Chapter 13: Electromagnetic Induction

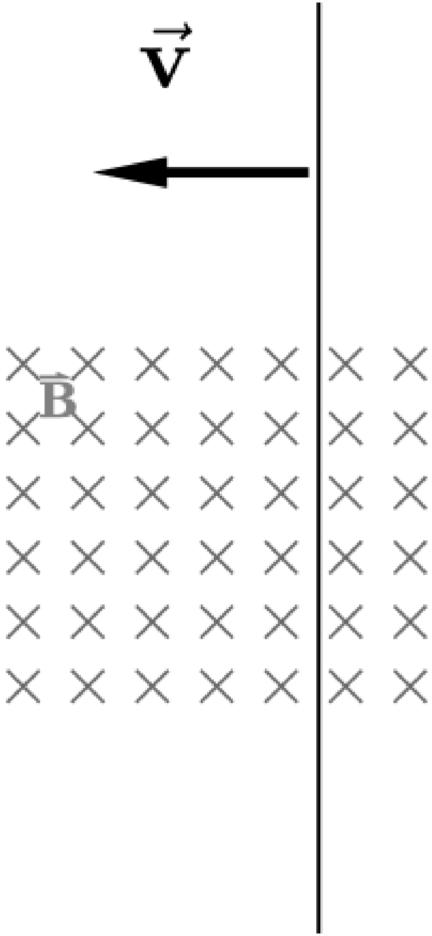
Faraday's Law
Lenz's Law
Motional Emf
Induced Electric Fields

Eddy Currents
Electric Generators and Back Emf
Applications of Electromagnetic Induction

Motional EMF

A wire is moved through a magnetic field, as shown. What is the direction of force on the (+) charges in the wire?

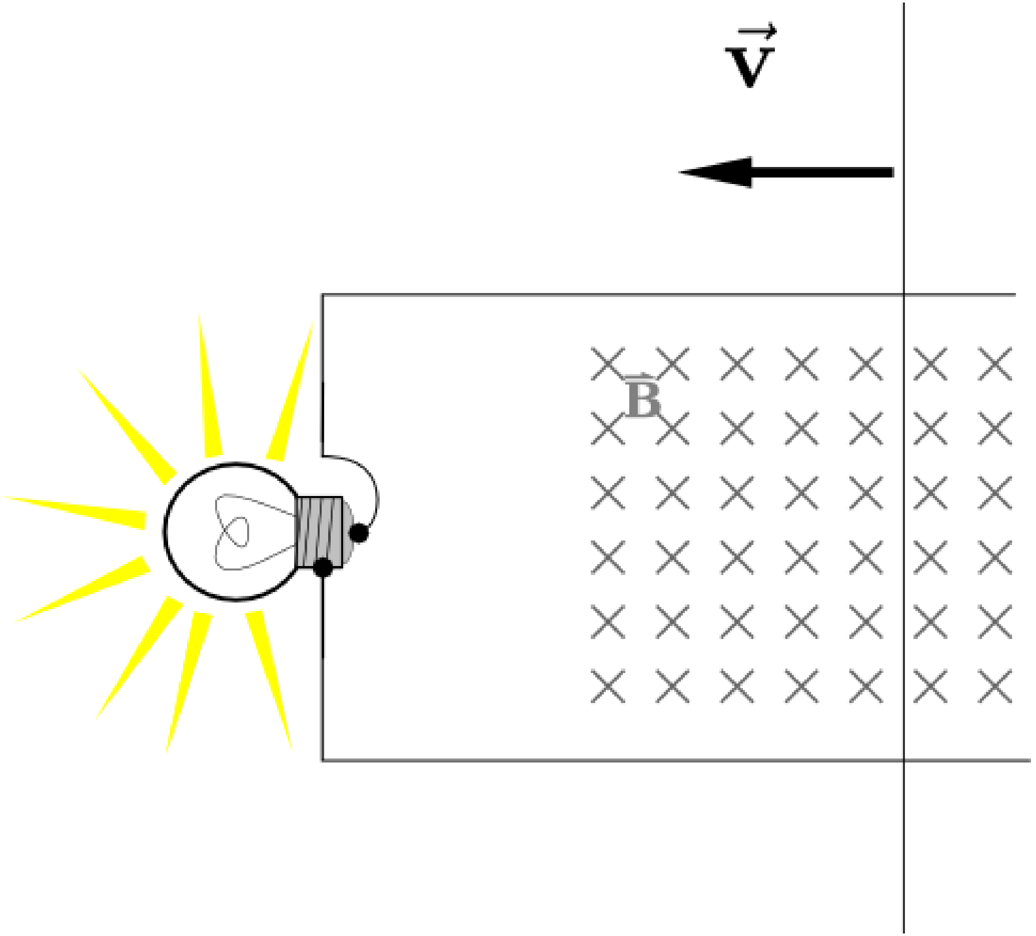
A. up
✔ B. down
C. in (×)
D. out (·)



