Induced Fields

Magnetic fields may vary in time.

Experiments conducted in 1831 showed that an emf can be induced in a circuit by a changing magnetic field.

- Experiments were done by Michael Faraday and Joseph Henry.

The results of these experiments led to *Faraday's Law of Induction.*

An *induced current* is produced by a changing magnetic field.

There is an *induced emf* associated with the induced current.

A current can be produced without a battery present in the circuit.

Faraday's law of induction describes the induced emf.

Michael Faraday

1791 – 1867

British physicist and chemist

Great experimental scientist

Contributions to early electricity include:

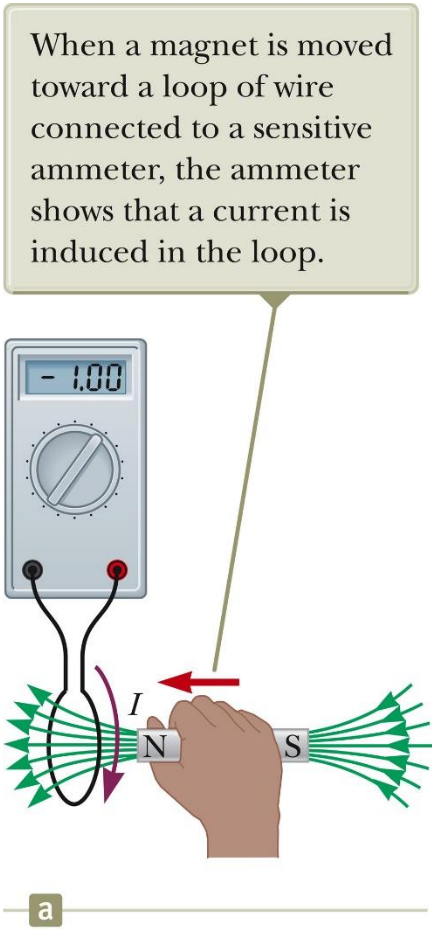
- Invention of motor, generator, and transformer
- Electromagnetic induction
- Laws of electrolysis

EMF Produced by a Changing Magnetic Field, 1

A loop of wire is connected to a sensitive ammeter.

When a magnet is moved toward the loop, the ammeter deflects.

- The direction was arbitrarily chosen to be negative.

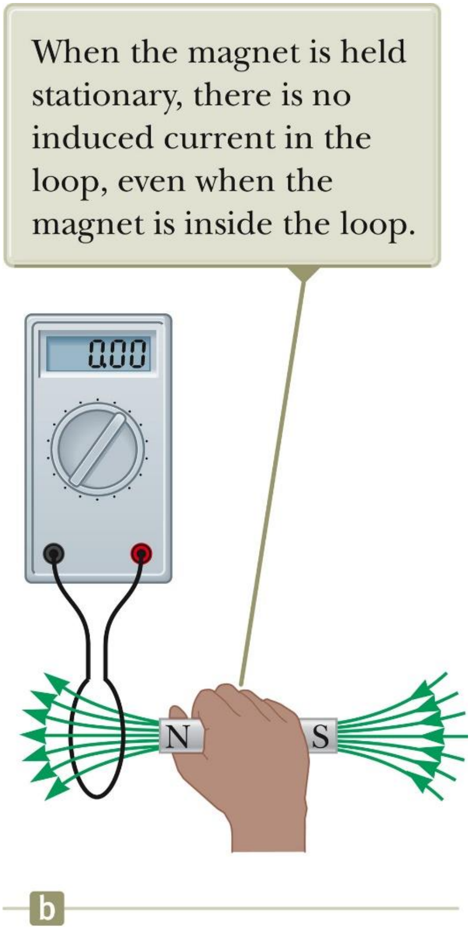


EMF Produced by a Changing Magnetic Field, 2

When the magnet is held stationary, there is no deflection of the ammeter.

Therefore, there is no induced current.

