Chapter 20

Magnetic Induction

Changing Magnetic Fields yield

Changing Electric Fields

Introduction

– The motion of a magnet can induce current in practical ways. If a credit card has a magnet strip on its back, “swiping” the card can generate tiny currents that send information to cash registers.

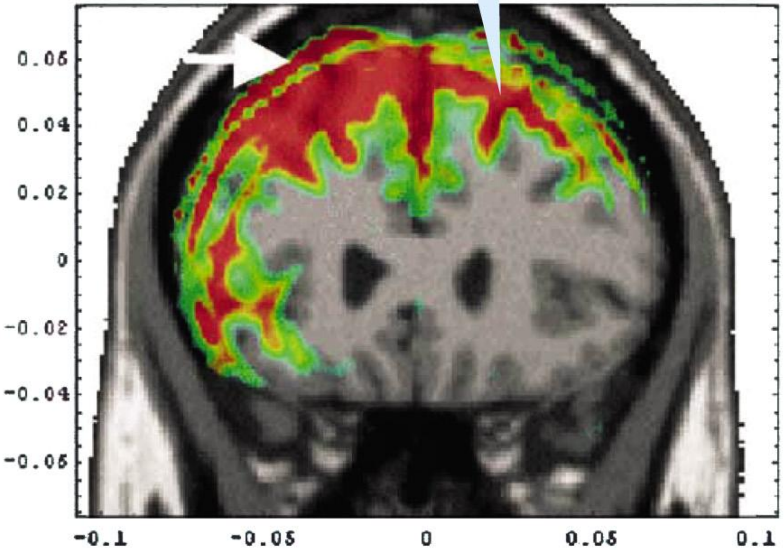
– A coil of wire and magnets set into motion around each other will generate currents in the wire. A source of mechanical energy can drive the rotation and make a waterfall into an electrical power station.

An electric generator produces current by electromagnetic induction: Coils of wire move relative to a magnetic field, which generates an emf in the coils. The motion can be powered by the wind, as in these wind turbines.

A changing magnetic field applied to the brain induces an electric field there, causing electric currents. Areas in red are where the currents are strongest.

(a)

(b)

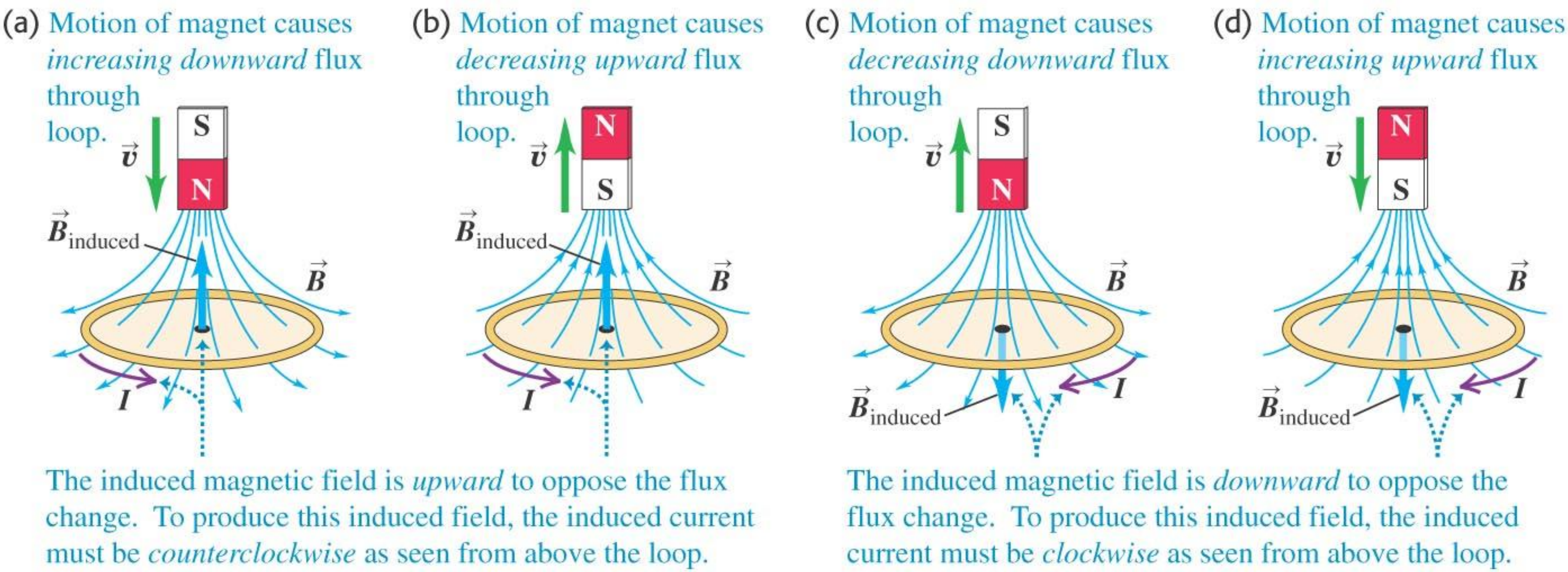


Lenz’s law

- Similar to Newton’s third law – action and reaction
- **Lenz’s law** – *“A changing magnetic field in a wire will induce a current to flow in the wire which will generate a current in the wire which will generate a magnetic field THAT OPPOSES the CHANGE in the original magnetic field “*

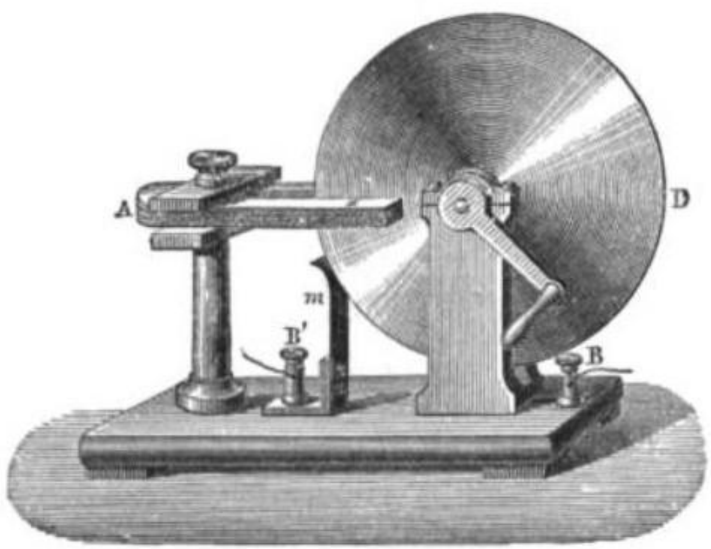
Lenz's Law

- The direction of any magnetic induction effect is such as to oppose the cause of the effect.



Faraday's Law

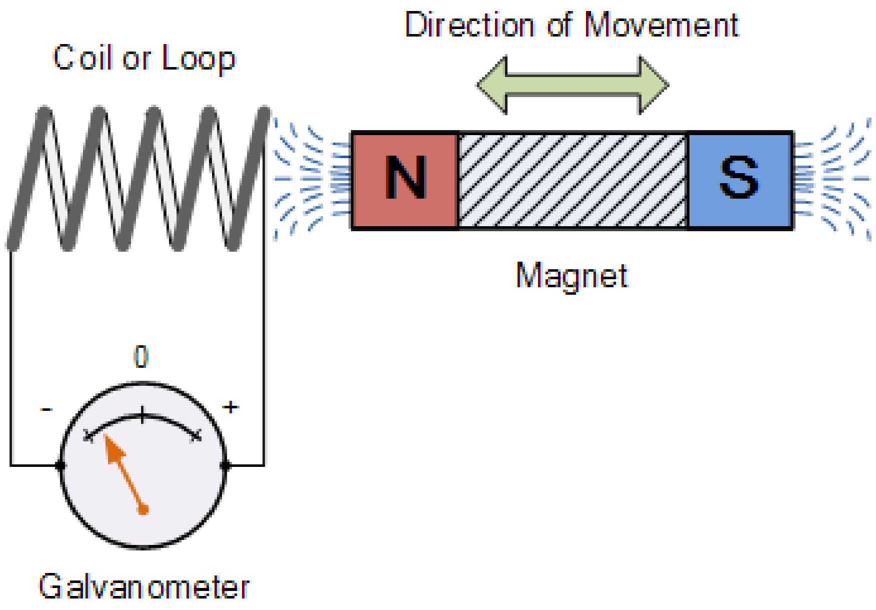
- A changing MAGNETIC FLUX will generate a voltage (EMF – electromotive force)
- Faraday 1831, Joseph Henry 1832
- EMF (voltage, potential) = -d□$_B$ /dt = - (time rate of change of magnetic flux)



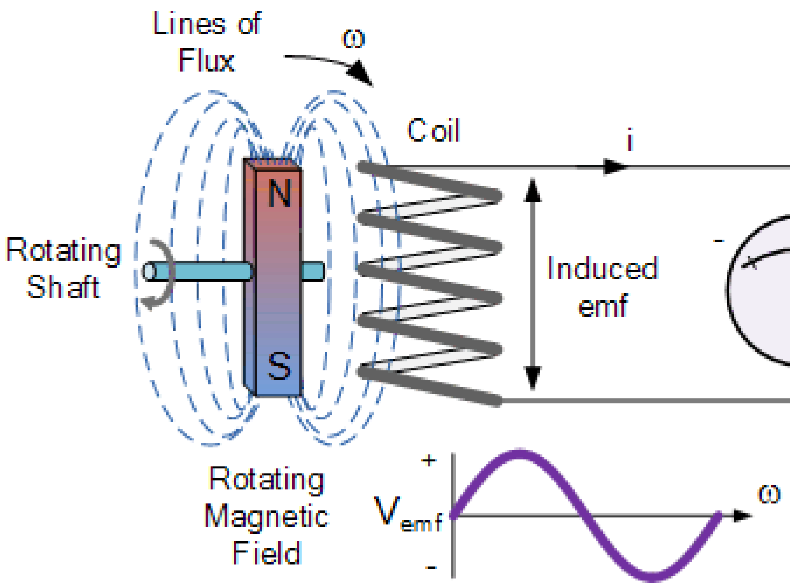
$$\mathcal{E} = -\frac{d\Phi_B}{dt}$$

Left – Faraday's disk – rotating a metal disk in a stationary magnetic field yields a DC current.

