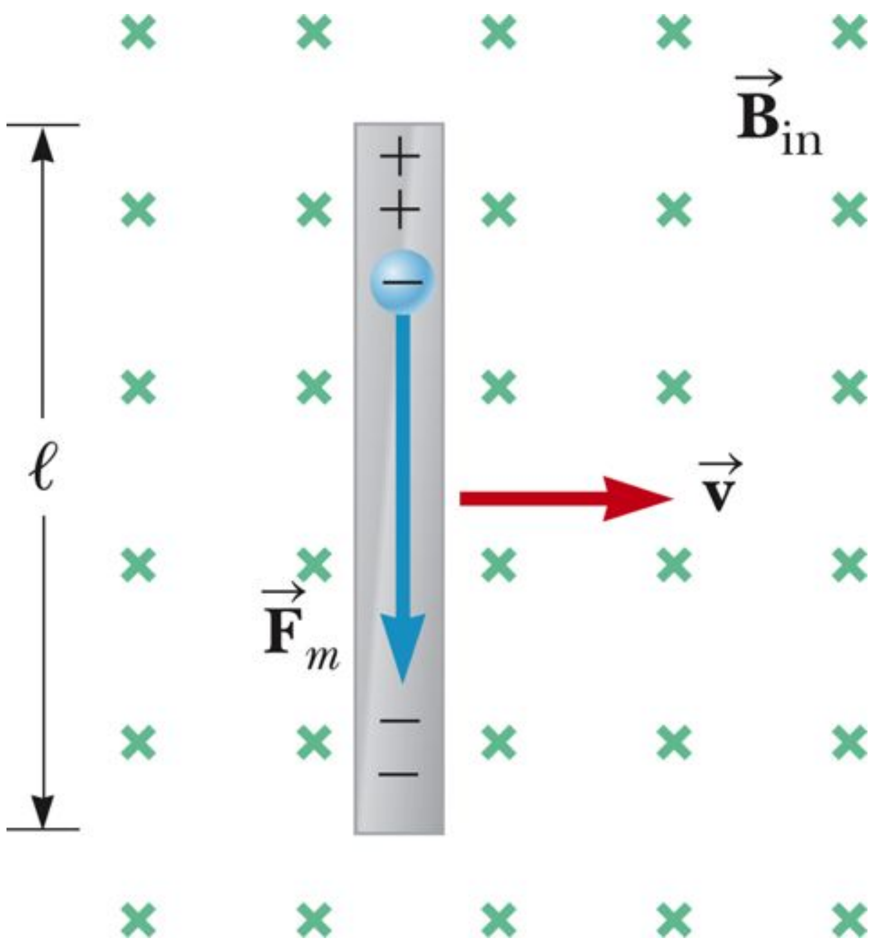
Applications of Faraday's Law – Ground Fault Interrupters

- The ground fault interrupter (GFI) is a safety device that protects against electrical shock.
  - Wire 1 leads from the wall outlet to the appliance.
  - Wire 2 leads from the appliance back to the wall outlet.
  - The iron ring confines the magnetic field, which is generally 0.
  - If a leakage occurs, the field is no longer 0 and the induced voltage triggers a circuit breaker shutting off the current.



Application of Faraday's Law – Motional emf

- A straight conductor of length ℓ moves perpendicularly with constant velocity through a uniform field.
- The electrons in the conductor experience a magnetic force.
  - F = q v B
- The electrons tend to move to the lower end of the conductor.