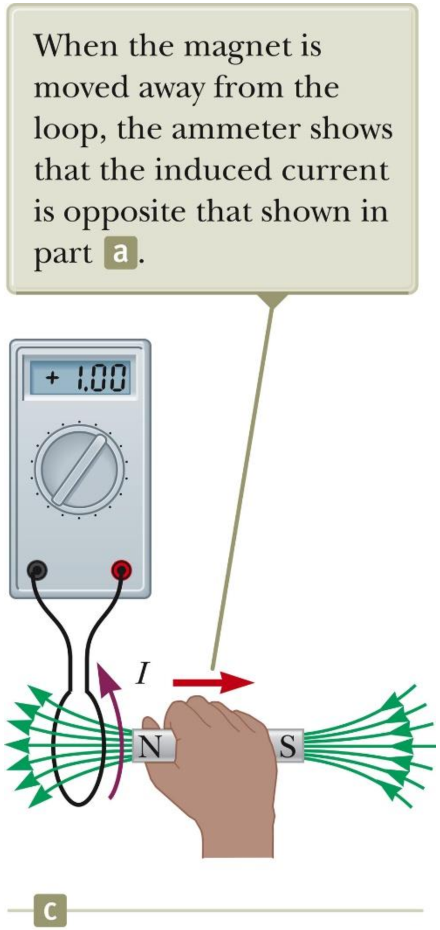
- Even though the magnet is in the loop



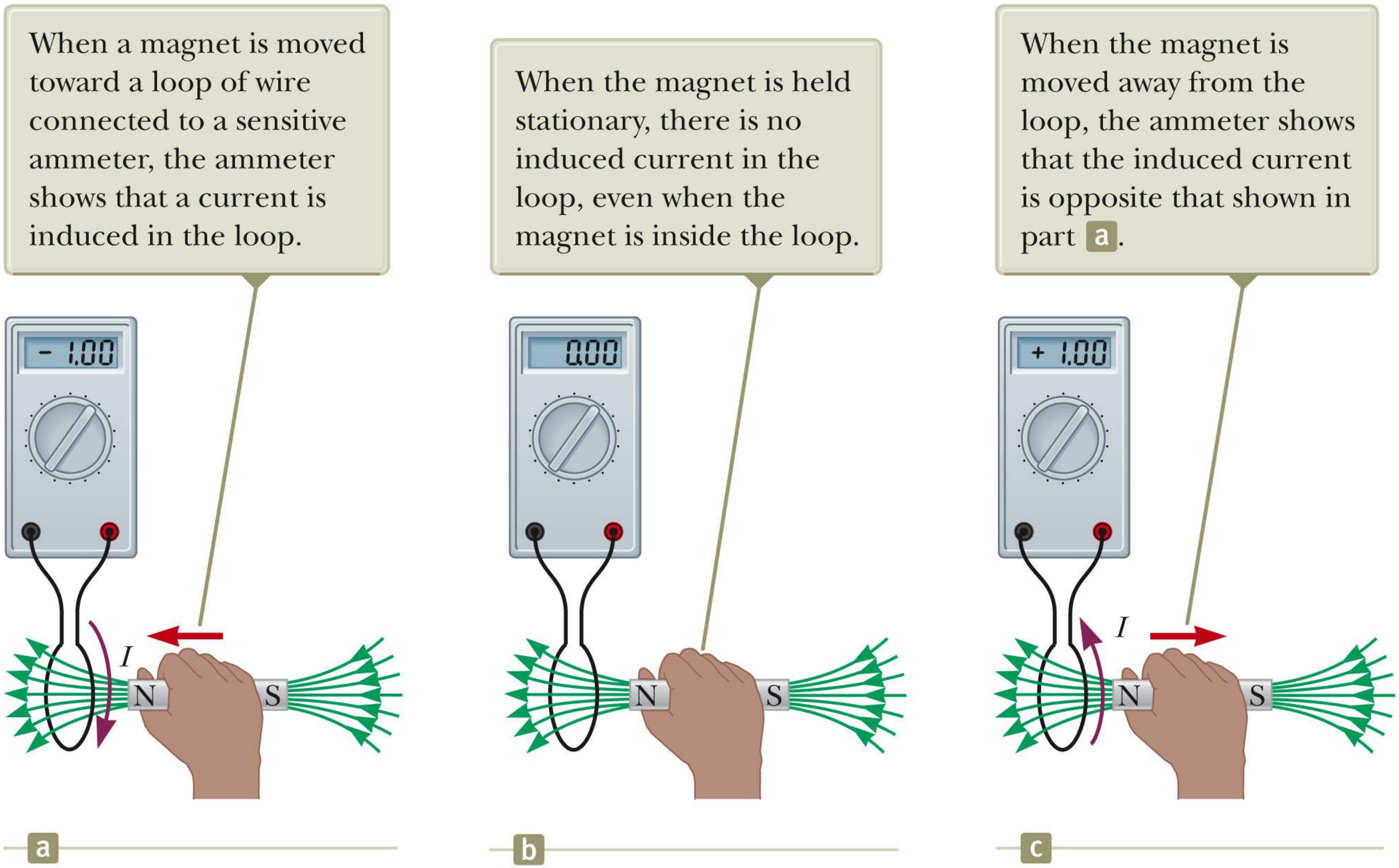
EMF Produced by a Changing Magnetic Field, 3

The magnet is moved away from the loop.

The ammeter deflects in the opposite direction.



Induced Current Experiment, Summary



EMF Produced by a Changing Magnetic Field, Summary

The ammeter deflects when the magnet is moving toward or away from the loop.

The ammeter also deflects when the loop is moved toward or away from the magnet.

Therefore, the loop detects that the magnet is moving relative to it.

- We relate this detection to a change in the magnetic field.
- This is the induced current that is produced by an induced emf.

Faraday's Experiment – Set Up

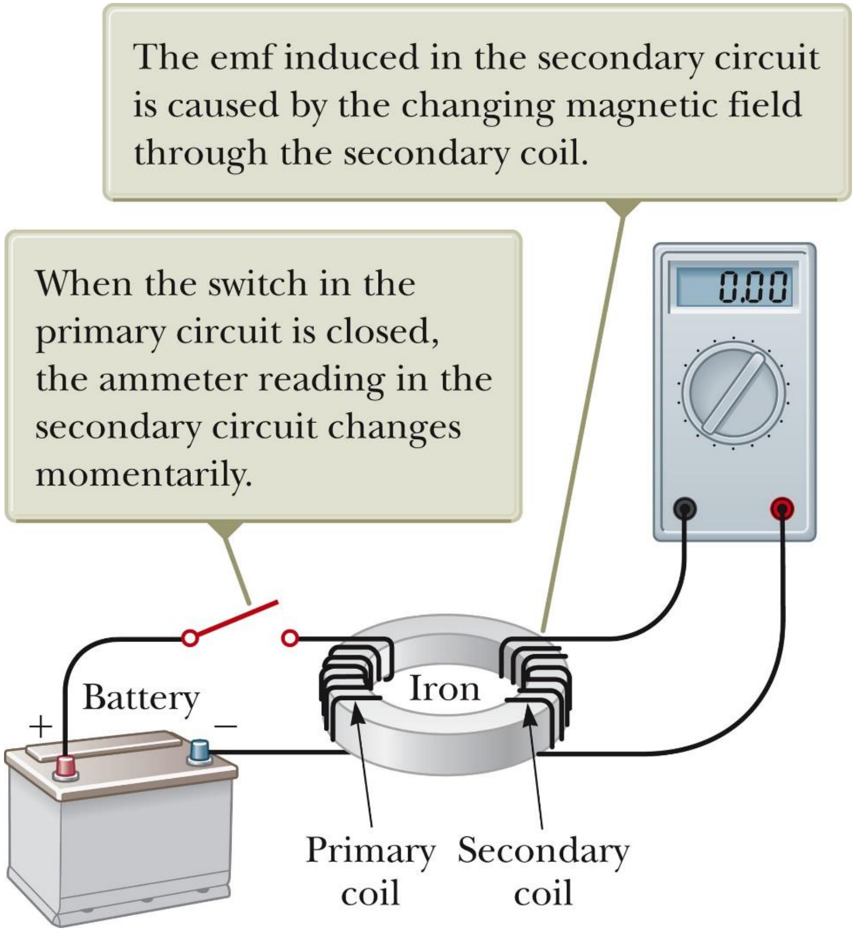
A primary coil is connected to a switch and a battery.

The wire is wrapped around an iron ring.