Changing Magnetic Flux Indices Current Flow

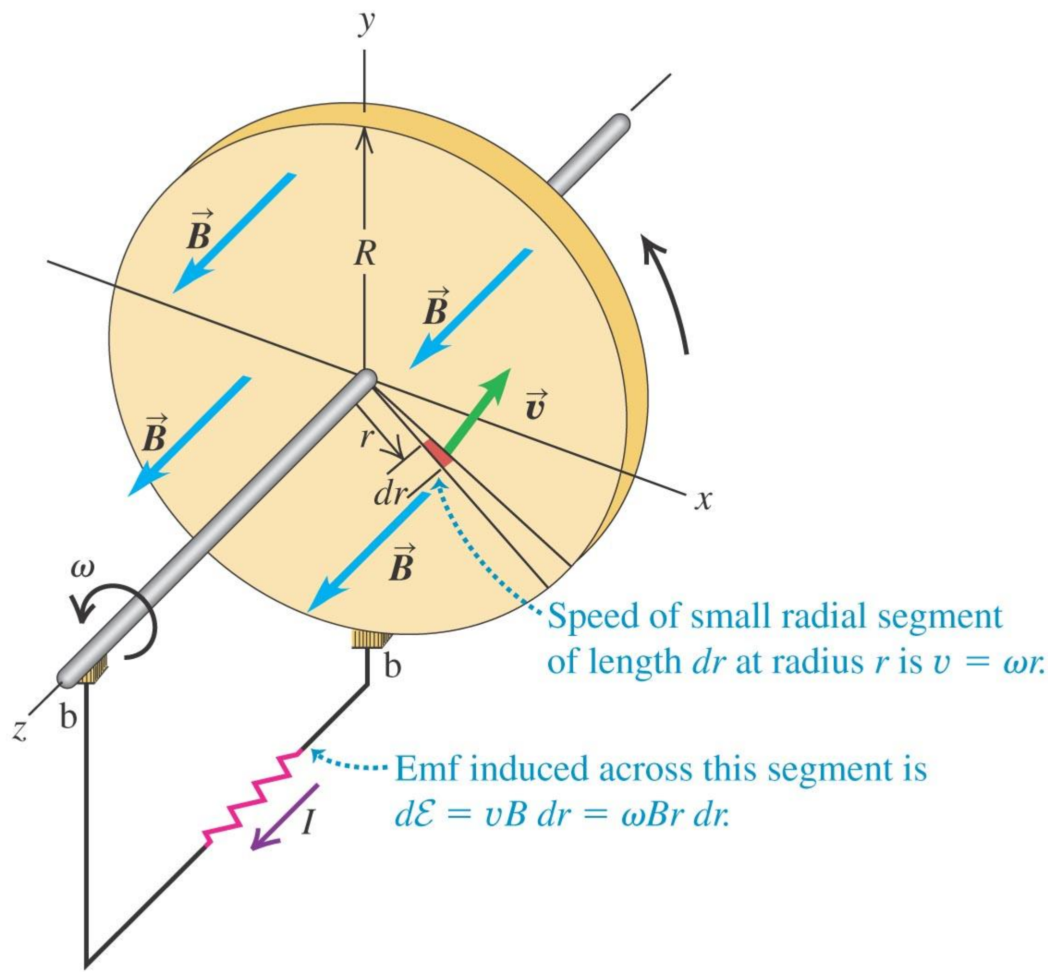


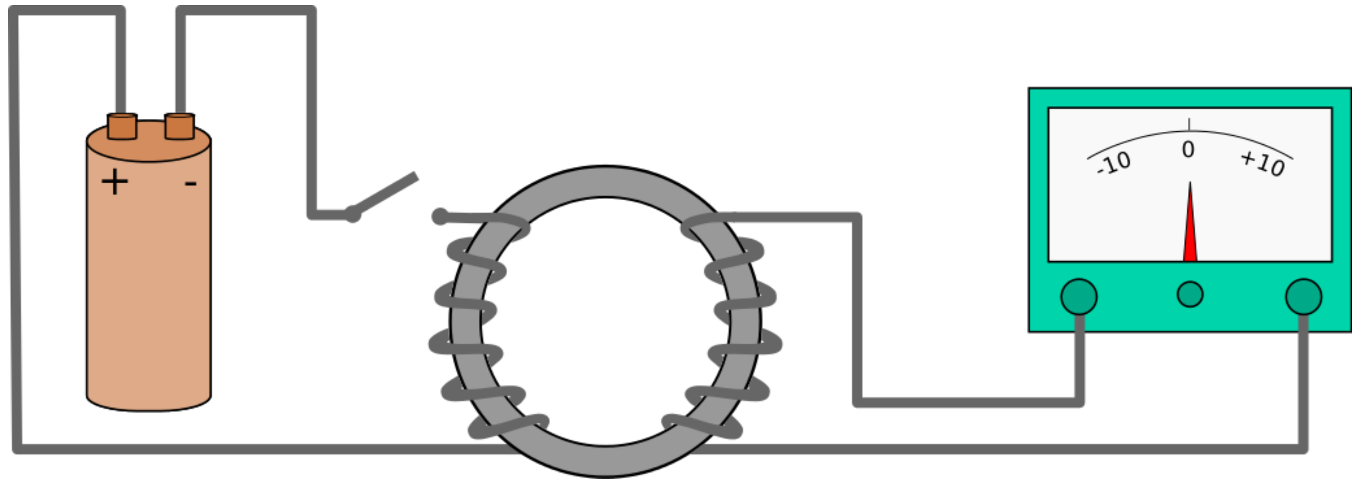
Rotating Magnet = Changing Flux



The Faraday Disk dynamo

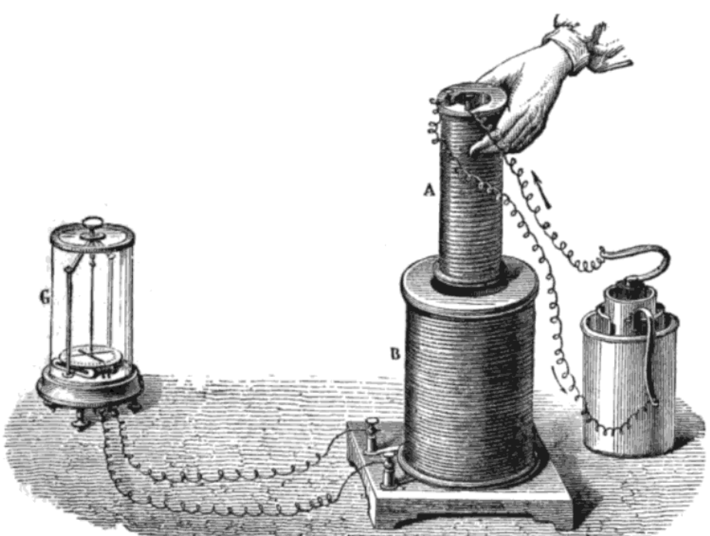
- Solid metal disk in a static B field
- What breaks the symmetry in this problem = rotation
- Eddy Current = electronic brakes





$$\mathcal{E} = -N\frac{d\Phi_B}{dt}$$

With N turns of wire and Φ_B in each turn then the EMF is N times larger in total – basis for step up and step down transformers

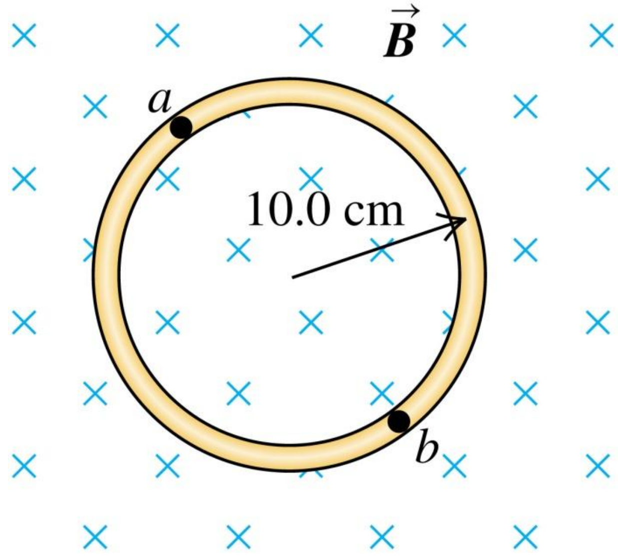


Upper – Faradays toroidal transformer (iron ring) experiment showing chaning B field generated changing voltage

Left – Faraday's induction between a DC electromagnet and a solenoidal coil. In this case a moving magnetic field from electromagnet yielded a current in the coil (solenoid) windings.

Q29.1

A circular loop of wire is in a region of spatially uniform magnetic field. The magnetic field is directed into the plane of the figure. If the magnetic field magnitude is constant,



A. the induced emf in the loop is clockwise.

B. the induced emf in the loop is counterclockwise.

C. the induced emf in the loop is zero.

D. Either A. or B. is possible.

E. Any of A., B., or C. is possible.

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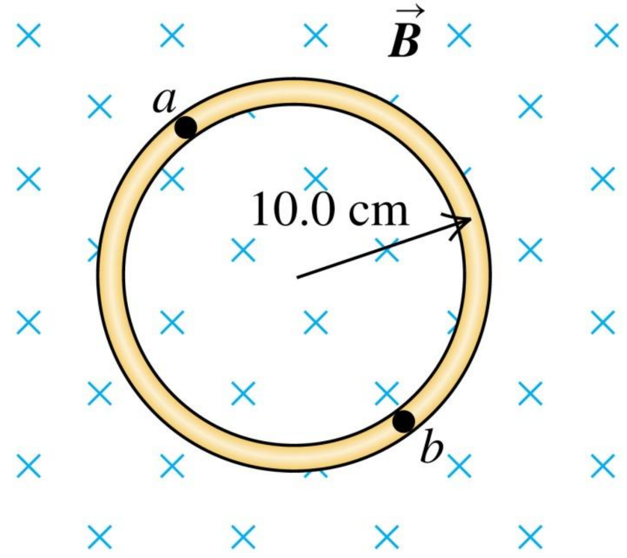

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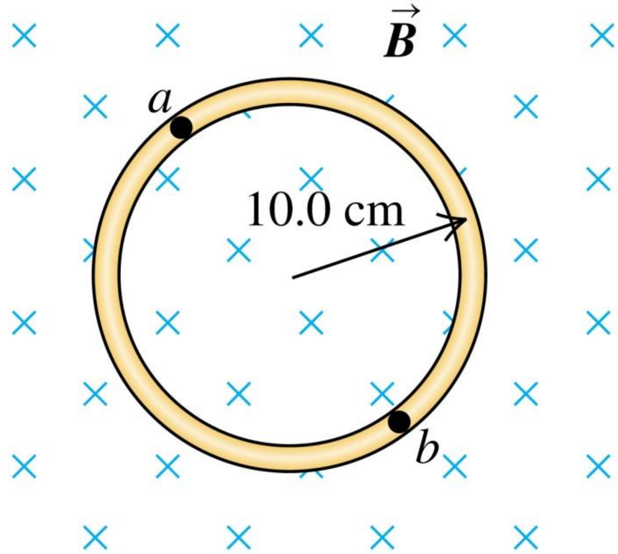
Q29.2

A circular loop of wire is in a region of spatially uniform magnetic field. The magnetic field is directed into the plane of the figure. If the magnetic field magnitude is *decreasing*,



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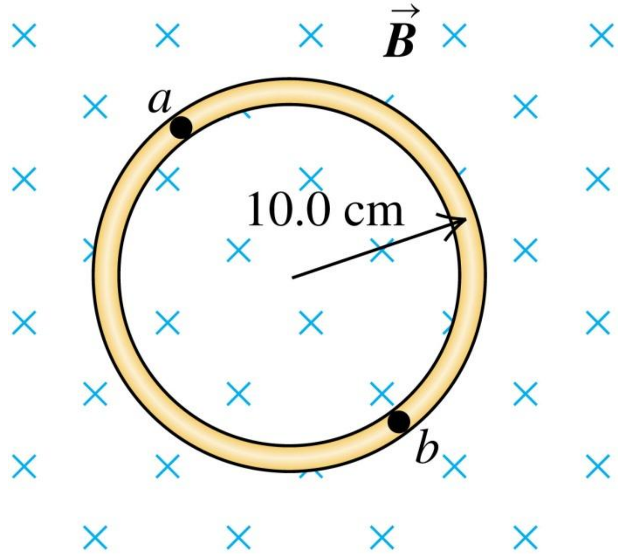

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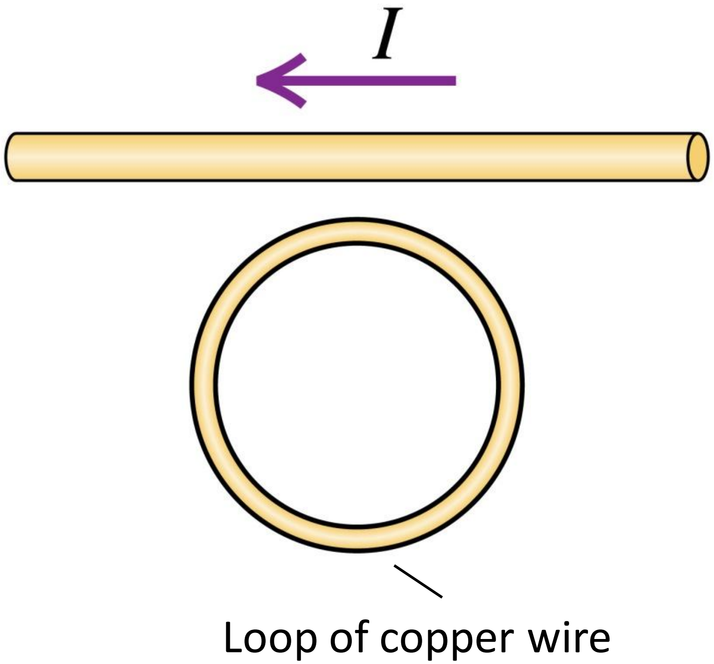
Q29.3

A circular loop of copper wire is placed next to a long straight wire. The current *I* in the long straight wire is increasing. What current does this induce in the circular loop?