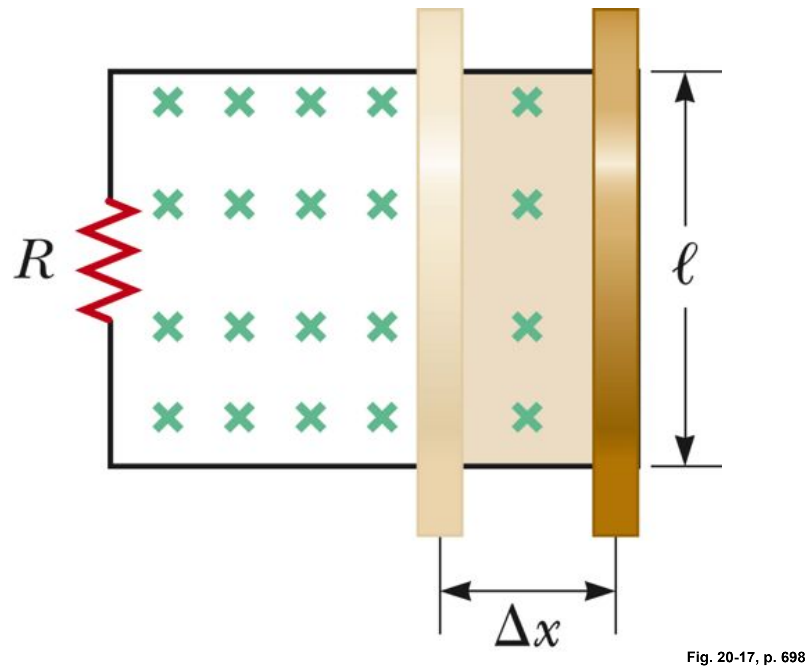


Motional emf

- As the negative charges accumulate at the base, a net positive charge exists at the upper end of the conductor.
- As a result of this charge separation, an electric field is produced in the conductor.
- Charges build up at the ends of the conductor until the downward magnetic force is balanced by the upward electric force.
- There is a potential difference between the upper and lower ends of the conductor.

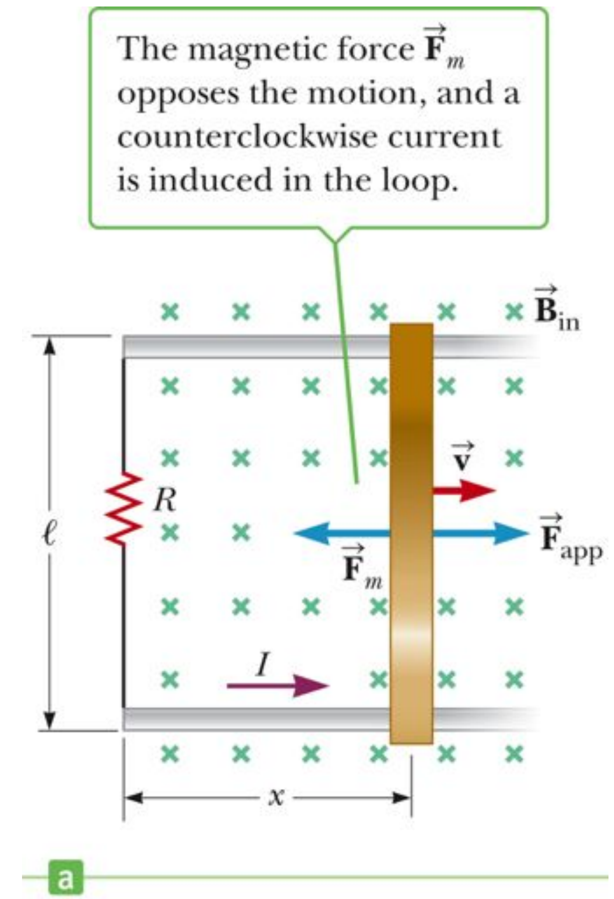
Motional emf, Cont.

- The potential difference between the ends of the conductor can be found by
  - $\Delta V = E\,l = B\,\ell\,v$
  - The upper end is at a higher potential than the lower end
- A potential difference is maintained across the conductor as long as there is motion through the field.
  - If the motion is reversed, the polarity of the potential difference is also reversed.



Motional emf in a Circuit

- Assume the moving bar has zero resistance.
- As the bar is pulled to the right with a given velocity under the influence of an applied force, the free charges experience a magnetic force along the length of the bar.
- This force sets up an induced current because the charges are free to move in the closed path.