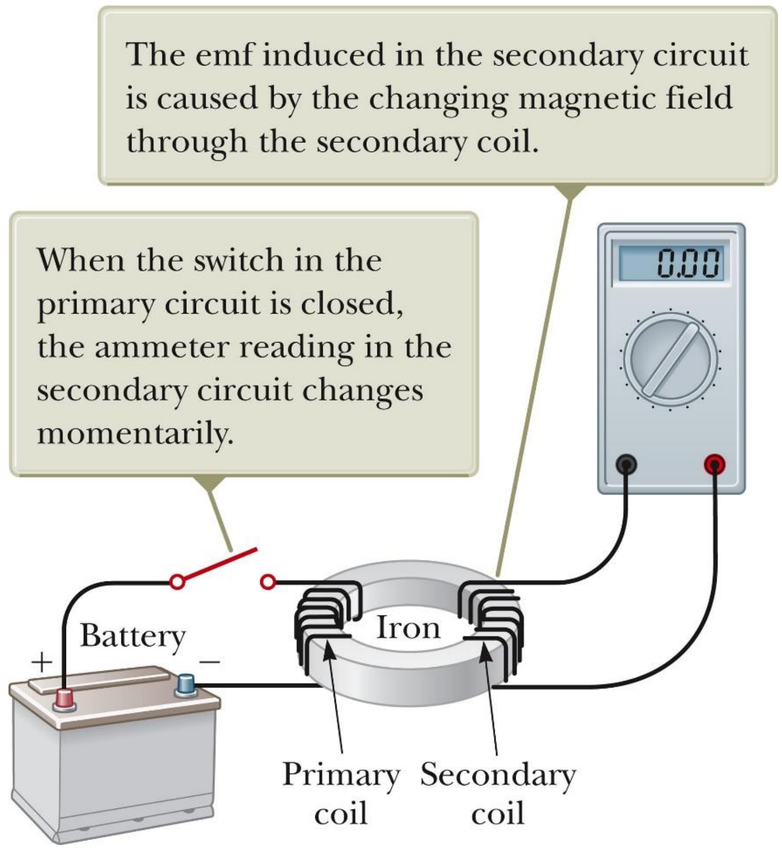
A secondary coil is also wrapped around the iron ring.

There is no battery present in the secondary coil.

The secondary coil is not directly connected to the primary coil.



Faraday's Experiment



Close the switch and observe the current readings given by the ammeter.

Faraday’s Experiment – Findings

At the instant the switch is closed, the ammeter changes from zero in one direction and then returns to zero.

When the switch is opened, the ammeter changes in the opposite direction and then returns to zero.

The ammeter reads zero when there is a steady current or when there is no current in the primary circuit.

Faraday’s Experiment – Conclusions

An electric current can be induced in a loop by a changing magnetic field.

- This would be the current in the secondary circuit of this experimental set-up.

The induced current exists only while the magnetic field through the loop is changing.

This is generally expressed as: ***an induced emf is produced in the loop by the changing magnetic field.***

- The actual existence of the magnetic flux is not sufficient to produce the induced emf, the flux must be changing.

Faraday's Law of Induction – Statements

The emf induced in a circuit is directly proportional to the time rate of change of the magnetic flux through the circuit.

Mathematically,

$$\varepsilon = -\frac{d\Phi_B}{dt}$$

Remember Φ_B is the magnetic flux through the circuit and is found by

$$\Phi_B = \int \vec{\mathbf{B}} \cdot d\vec{\mathbf{A}}$$

If the circuit consists of N loops, all of the same area, and if Φ_B is the flux through one loop, an emf is induced in every loop and Faraday's law becomes

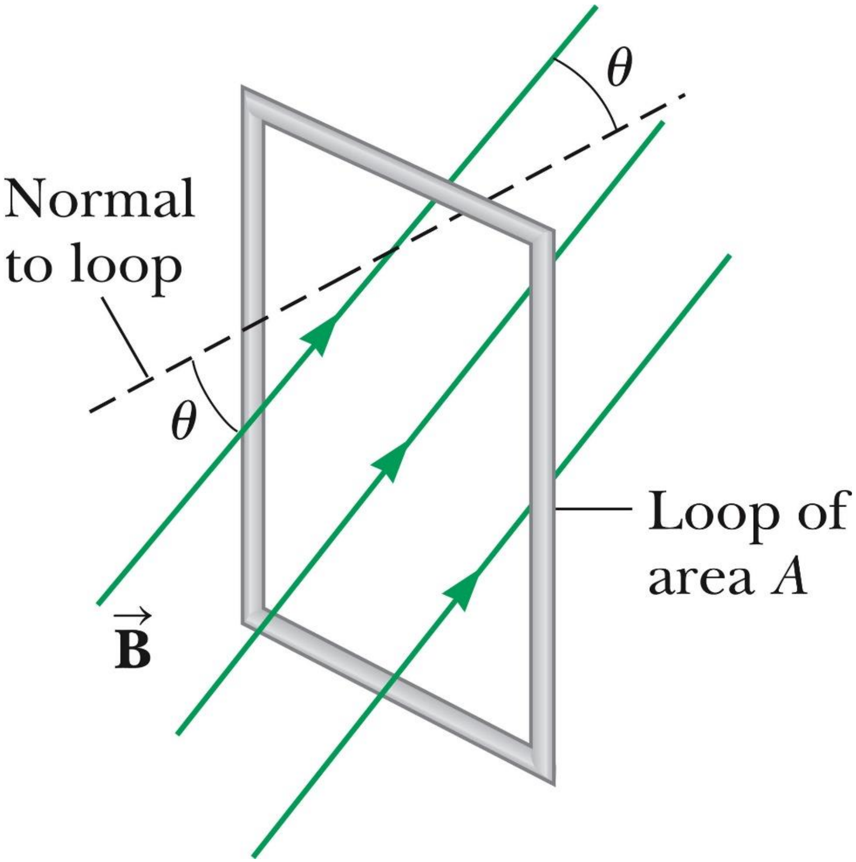
$$\varepsilon = -N\frac{d\Phi_B}{dt}$$

Faraday’s Law – Example

Assume a loop enclosing an area A lies in a uniform magnetic field.

The magnetic flux through the loop is $\Phi_B = BA \cos \theta$.

The induced emf is $\varepsilon = -\, d/dt\,(BA \cos \theta)$.



Ways of Inducing an emf

The magnitude of the magnetic field can change with time.

The area enclosed by the loop can change with time.

The angle between the magnetic field and the normal to the loop can change with time.

Any combination of the above can occur.