A. a clockwise current

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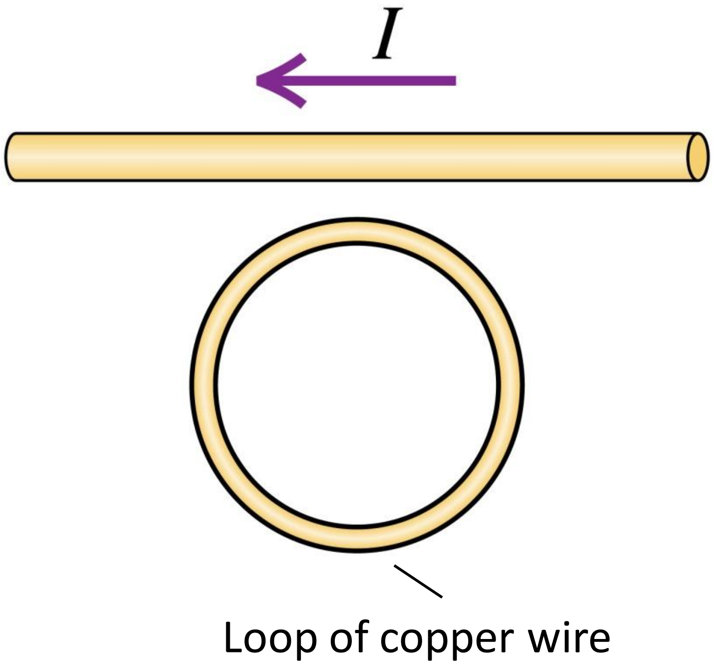

✔ A. a clockwise current

B. a counterclockwise current

C. zero current

D. Either A. or B. is possible.

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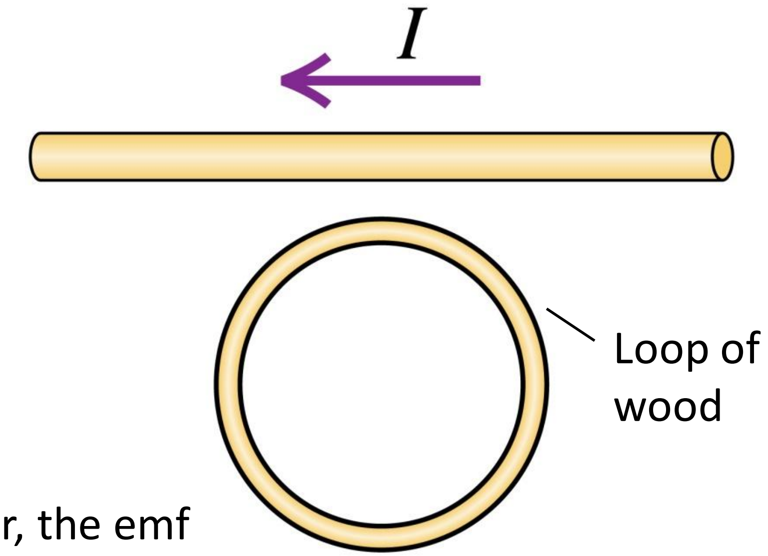
Q29.4

A circular loop of *wood* is placed next to a long straight wire. The resistivity of wood is about 10^{20} times greater than that of copper. The current I in the long straight wire is increasing. Compared to the emf that



would be induced if the loop were made of copper, the emf induced in the loop of wood is

A. about 10^{-20} as great.

B. about 10^{-10} as great.

C. about 10^{-5} as great.

D. the same.

E. greater.

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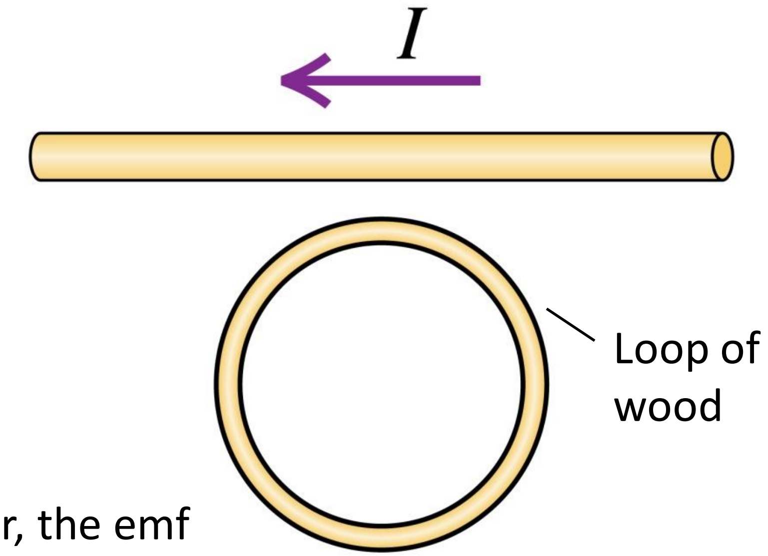

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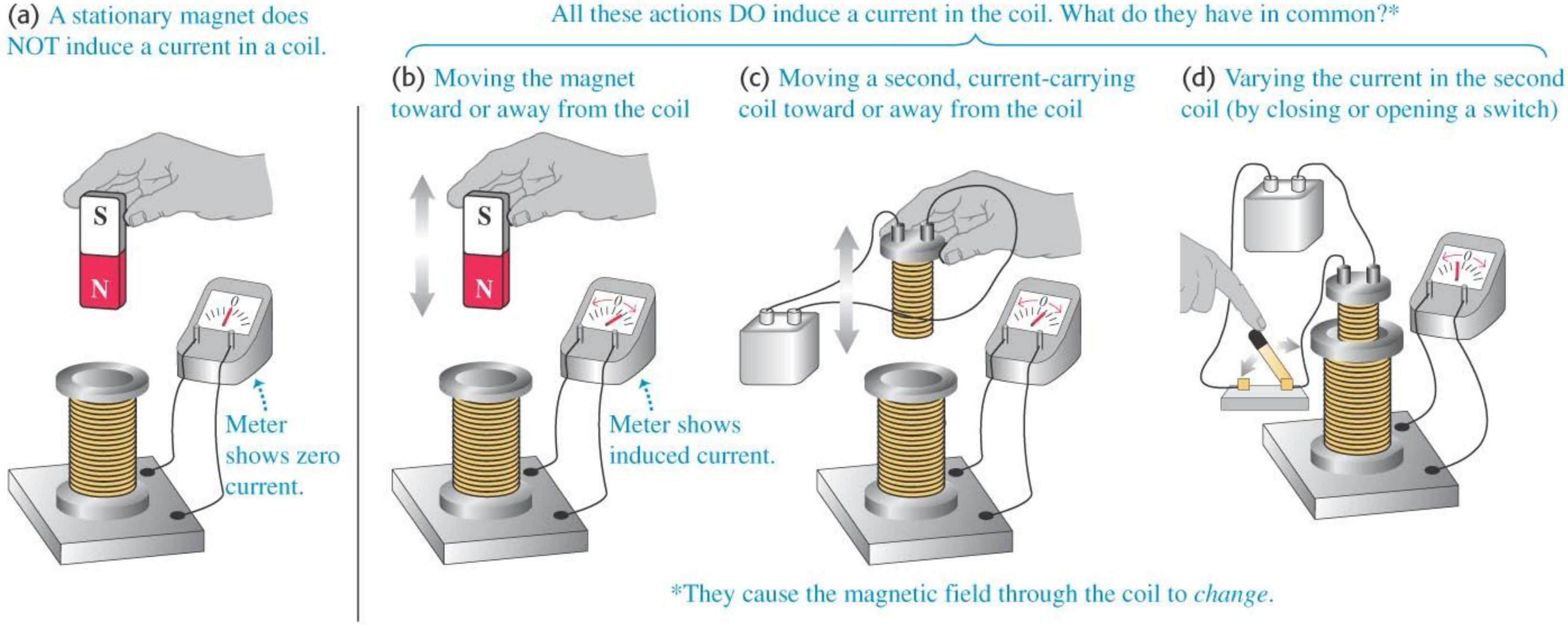
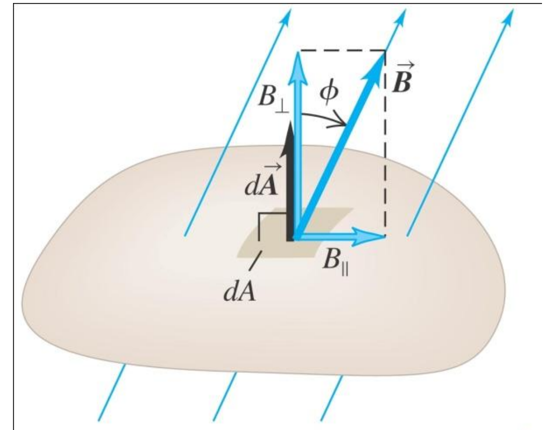
Induced current

– Joseph Henry worked in the United States and Michael Faraday worked in England to discern the details of current generated in wire and permanent magnets in motion relative to each other.



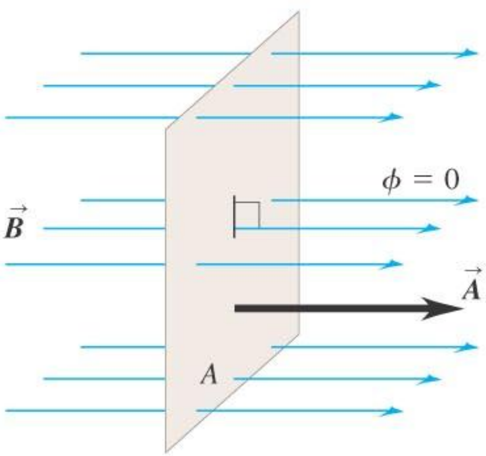
Knowing the magnetic flux

– Regardless of what moves, knowing the magnetic flux around a conducting entity will allow determination of current induced.

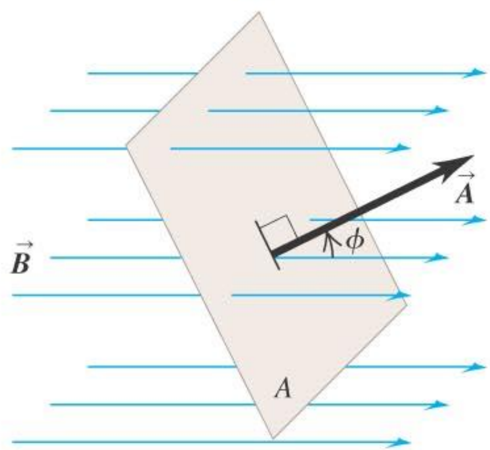


Magnetic flux through element of area $d\vec{A}$:
$d\Phi_B = \vec{B} \cdot d\vec{A} = B_\perp dA = B\, dA \cos\phi$

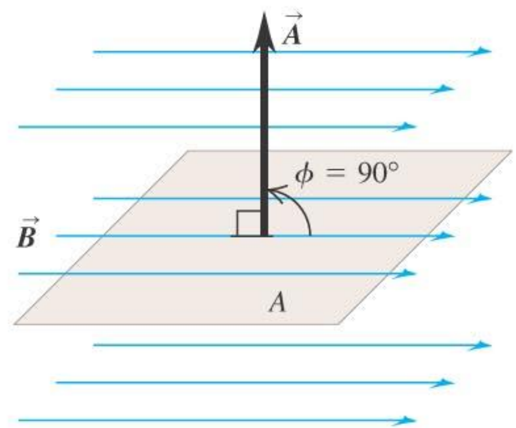
Surface is face-on to magnetic field:
- $\vec{B}$ and $\vec{A}$ are parallel (the angle between $\vec{B}$ and $\vec{A}$ is $\phi = 0$).
- The magnetic flux $\Phi_B = \vec{B} \cdot \vec{A} = BA$.



Surface is tilted from a face-on orientation by an angle ϕ:
- The angle between $\vec{B}$ and $\vec{A}$ is ϕ.
- The magnetic flux $\Phi_B = \vec{B} \cdot \vec{A} = BA \cos\phi$.