Section 20.3

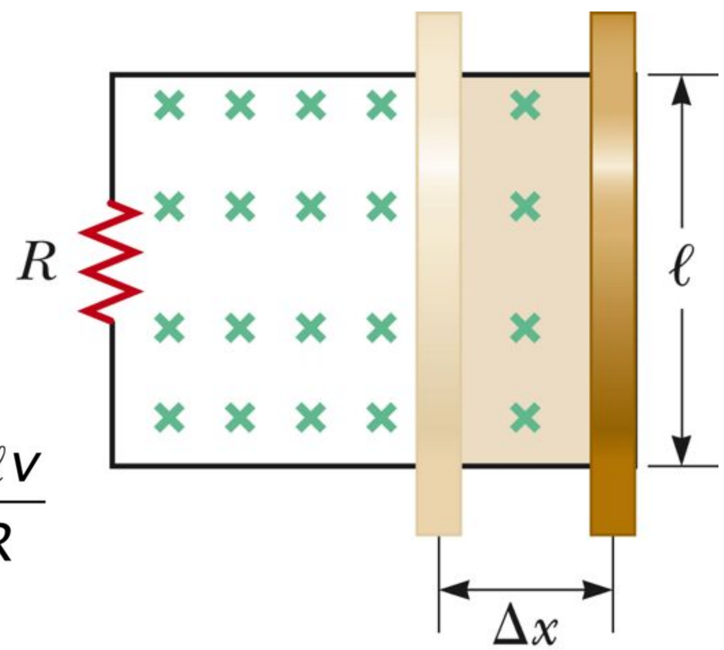
As the bar is pulled to the right there is a charge separation in the bar

This gives rise to a vertical velocity of the protons in the bar leading to a force to the left

Motional emf in a Circuit, Cont.

- The changing magnetic flux through the loop and the corresponding induced emf in the bar result from the *change in area* of the loop.
- The induced, motional, emf acts like a battery in the circuit.