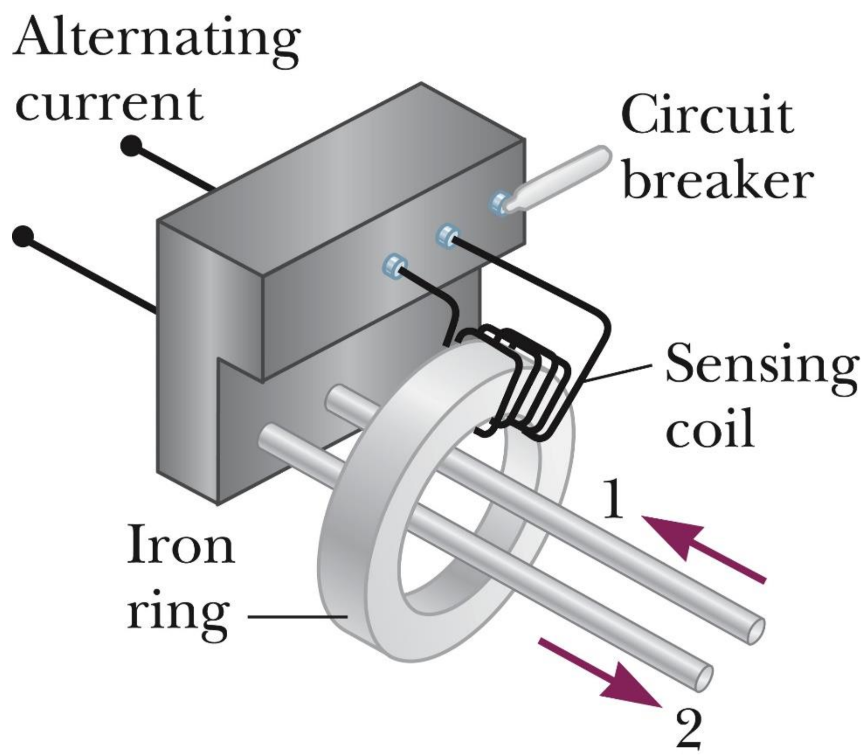
Applications of Faraday's Law – GFCI

A GFCI (ground fault circuit interrupter) protects users of electrical appliances against electric shock.

When the currents in the wires are in opposite directions, the flux is zero.

When the return current in wire 2 changes, the flux is no longer zero.

The resulting induced emf can be used to trigger a circuit breaker.



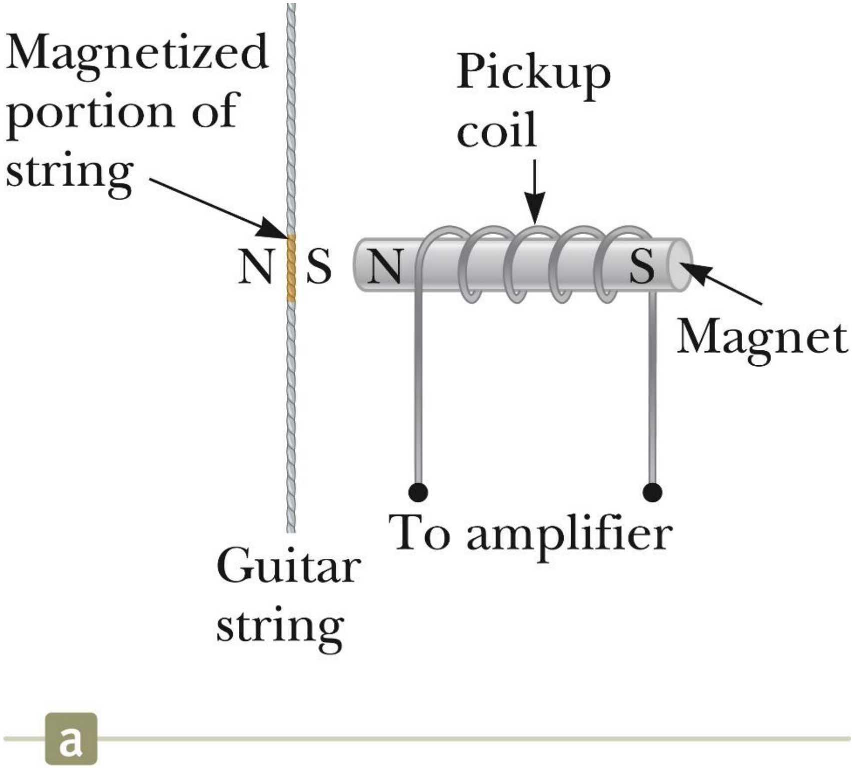
Applications of Faraday's Law – Pickup Coil

The pickup coil of an electric guitar uses Faraday's law.

The coil is placed near the vibrating string and causes a portion of the string to become magnetized.

When the string vibrates at some frequency, the magnetized segment produces a changing flux through the coil.

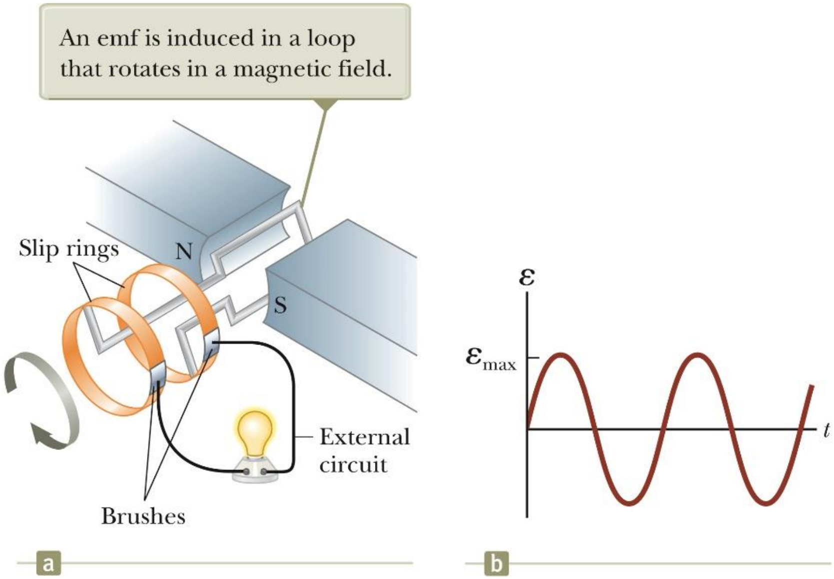
The induced emf is fed to an amplifier.



Motional emf

A motional emf is the emf induced in a conductor moving through a constant magnetic field.

The electrons in the conductor experience a force, $\vec{\mathbf{F}} = q\vec{\mathbf{v}} \times \vec{\mathbf{B}}$ that is directed along ℓ .



Motional emf, cont.

Under the influence of the force, the electrons move to the lower end of the conductor and accumulate there.

As a result of the charge separation, an electric field is produced inside the conductor.

The charges accumulate at both ends of the conductor until they are in equilibrium with regard to the electric and magnetic forces.