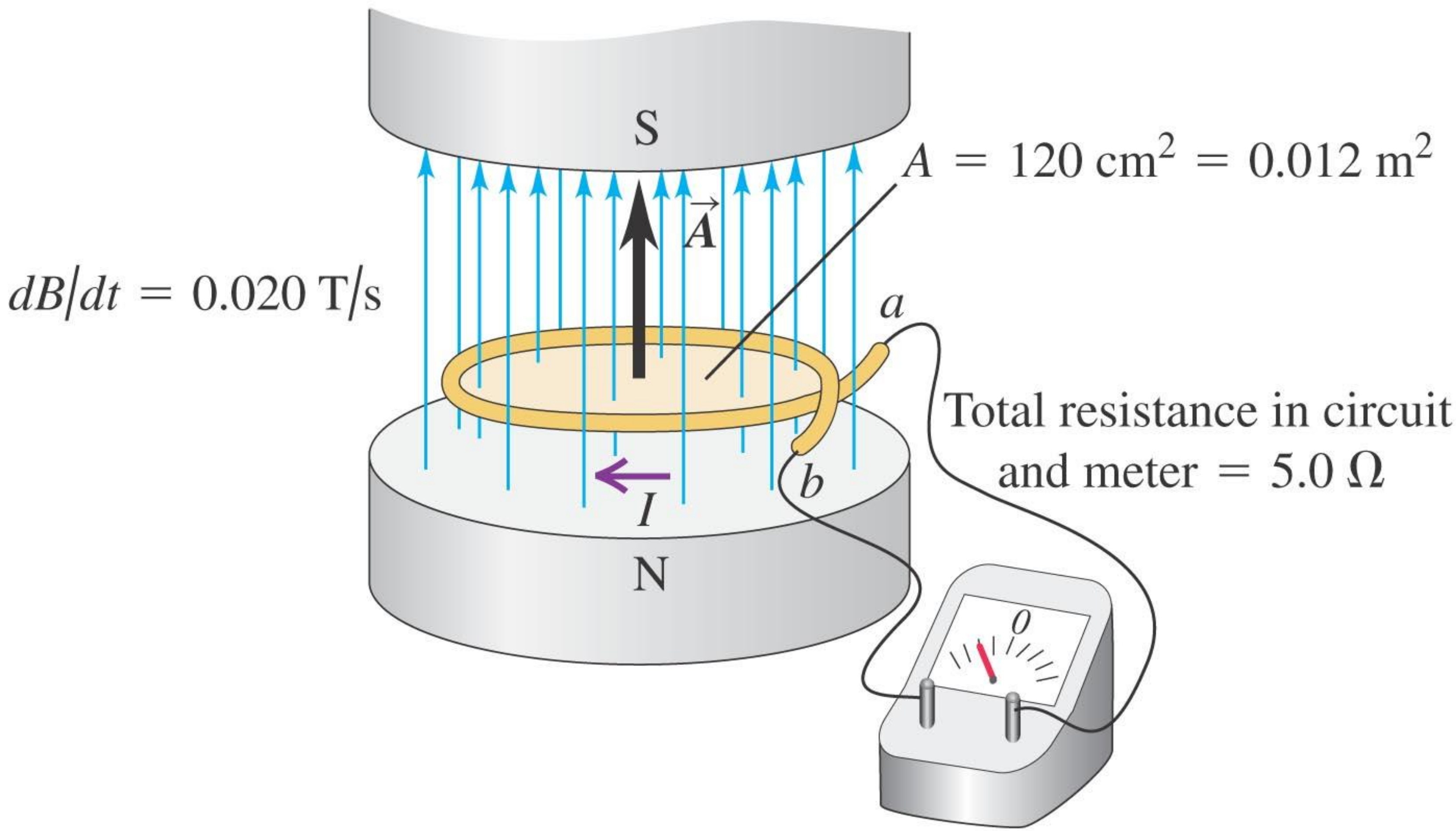


Surface is edge-on to magnetic field:
- $\vec{B}$ and $\vec{A}$ are perpendicular (the angle between $\vec{B}$ and $\vec{A}$ is $\phi = 90°$).
- The magnetic flux $\Phi_B = \vec{B} \cdot \vec{A} = BA \cos 90° = 0$.

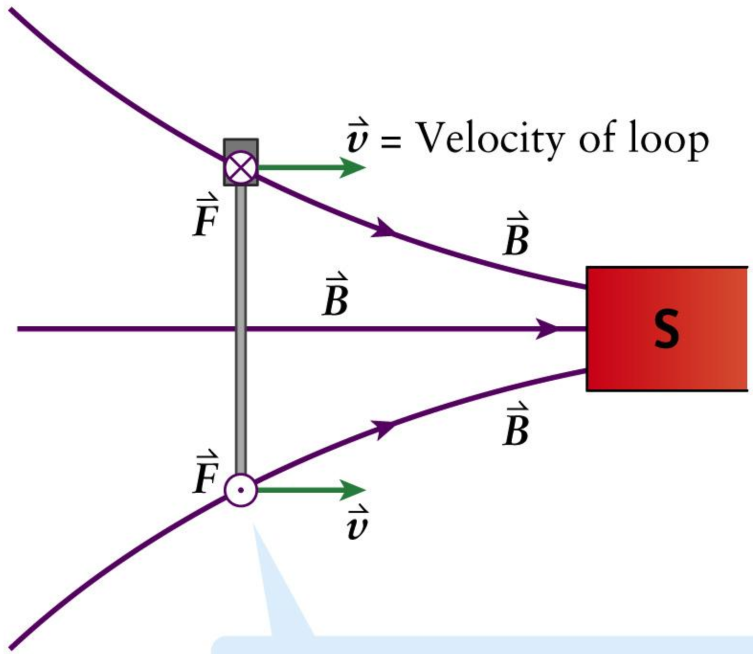


EMF and the current induced in a loop

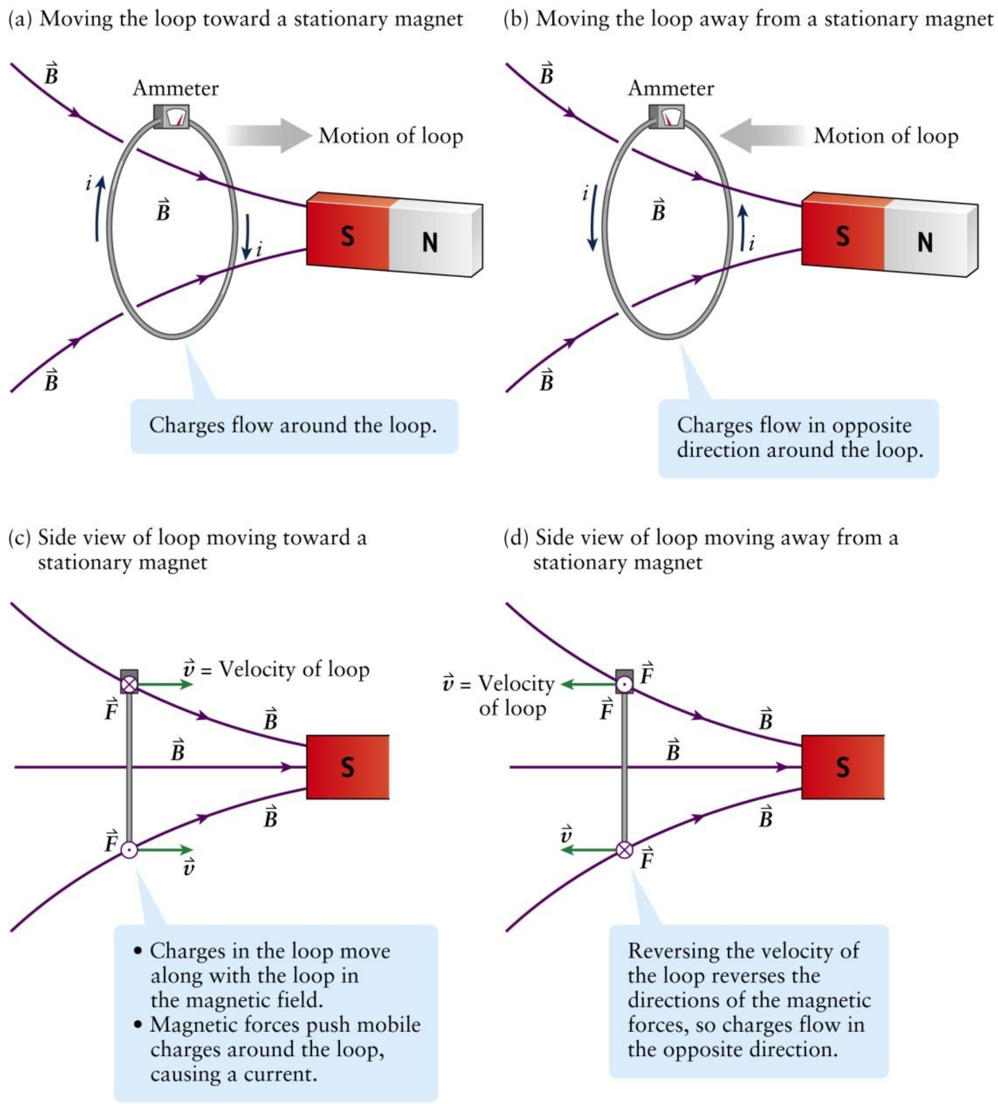
- A changing magnetic field induces an electric field – here the electric field is changing as well



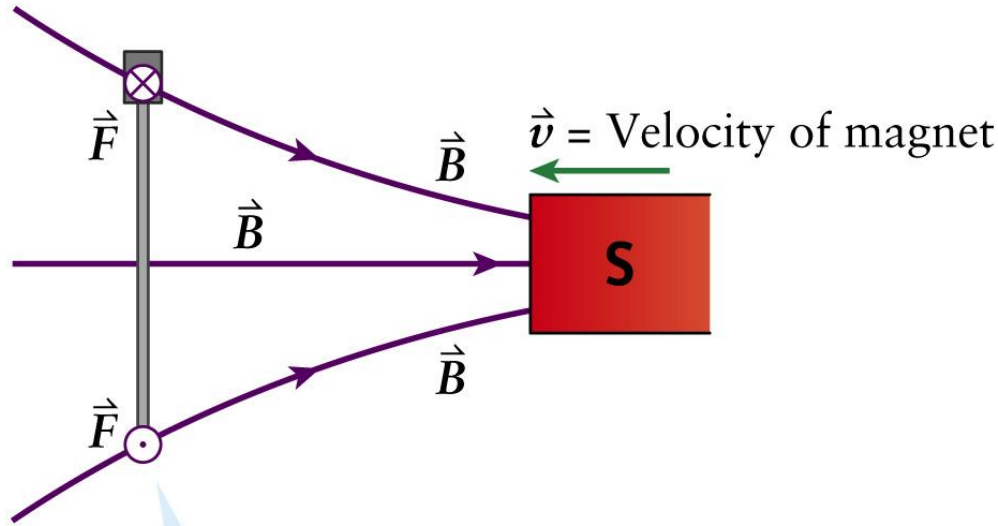
(c) Side view of loop moving toward a stationary magnet



- Charges in the loop move along with the loop in the magnetic field.
- Magnetic forces push mobile charges around the loop, causing a current.