$$|\varepsilon| = B\ell v \text{ and } I = \frac{B\ell v}{R}$$



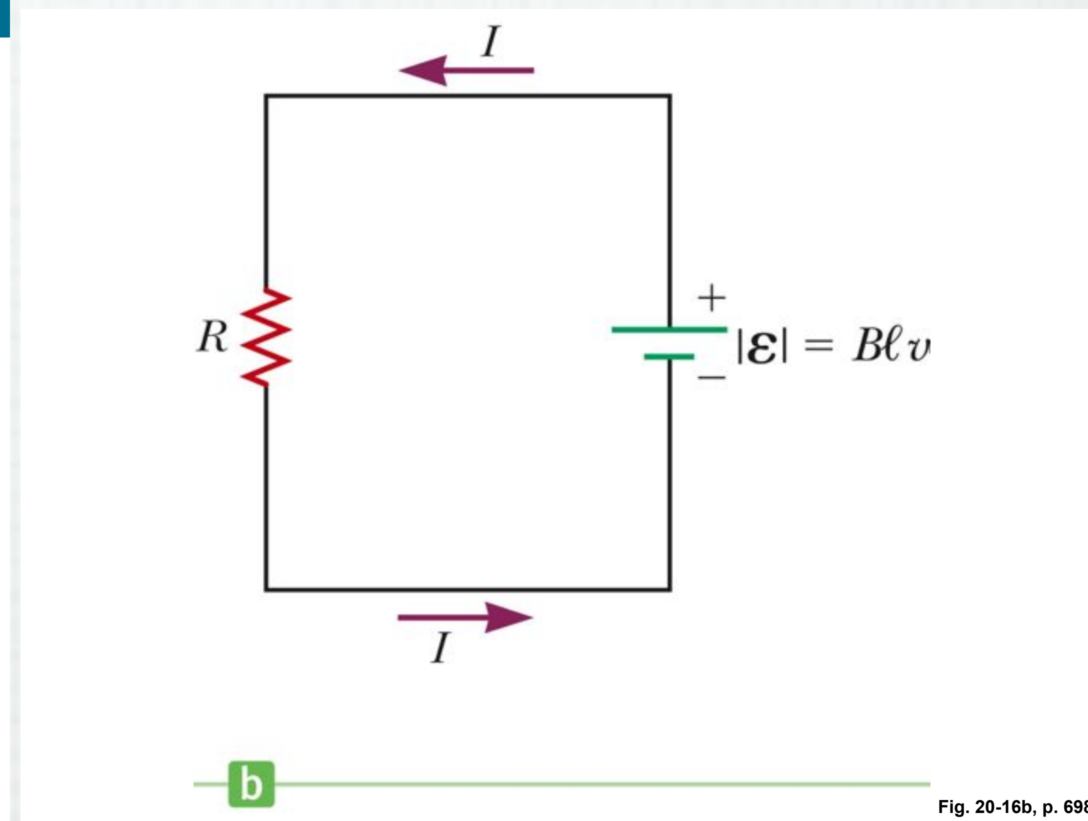


Fig. 20-16b, p. 698

* Hw 24
* Example 20.4

A straight wire of length is oriented east-west and is in a magnetic field B pointing north. The wire is moving downward at a constant speed v. Which end of the rod is positively charged?
a.neither
b.the east end
c.the west end
d.both ends

An airplane with a wingspan of 60.0 m flies parallel to the Earth's surface at a point where the downward component of the Earth's magnetic field is 0.400×10^{-4} T. If the induced potential between wingtips is 0.900 V, what is the plane's speed?
a.250 m/s
b.338 m/s
c.375 m/s
d.417 m/s

A large jetliner with a wingspan of 40 m flies horizontally and due north at a speed of 300 m/s in a region where the magnetic field of the earth is 60 μT directed 50° below the horizontal. What is the magnitude of the induced emf between the ends of the wing?
a.250 mV
b.350 mV
c.550 mV
d.750 mV

Generators

- Alternating Current (AC) generator
  - Converts mechanical energy to electrical energy
  - Consists of a wire loop rotated by some external means
  - There are a variety of sources that can supply the energy to rotate the loop.
    - These may include falling water, heat by burning coal to produce steam

Motors

- Motors are devices that convert electrical energy into mechanical energy.
  - A motor is a generator run in reverse.
- A motor can perform useful mechanical work when a shaft connected to its rotating coil is attached to some external device.

Self-inductance

- *Self-inductance* occurs when the changing flux through a circuit arises from the circuit itself.
  - As the current increases, the magnetic flux through a loop due to this current also increases.
  - The increasing flux induces an emf that opposes the change in magnetic flux.
  - As the magnitude of the current increases, the rate of increase lessens and the induced emf decreases.
  - This decreasing emf results in a gradual increase of the current.

Self-inductance, Cont.

- The self-induced emf must be proportional to the time rate of change of the current.

$$\varepsilon = -L\frac{\Delta I}{\Delta t}$$

  - L is a proportionality constant called the **inductance** of the device.
  - The negative sign indicates that a changing current induces an emf in opposition to that change.

Self-inductance, Final

- The inductance of a coil depends on geometric factors.
- The SI unit of self-inductance is the *Henry*
  - 1 H = 1 (V · s) / A
- You can determine an expression for L

$$L = N\frac{\Delta\Phi_B}{\Delta I} = \frac{N\Phi_B}{I}$$

Section 20.5

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The current in a coil with a self-inductance of 1.5 mH increases from 0 to 1.0 A in a tenth of a second. What is the induced emf in the coil?

a.15 mV
b.30 mV
c.0.10 V
d.0.30 V

What is the self-inductance in a coil that experiences a 3.0-V induced emf when the current is changing at a rate of 110 A/s?

a.83 mH
b.45 mH
c.37 mH
d.27 mH

Key Concepts

* Nature abhors a change in flux
* Motional emfs - charges separate in a moving conductor setting up a potential difference
* Law of induction - a changing flux sets up a potential difference
* Self induction - turning on a current generates a flux of field that opposes the change in current

Key Equations

$$\Phi_B = BAcos\theta$$

$$\epsilon = -N\frac{\Delta\Phi_B}{\Delta t}$$

$$|\epsilon| = Blv$$

$$\epsilon = -L\frac{\Delta I}{\Delta t}$$