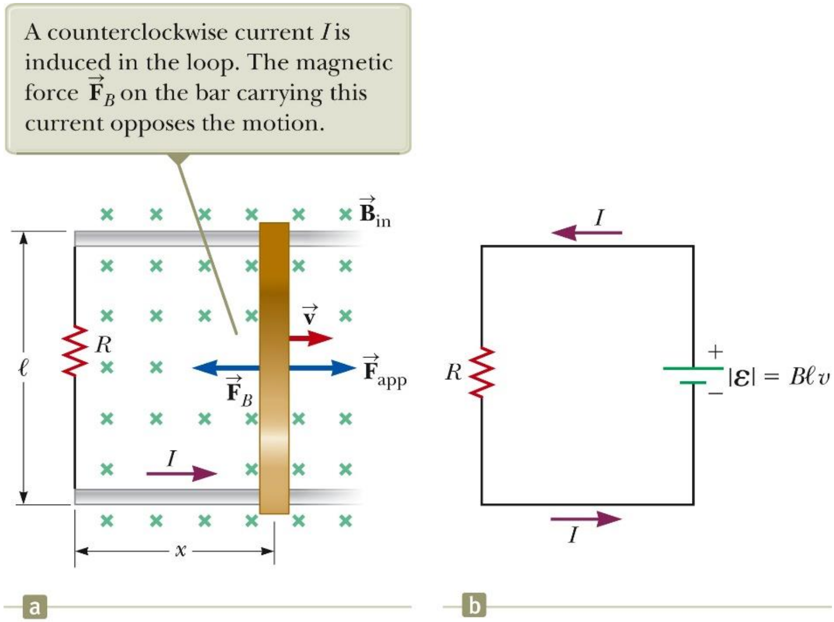
For equilibrium, $qE = qvB$ or $E = vB$.

The electric field is related to the potential difference across the ends of the conductor: $\Delta V = E \ell = B \ell v$.

A potential difference is maintained between the ends of the conductor as long as the conductor continues to move through the uniform magnetic field.

If the direction of the motion is reversed, the polarity of the potential difference is also reversed.

Sliding Conducting Bar



A conducting bar moving through a uniform field and the equivalent circuit diagram.

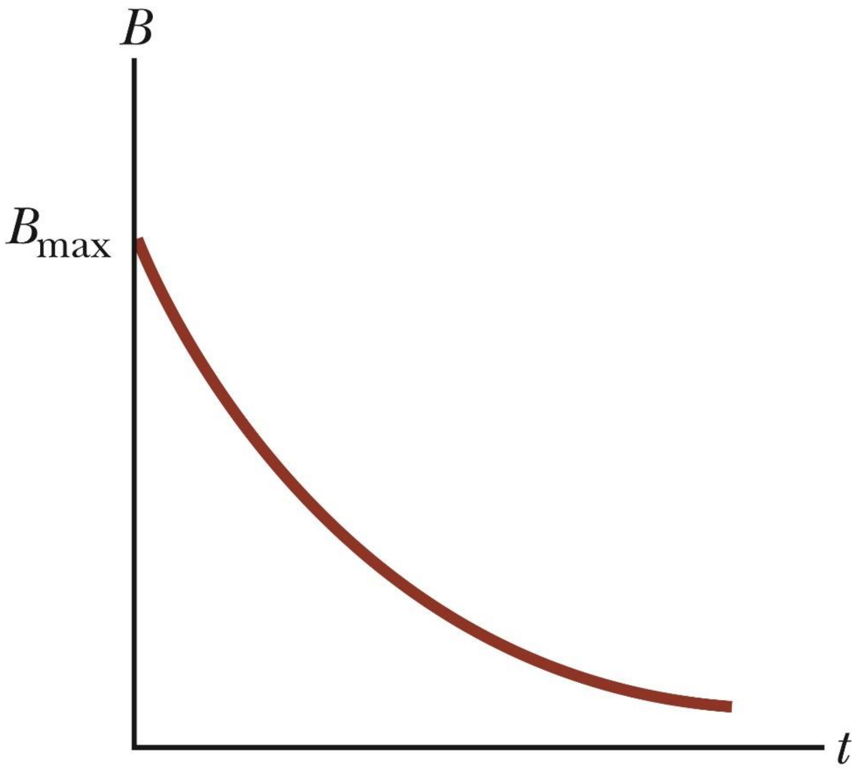
Assume the bar has zero resistance.

The stationary part of the circuit has a resistance R.

Moving Conductor, Variations

Use the active figure to adjust the applied force, the electric field and the resistance.

Observe the effects on the motion of the bar.



Sliding Conducting Bar, cont.

The induced emf is

$$\varepsilon = -\frac{d\Phi_B}{dt} = -B\ell\frac{dx}{dt} = -B\ell v$$

Since the resistance in the circuit is *R*, the current is

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

Sliding Conducting Bar, Energy Considerations

The applied force does work on the conducting bar.

- Model the circuit as a nonisolated system.

This moves the charges through a magnetic field and establishes a current.

The change in energy of the system during some time interval must be equal to the transfer of energy into the system by work.

The power input is equal to the rate at which energy is delivered to the resistor.

$$P = F_{\text{app}} v = (I \ell B) v = \frac{\varepsilon^2}{R}$$

Lenz’s Law

Faraday’s law indicates that the induced emf and the change in flux have opposite algebraic signs.

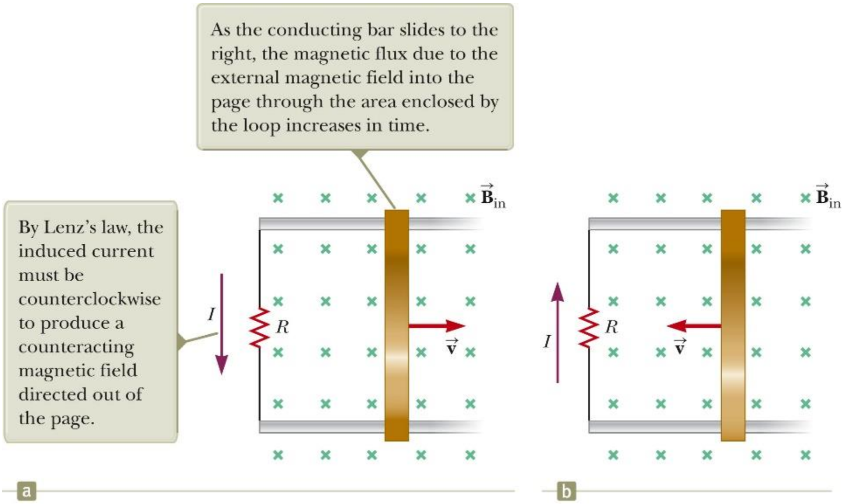
This has a physical interpretation that has come to be known as Lenz’s law.

Developed by German physicist Heinrich Lenz

Lenz’s law: *the induced current in a loop is in the direction that creates a magnetic field that opposes the change in magnetic flux through the area enclosed by the loop.*

The induced current tends to keep the original magnetic flux through the circuit from changing.

Lenz' Law, Example



The conducting bar slides on the two fixed conducting rails.

The magnetic flux due to the external magnetic field through the enclosed area increases with time.

The induced current must produce a magnetic field out of the page.

- The induced current must be counterclockwise.