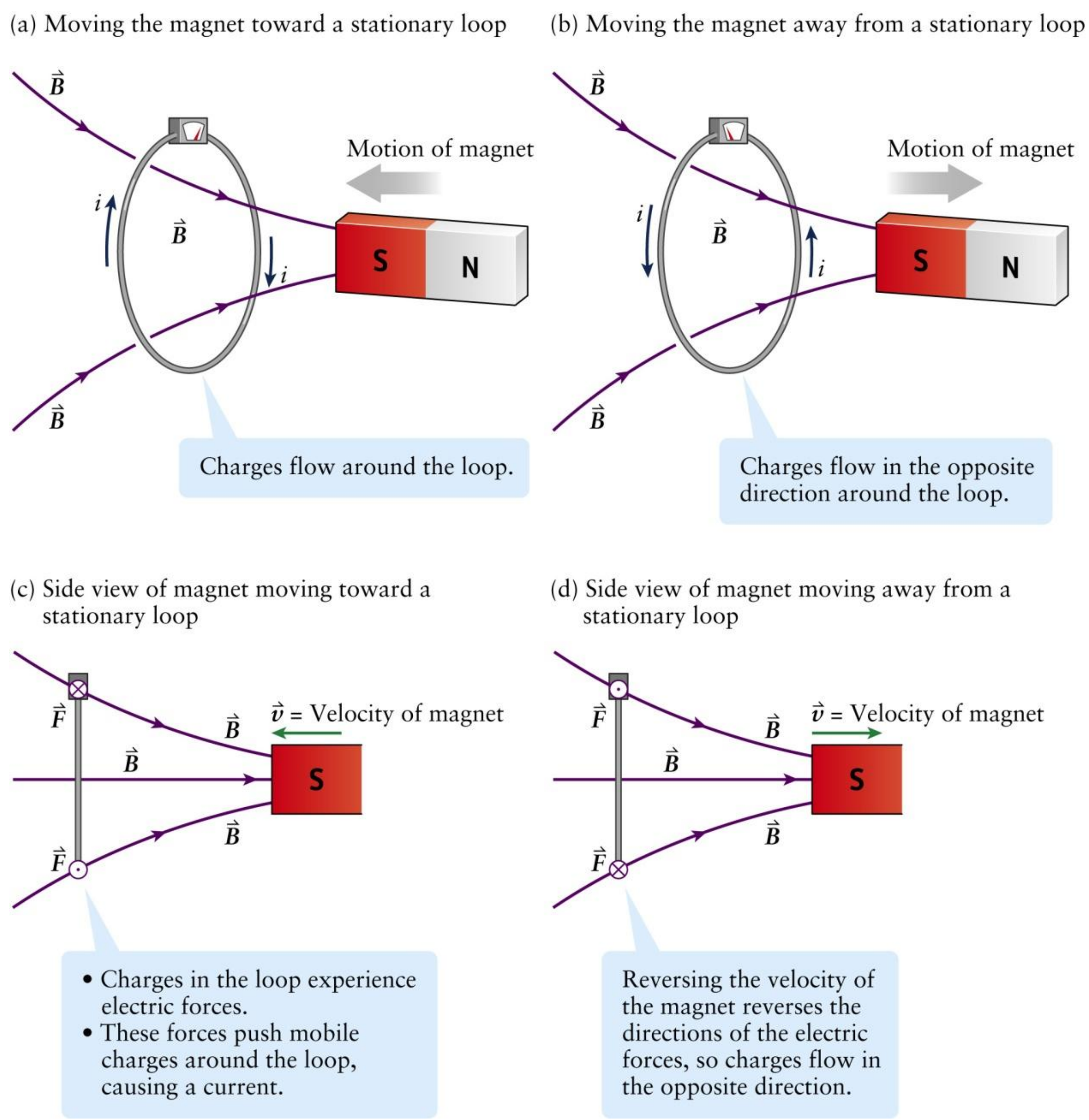

(a) Moving the loop toward a stationary magnet
B
Ammeter
Motion of loop
i
B
i
S
N
B
Charges flow around the loop.
(b) Moving the loop away from a stationary magnet
B
Ammeter
Motion of loop
i
B
i
S
N
B
Charges flow in opposite direction around the loop.
(c) Side view of loop moving toward a stationary magnet
v = Velocity of loop
F
B
B
S
B
F
v
• Charges in the loop move along with the loop in the magnetic field.
• Magnetic forces push mobile charges around the loop, causing a current.
(d) Side view of loop moving away from a stationary magnet
v = Velocity of loop
F
F
B
B
S
B
v
F
Reversing the velocity of the loop reverses the directions of the magnetic forces, so charges flow in the opposite direction.

(c) Side view of magnet moving toward a stationary loop



- Charges in the loop experience electric forces.
- These forces push mobile charges around the loop, causing a current.

CHAPTER 20: FIGURE 20-3



Magnetic flux through a surface

Area of the surface

Angle between the magnetic field and the perpendicular to the surface

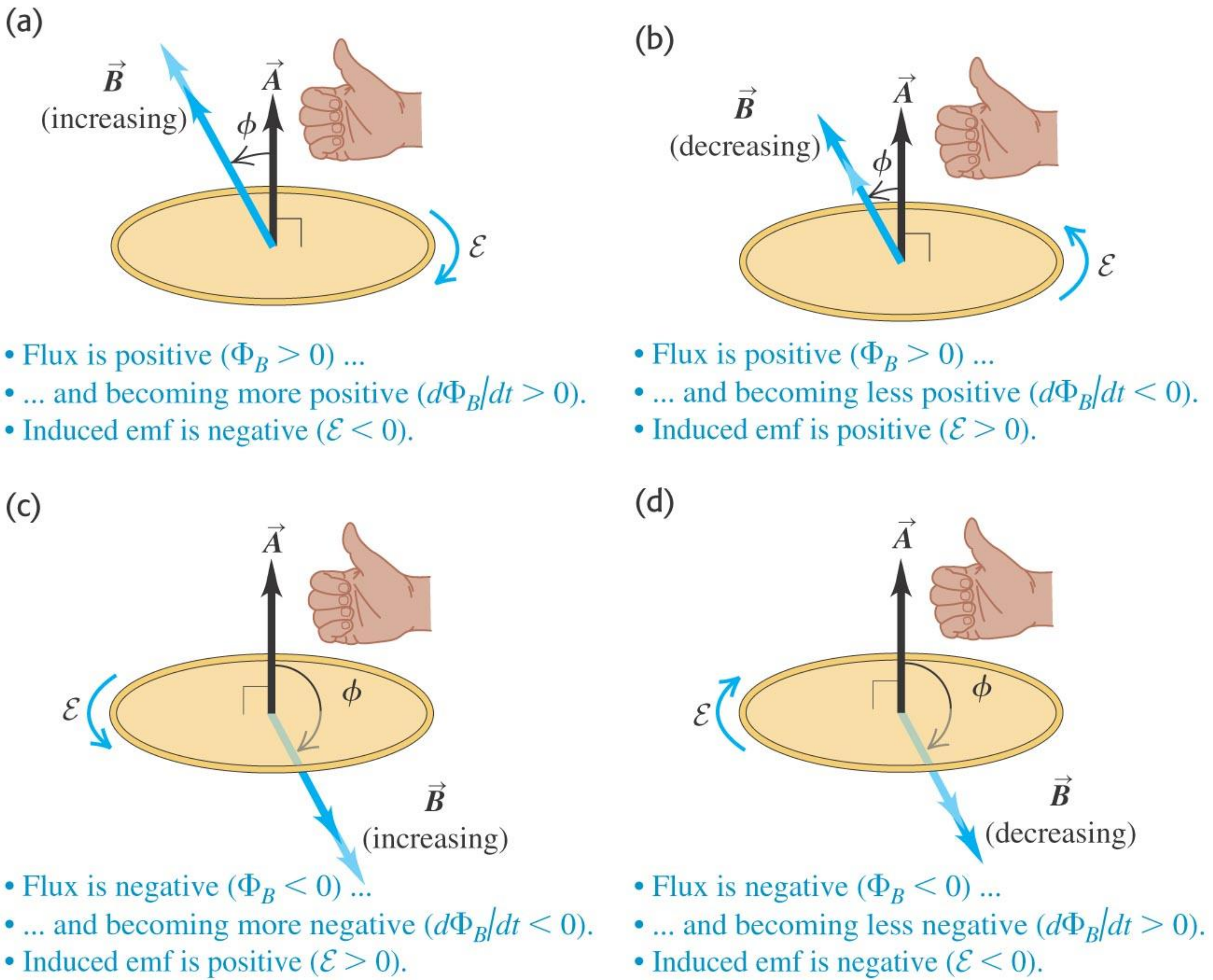
$$\Phi_B = AB_{\perp} = AB\cos\theta$$

The component of magnetic field perpendicular to the surface

Magnitude of the magnetic field

Finding the direction of an induced emf

Induced EMF will produce current to create a magnetic field to OPPOSE the CHANGE in the original magnetic field



Magnitude of the induced or motional emf in a loop

Change in the magnetic flux through the surface outlined by the loop

$$|\varepsilon| = \left|\frac{\Delta\Phi_B}{\Delta t}\right|$$

Time interval over which the change in magnetic flux takes place

Induced or motional emf in a loop

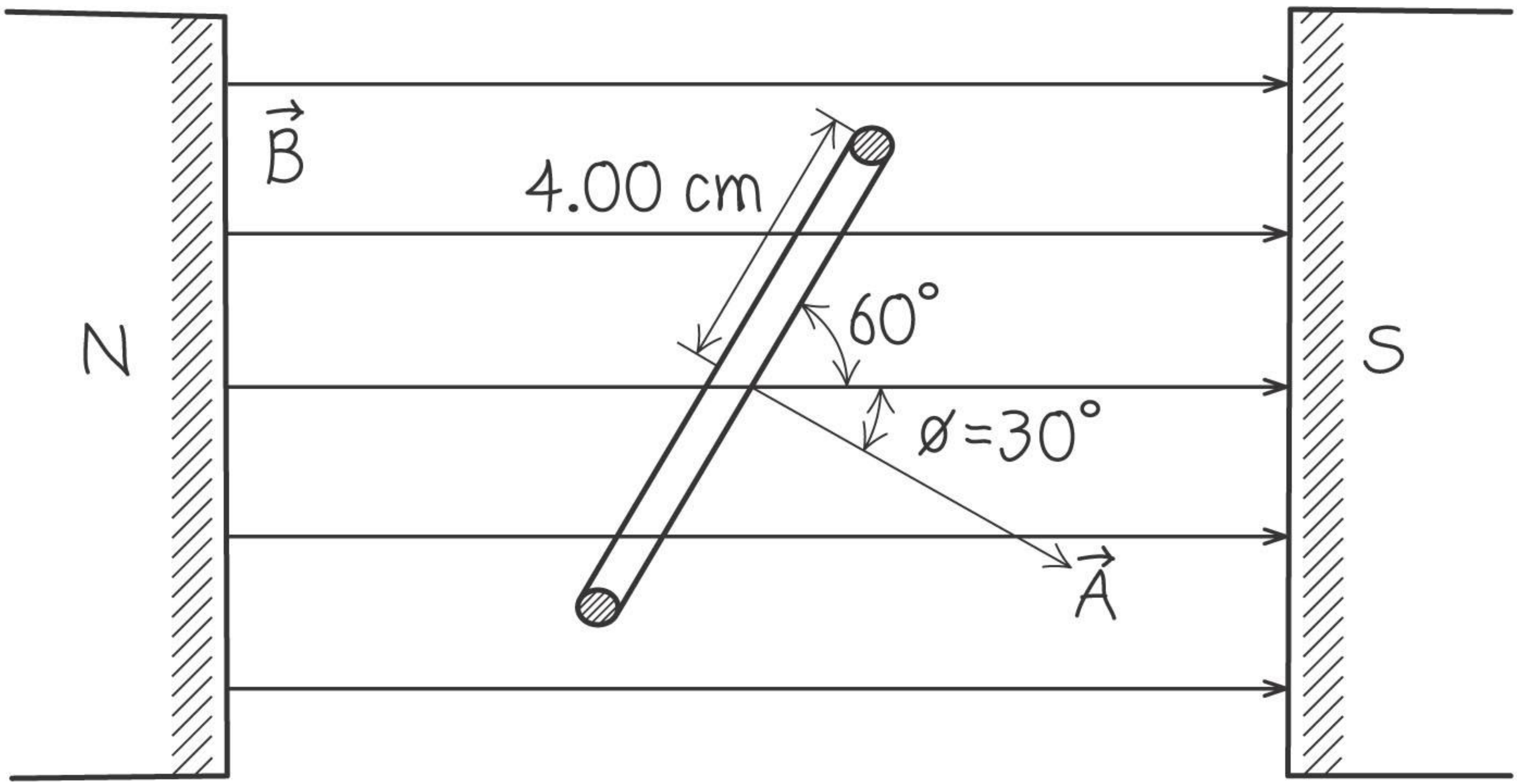
Change in the magnetic flux through the surface outlined by the loop

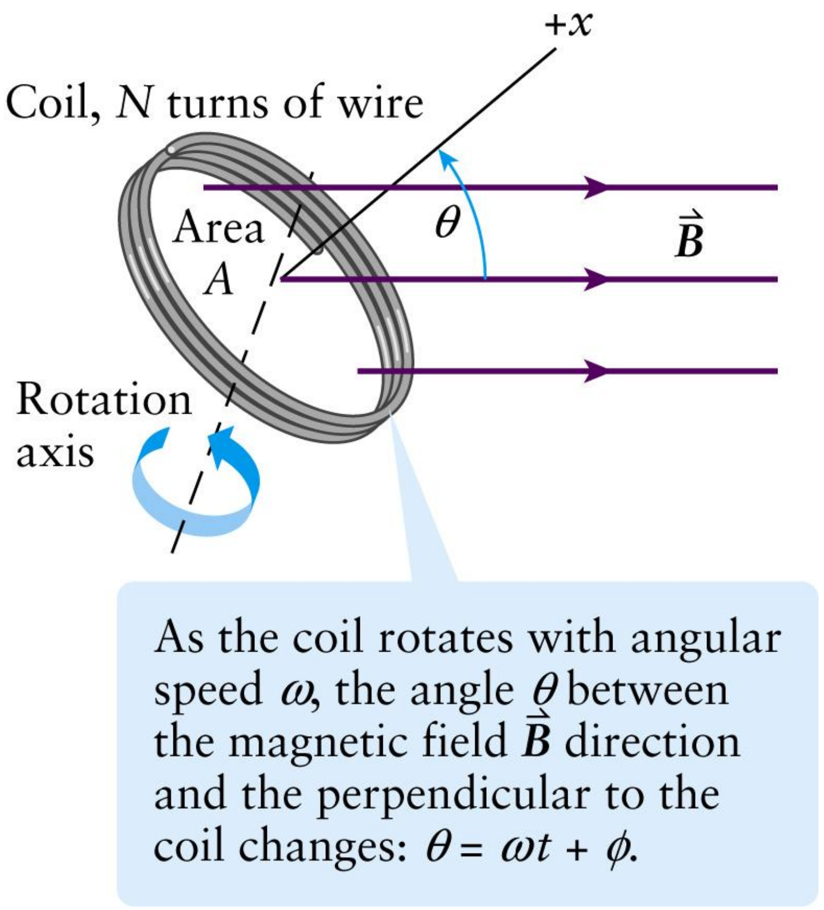
$$\varepsilon = -\frac{\Delta\Phi_B}{\Delta t}$$

Time interval over which the change in magnetic flux takes place

The minus sign indicates that the current caused by the emf induces a magnetic field which opposes the change in flux.

Faraday's Law




+x
Coil, N turns of wire
Area
A
θ
B
Rotation
axis
As the coil rotates with angular speed ω, the angle θ between the magnetic field B direction and the perpendicular to the coil changes: θ = ωt + ϕ.

Angular speed of the rotating coil

Time

Angle of the coil at $t = 0$

Emf produced by an ac generator

$$\varepsilon = \omega NAB \sin(\omega t + \phi)$$

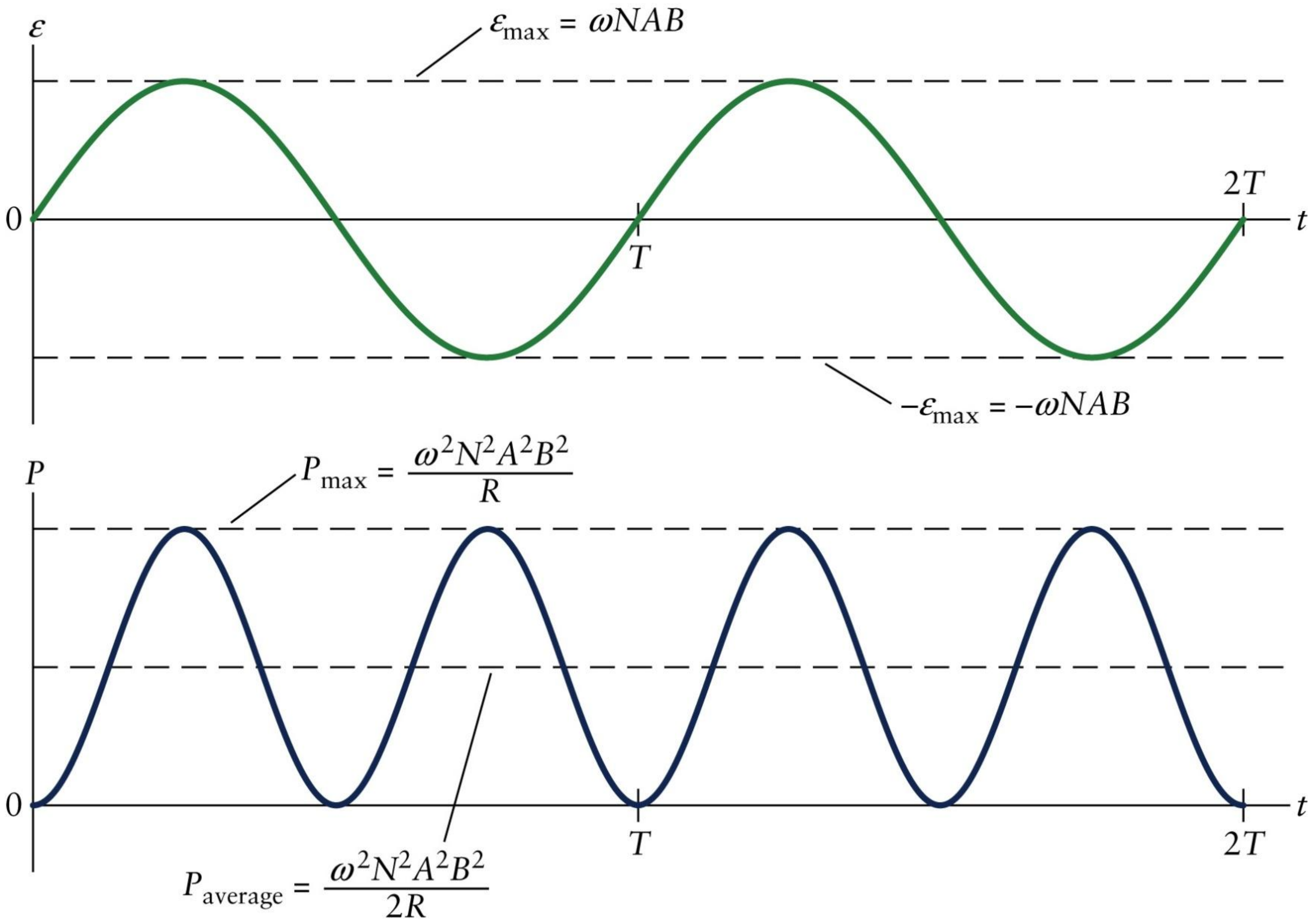
Number of turns in the coil

Area of the coil

Magnitude of the magnetic field to which the coil is exposed

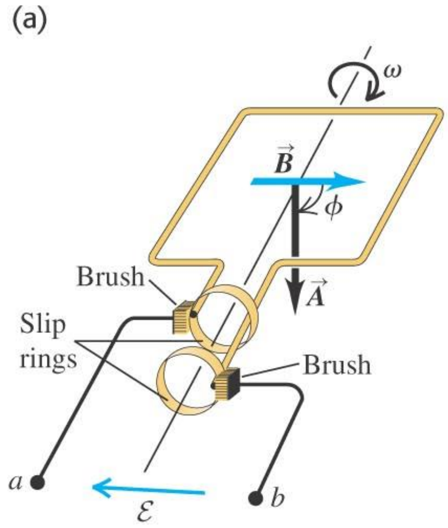
$$\varepsilon = \omega NAB \sin(\omega t + \phi)$$

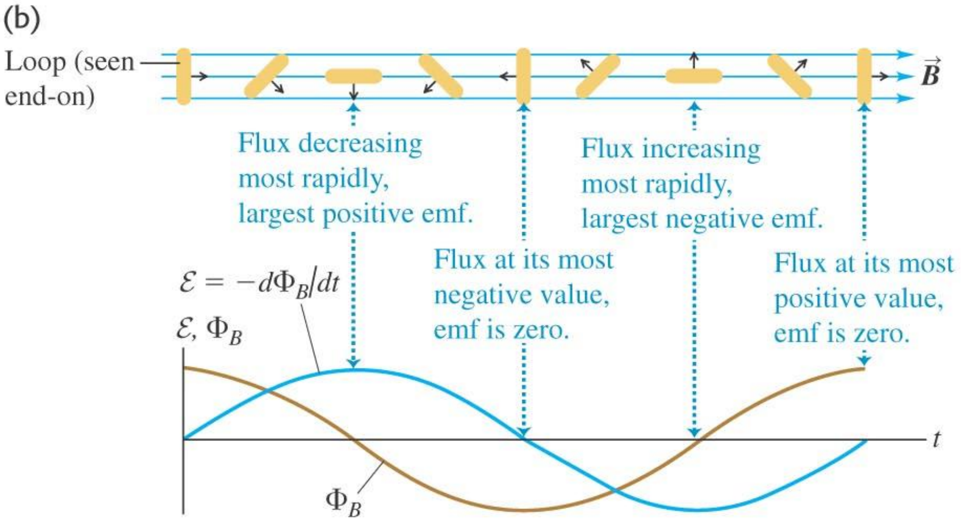
- ε: Emf produced by an ac generator
- ω: Angular speed of the rotating coil
- N: Number of turns in the coil
- A: Area of the coil
- B: Magnitude of the magnetic field to which the coil is exposed
- t: Time
- ϕ: Angle of the coil at $t = 0$


ε
$\varepsilon_{max} = \omega NAB$
0
t
T
$2T$
$-\varepsilon_{max} = -\omega NAB$
P
$P_{max} = \dfrac{\omega^2 N^2 A^2 B^2}{R}$
0
t
T
$2T$
$P_{average} = \dfrac{\omega^2 N^2 A^2 B^2}{2R}$

Generator example

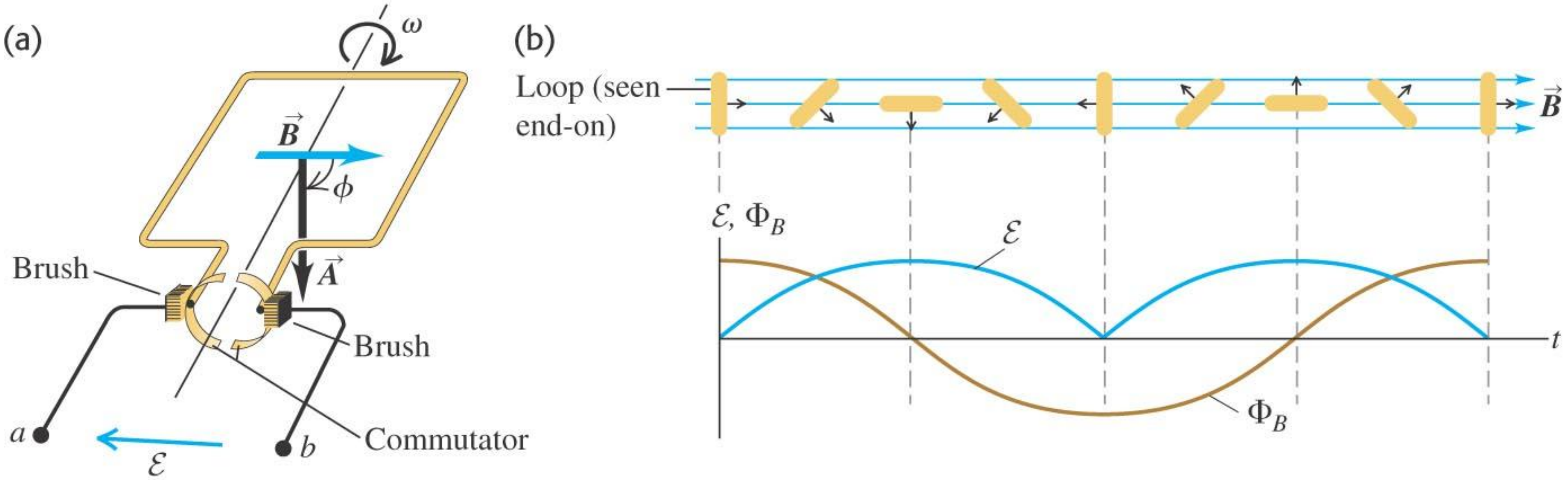
- A changing magnetic flux is actually what induces a changing electric field.
- Magnetic flux change is the field changes or if the direction changes