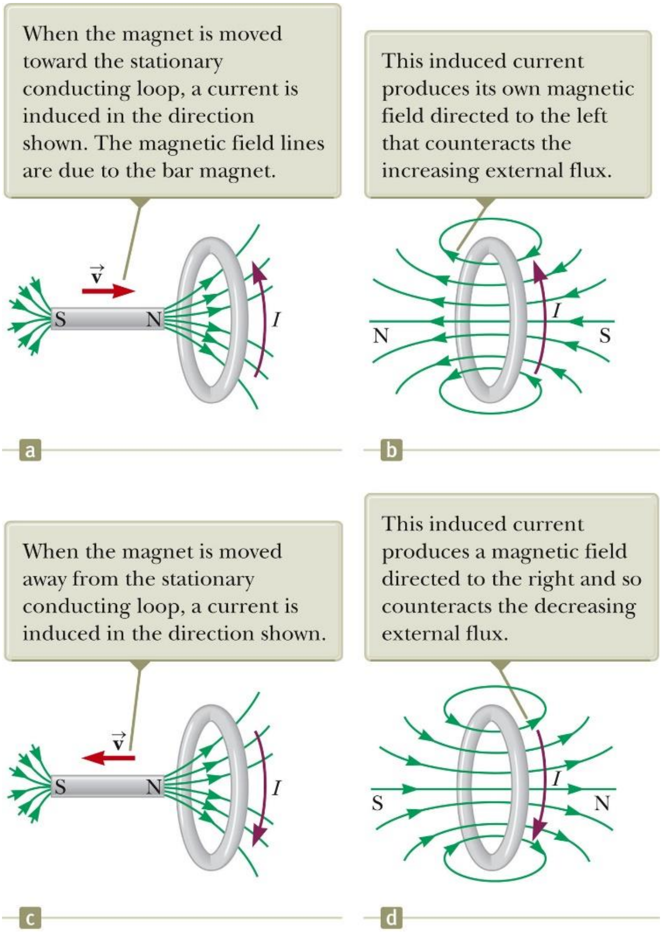
If the bar moves in the opposite direction, the direction of the induced current will also be reversed.

Induced Current Directions – Example

A magnet is placed near a metal loop.

a) Find the direction of the induced current in the loop when the magnet is pushed toward the loop (a and b).

b) Find the direction of the induced current in the loop when the magnet is pulled away from the loop (c and d).



Induced emf and Electric Fields

An electric field is created in the conductor as a result of the changing magnetic flux.

Even in the absence of a conducting loop, a changing magnetic field will generate an electric field in empty space.

This induced electric field is nonconservative.

- Unlike the electric field produced by stationary charges

The emf for any closed path can be expressed as the line integral of $\vec{\mathbf{E}} \cdot d\vec{\mathbf{s}}$ over the path.

Faraday's law can be written in a general form:

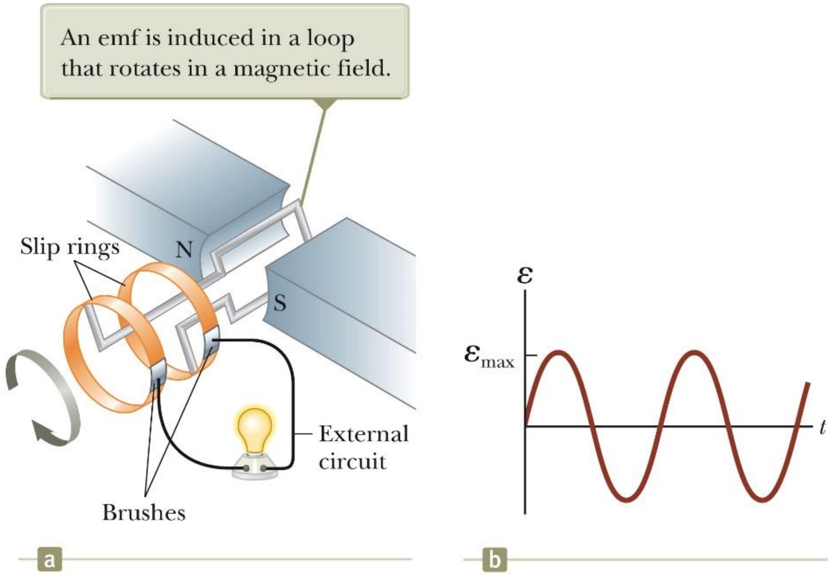
$$\oint \vec{\mathbf{E}} \cdot d\vec{\mathbf{s}} = -\frac{d\Phi_B}{dt}$$

Induced emf and Electric Fields, cont.

The induced electric field is a nonconservative field that is generated by a changing magnetic field.

The field cannot be an electrostatic field because if the field were electrostatic, and hence conservative, the line integral of $\vec{\mathbf{E}} \cdot d\vec{\mathbf{s}}$ over a closed loop would be zero and it isn't.

Generators



Electric generators take in energy by work and transfer it out by electrical transmission.

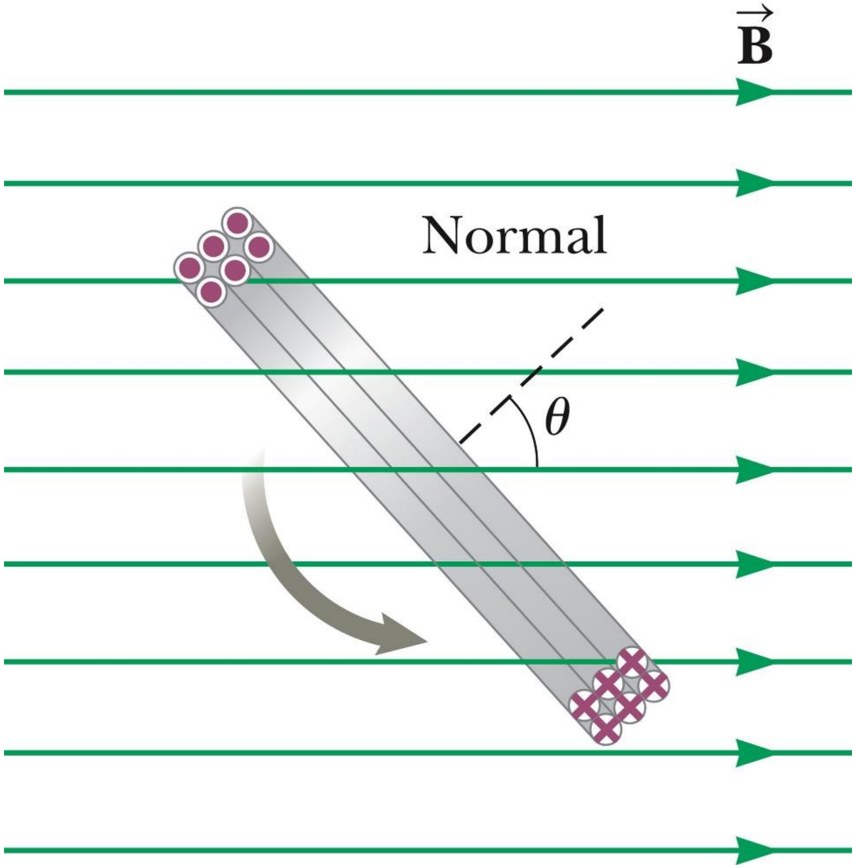
The AC generator consists of a loop of wire rotated by some external means in a magnetic field.

Use the active figure to adjust the speed of rotation and observe the effect on the emf generated.

Rotating Loop

Assume a loop with N turns, all of the same area rotating in a magnetic field.

The flux through the loop at any time t is
$\Phi_B = BA \cos \theta = BA \cos \omega t$

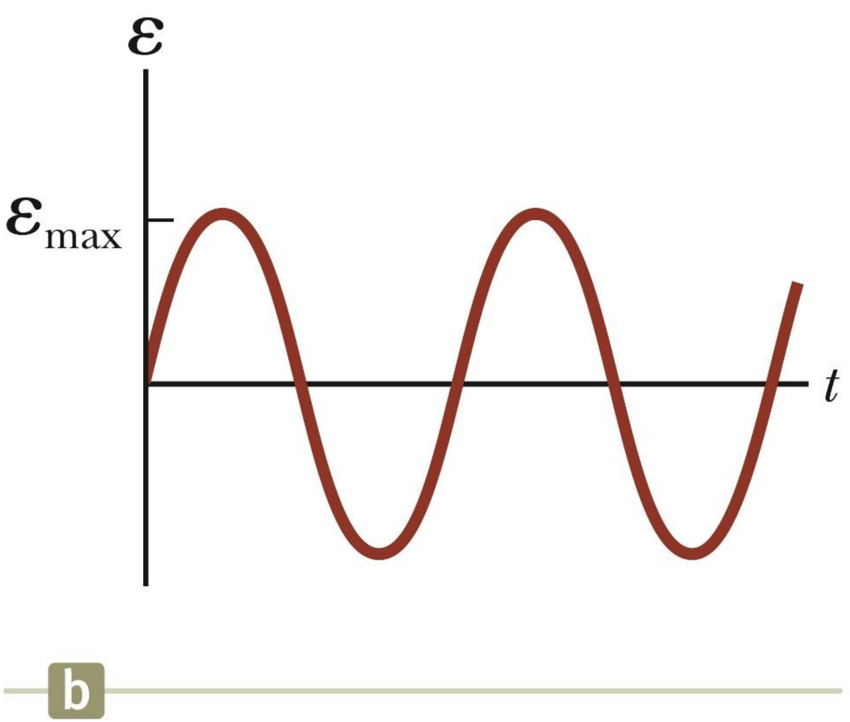


Induced emf in a Rotating Loop

The induced emf in the loop is

$$\varepsilon = -N\frac{d\Phi_B}{dt}$$
$$= NAB\omega \sin \omega t$$

This is sinusoidal, with $\varepsilon_{max} = NAB\omega$



Induced emf in a Rotating Loop, cont.

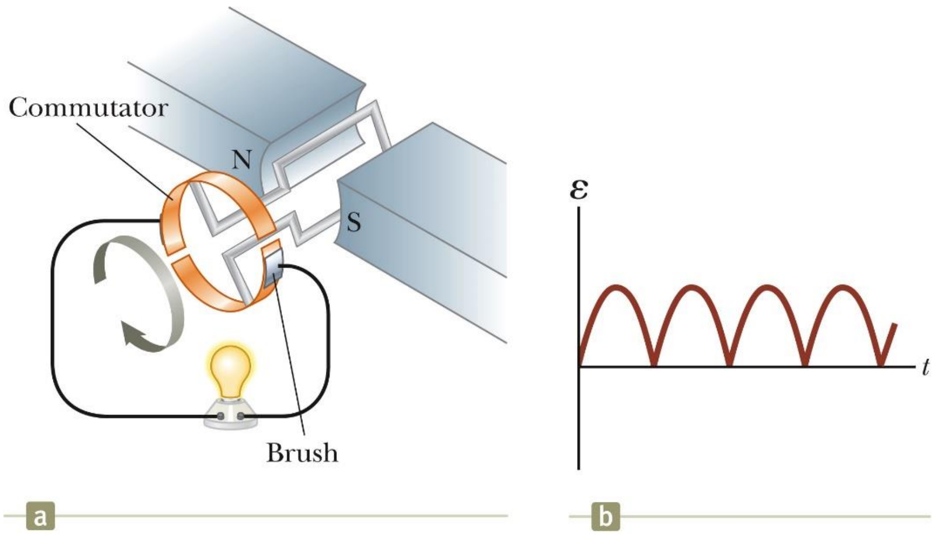
ε_{max} occurs when ωt = 90^o or 270^o

- This occurs when the magnetic field is in the plane of the coil and the time rate of change of flux is a maximum.

ε = 0 when ωt = 0^o or 180^o

- This occurs when the magnetic field is perpendicular to the plane of the coil and the time rate of change of flux is zero.

DC Generators



The DC (direct current) generator has essentially the same components as the AC generator.

The main difference is that the contacts to the rotating loop are made using a split ring called a *commutator*.

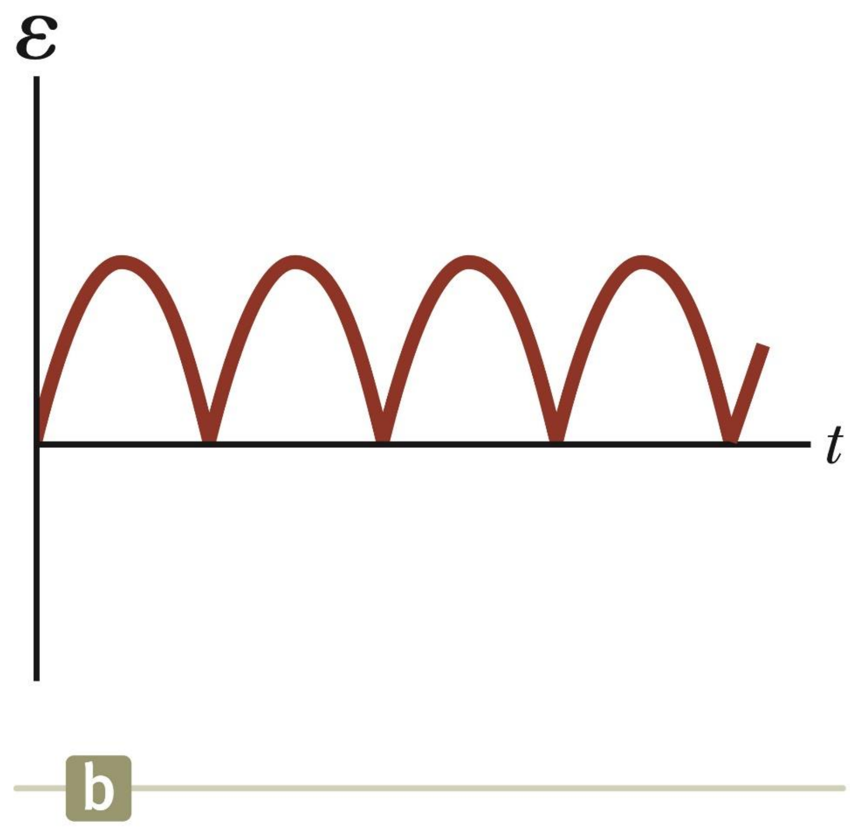
Use the active figure to vary the speed of rotation and observe the effect on the emf generated.