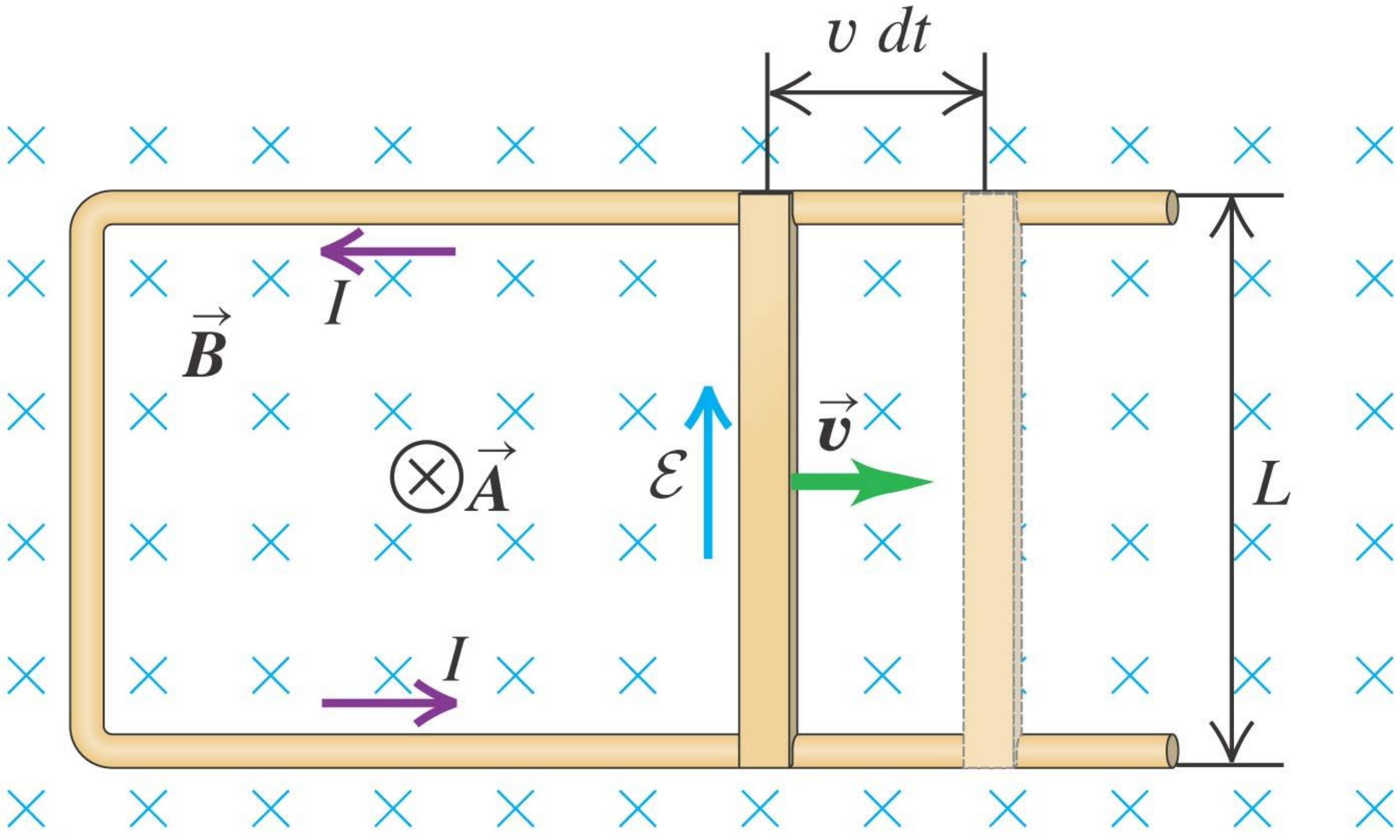
Generator example II

- In a sense a DC generator is a motor run in reverse
- Back EMF in a motor.
- Motor back EMF ultimately limits the motor speed
- Back EMF reduces voltage available to drive the motor
- Hence the motor current is less with speed – torque drops



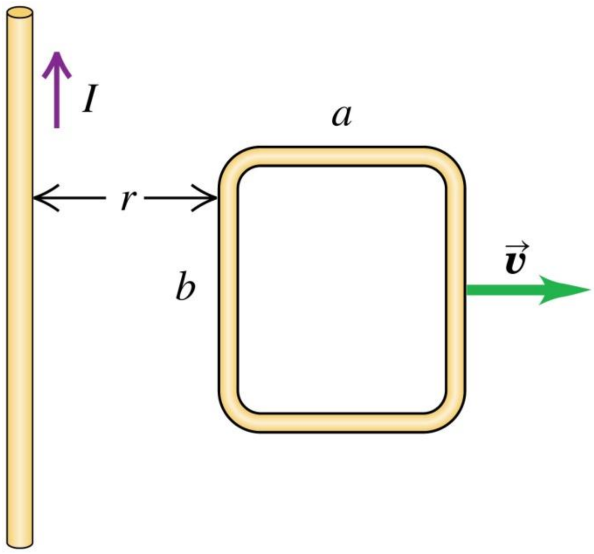
Generator example III

- A linear motor is similar to a rotary motor but is linear
- A "rail gun" is an example



Q29.8

The rectangular loop of wire is being moved to the right at constant velocity. A constant current *I* flows in the long wire in the direction shown. What are the directions of the magnetic forces on the left-hand (L) and right-hand (R) sides of the loop?



A. L: to the left; R: to the left

B. L: to the left; R: to the right

C. L: to the right; R: to the left

D. L: to the right; R: to the right

E. none of the above

A29.8

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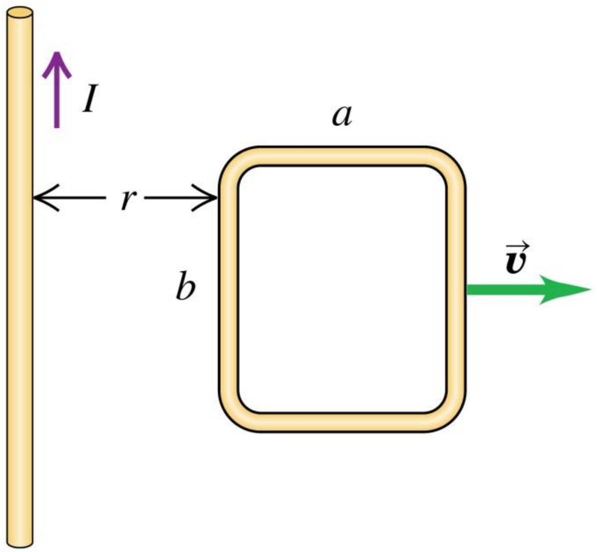


To oppose decreasing flux (moving further away) current must flow to increase flux (opposes decrease) → current flow in clockwise direction → B since parallel currents attract and opposite currents attract

A. L: to the left; R: to the left

✓ B. L: to the left; R: to the right

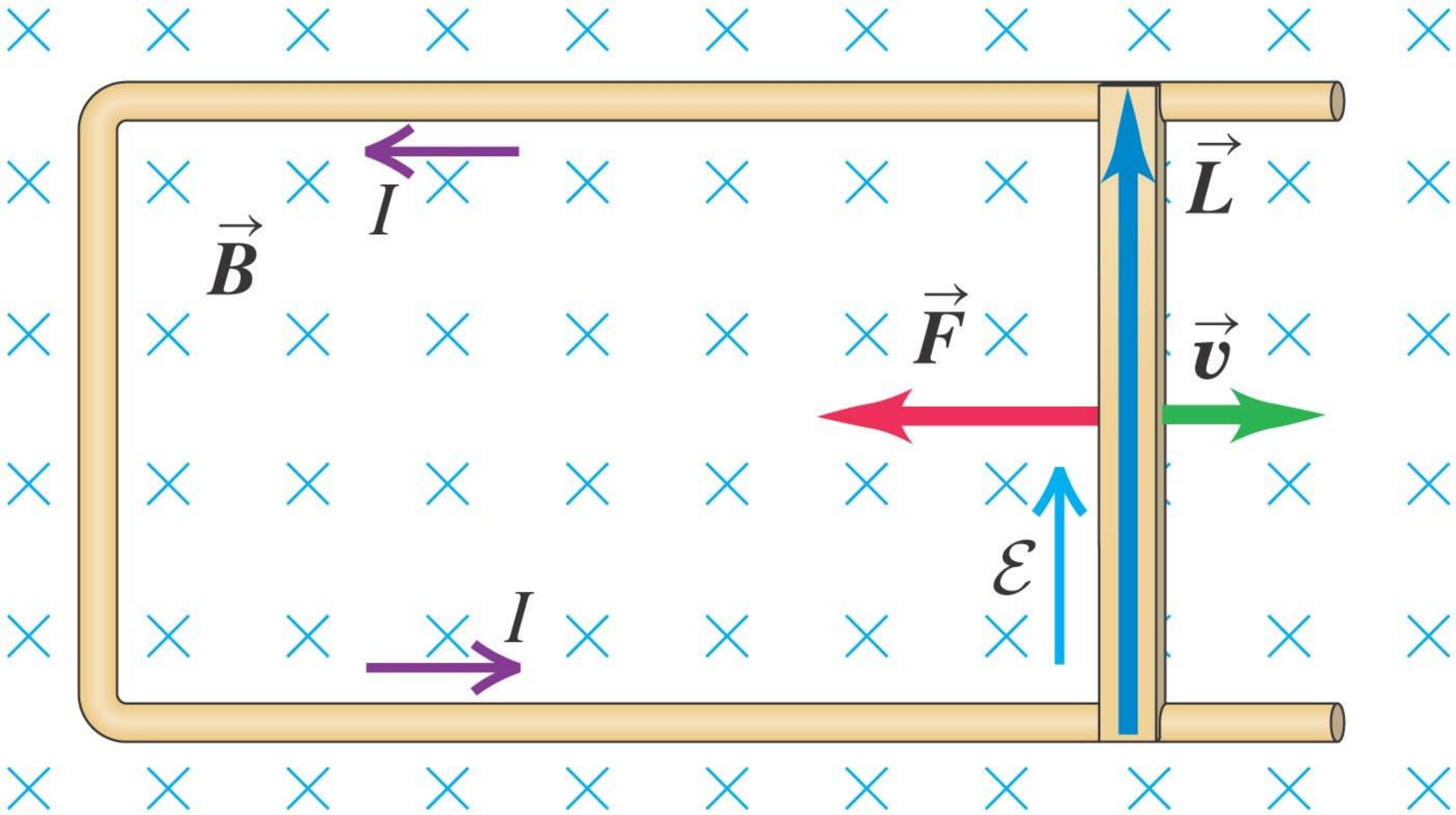
C. L: to the right; R: to the left

D. L: to the right; R: to the right

E. none of the above

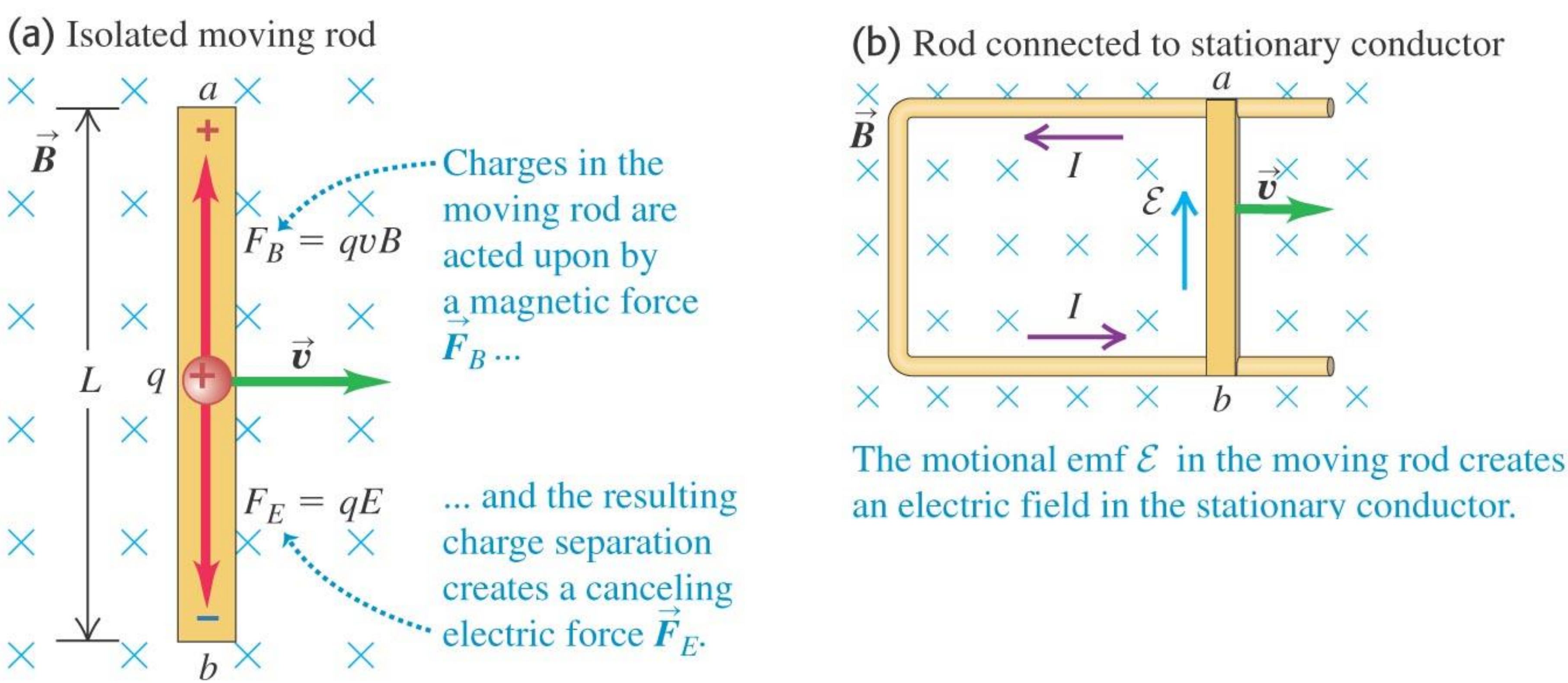
Work and power in a slidewire generator

- A linear motor run backwards is a generator



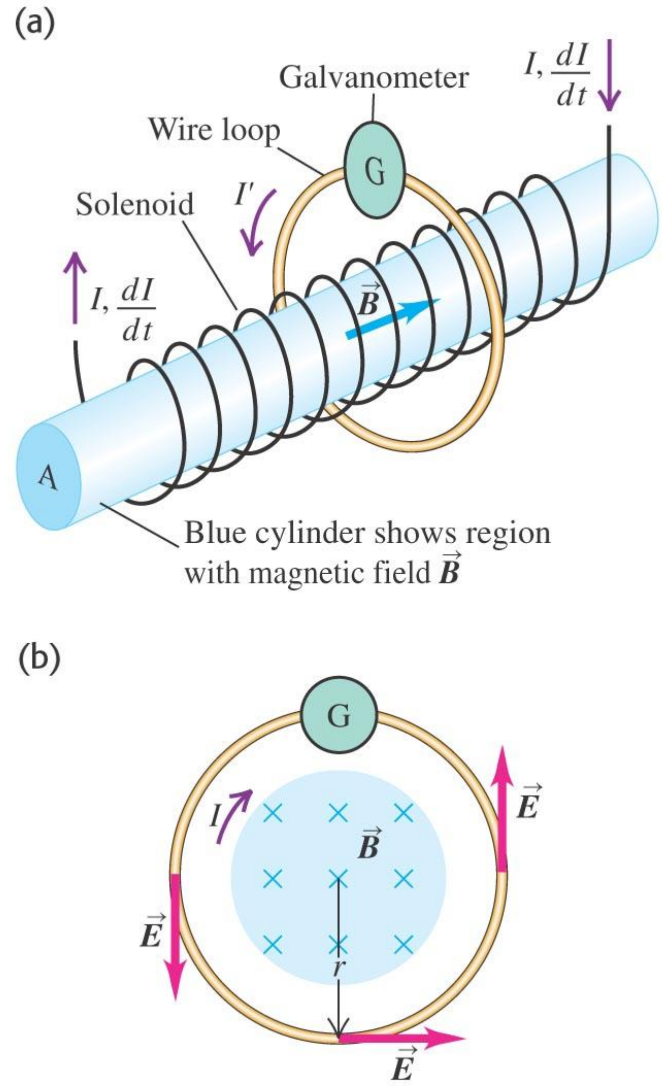
A conducting rod moving in a uniform magnetic field

- The rod, velocity, and current are mutually perpendicular



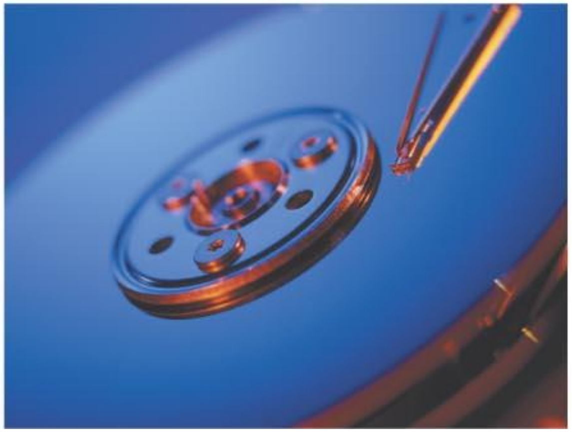
Induced electric fields I

- The windings of a long solenoid carrying a current I



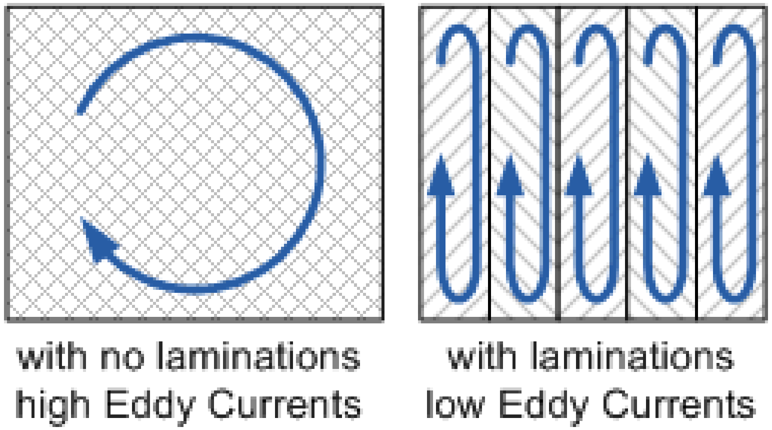
Induced electric fields II

- Practical examples of induction
- It is in your everyday life



- Hard disks – read and write
- Motors in electric cars and hybrids – regenerative breaking
- Ignition in gas engines

Breaking up magnetic core into laminations reduces Eddy current losses

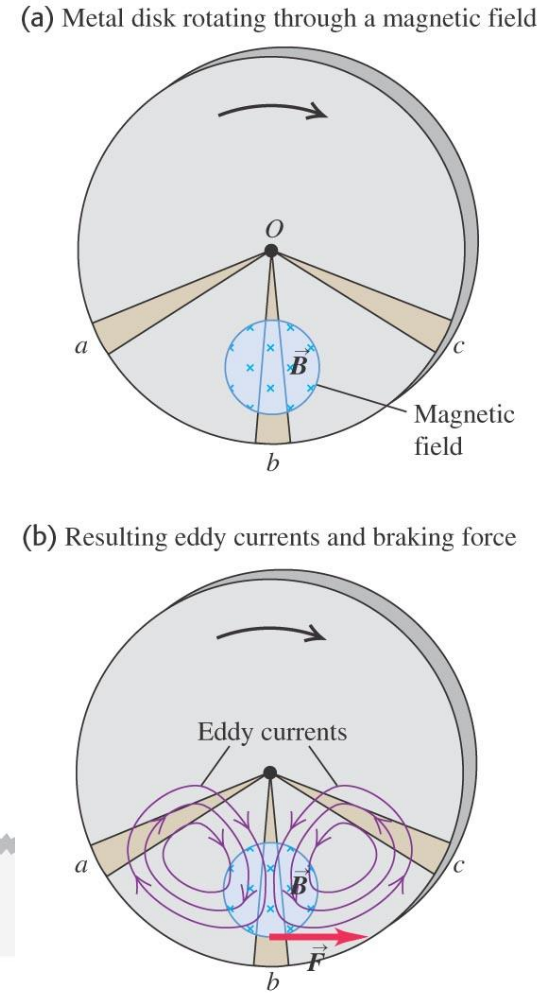


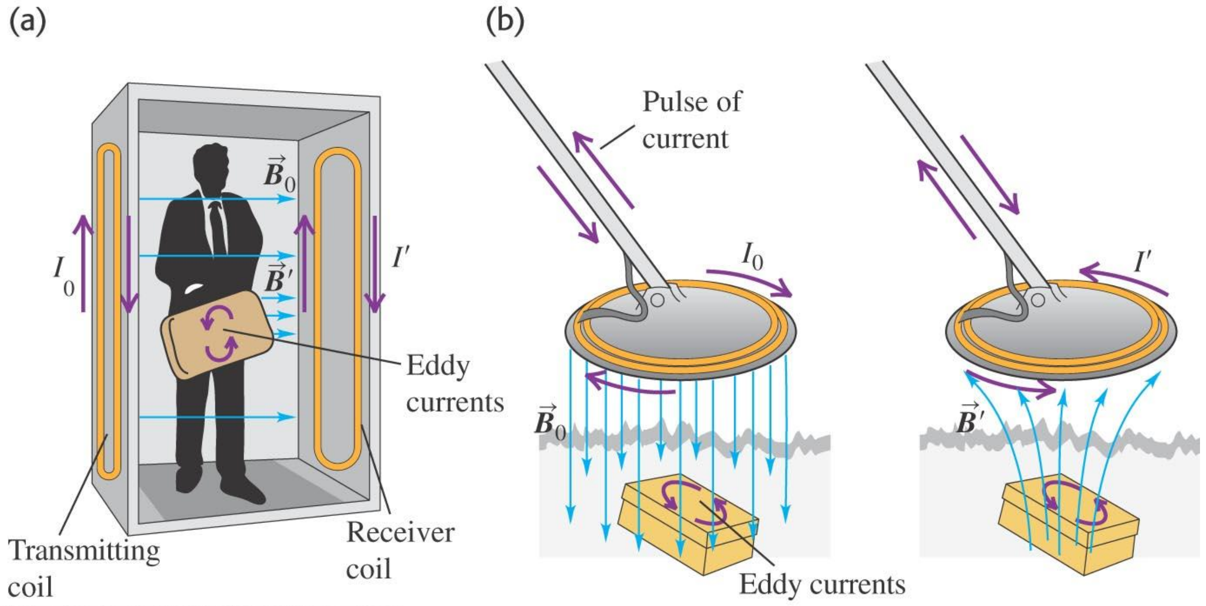
Small motor armature winding

Note – laminated metal core to reduce eddy currents

Eddy currents

- Metal detection
- Airport and music store
- Eddy current braking

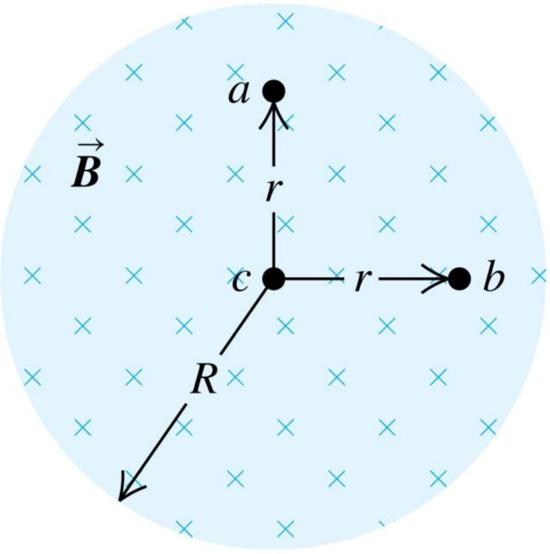




Q29.9

The drawing shows the uniform magnetic field inside a long, straight solenoid. The field is directed into the plane of the drawing and is increasing.

What is the direction of the *electric* force on a positive point charge placed at point *a*?



A. to the left

B. to the right

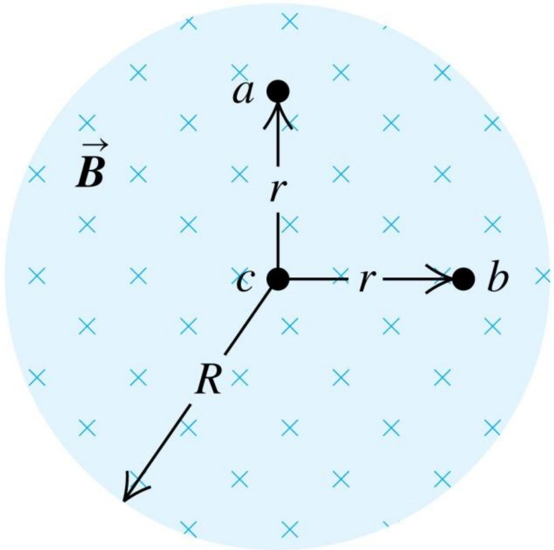
C. straight up

D. straight down

E. misleading question—the electric force at this point is zero

A29.9

The drawing shows the uniform magnetic field inside a long, straight solenoid. The field is directed into the plane of the drawing and is increasing.



What is the direction of the *electric* force on a positive point charge placed at point *a*?

(it must produce a current that produces a B field that opposes the change of the original changing flux) – imagine a wire loop with radius r

A. to the left

B. to the right

C. straight up

D. straight down

E. misleading question—the electric force at this point is zero