DC Generators, cont.

In this configuration, the output voltage always has the same polarity.

It also pulsates with time.

To obtain a steady DC current, commercial generators use many coils and commutators distributed so the pulses are out of phase.



Motors

Motors are devices into which energy is transferred by electrical transmission while energy is transferred out by work.

A motor is a generator operating in reverse.

A current is supplied to the coil by a battery and the torque acting on the current-carrying coil causes it to rotate.

Useful mechanical work can be done by attaching the rotating coil to some external device.

However, as the coil rotates in a magnetic field, an emf is induced.

- This induced emf always acts to reduce the current in the coil.
- The back emf increases in magnitude as the rotational speed of the coil increases.

Motors, cont.

The current in the rotating coil is limited by the back emf.

- The term *back emf* is commonly used to indicate an emf that tends to reduce the supplied current.

The induced emf explains why the power requirements for starting a motor and for running it are greater for heavy loads than for light ones.

Hybrid Drive Systems

In an automobile with a hybrid drive system, a gasoline engine and an electric motor are combined to increase the fuel economy of the vehicle and reduce its emissions.

Power to the wheels can come from either the gasoline engine or the electric motor.

In normal driving, the electric motor accelerates the vehicle from rest until it is moving at a speed of about 15 mph.

During the acceleration periods, the engine is not running, so gasoline is not used and there is no emission.

At higher speeds, the motor and engine work together so that the engine always operates at or near its most efficient speed.

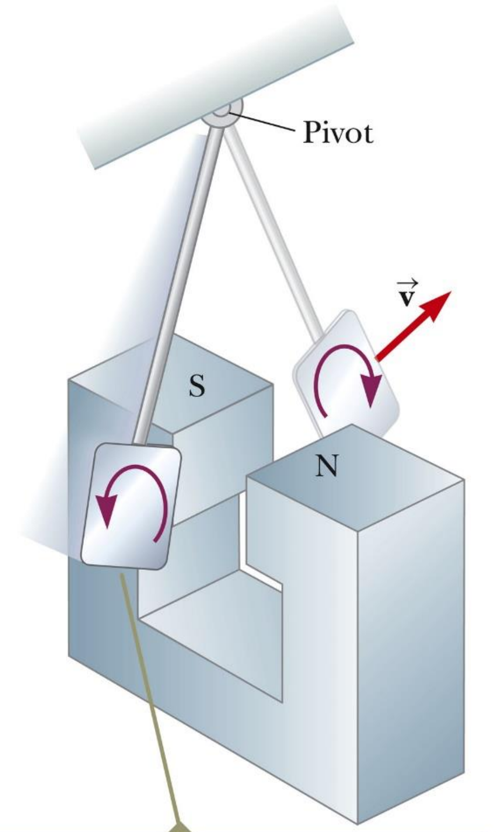
The result is significantly higher gas mileage than a traditional gasoline-powered automobile.

Eddy Currents

Circulating currents called eddy currents are induced in bulk pieces of metal moving through a magnetic field.

The eddy currents are in opposite directions as the plate enters or leaves the field.

Eddy currents are often undesirable because they represent a transformation of mechanical energy into internal energy.



As the plate enters or leaves the field, the changing magnetic flux induces an emf, which causes eddy currents in the plate.

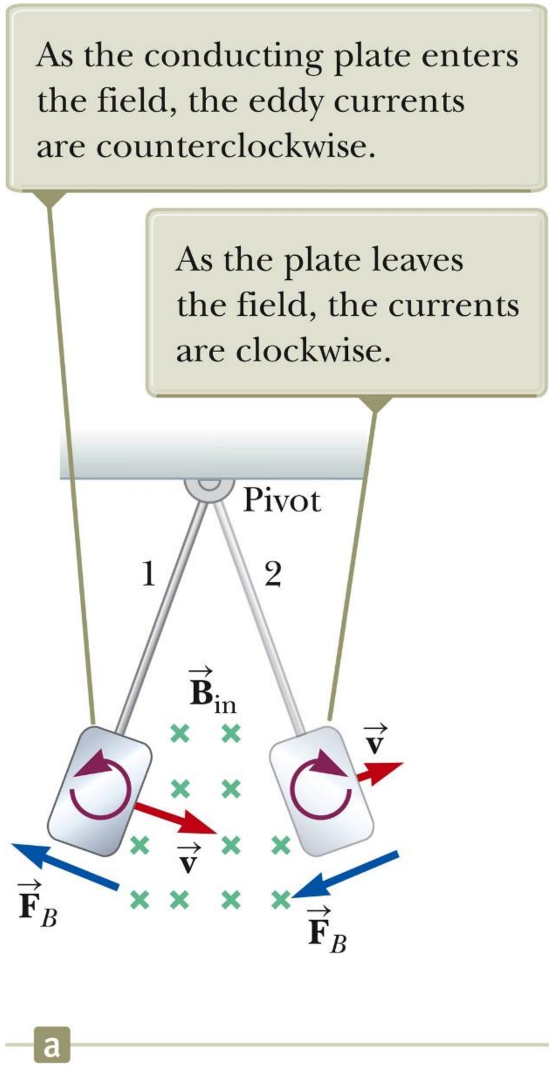
Eddy Currents, Example

The magnetic field is directed into the page.

The induced eddy current is counterclockwise as the plate enters the field.

It is opposite when the plate leaves the field.

The induced eddy currents produce a magnetic retarding force and the swinging plate eventually comes to rest.



Eddy Currents, Final

To reduce energy loses by the eddy currents, the conducting parts can.

- Be built up in thin layers separated by a nonconducting material
- Have slots cut in the conducting plate

Both prevent large current loops and increase the efficiency of the device.