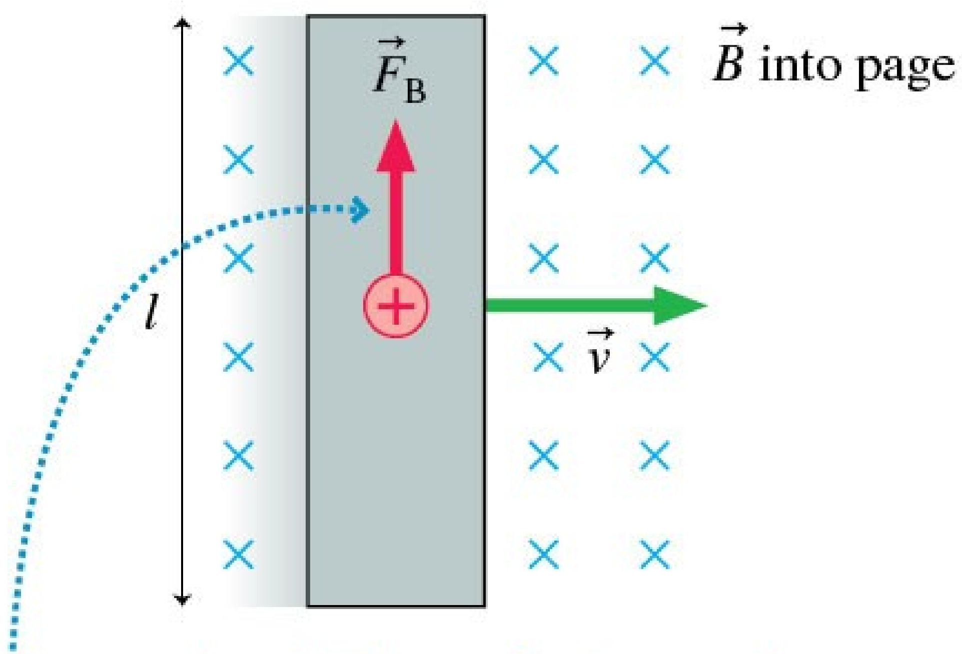
Current Induction

What is the direction of the current through the bulb?

- ✔ A. up
- B. down
- C. dunno

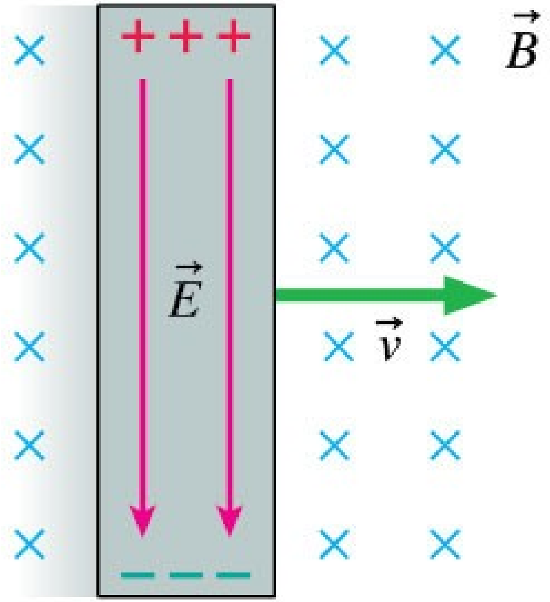


Induced EMF



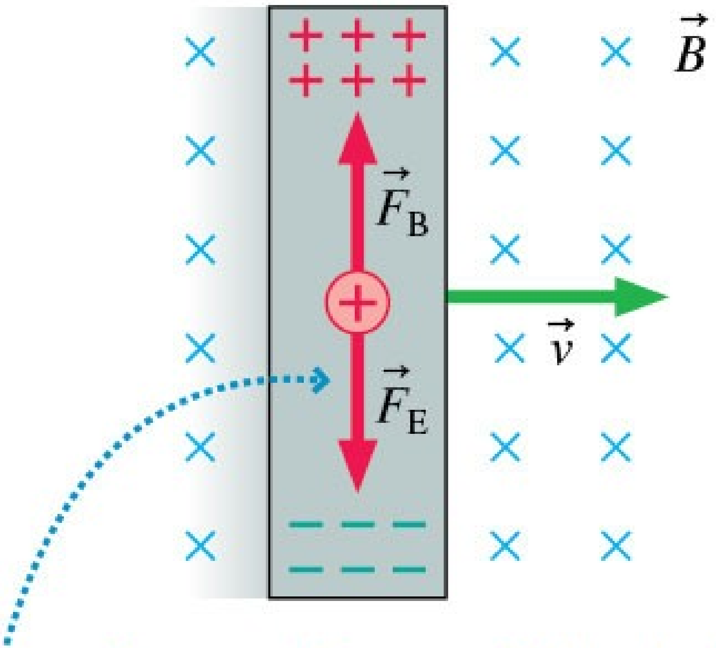
Charge carriers in the conductor experience a force of magnitude $F_B = qvB$. Positive charges are free to move and drift upward.

Induced EMF



The resulting charge separation creates an electric field in the conductor. $\vec{E}$ increases as more charge flows.

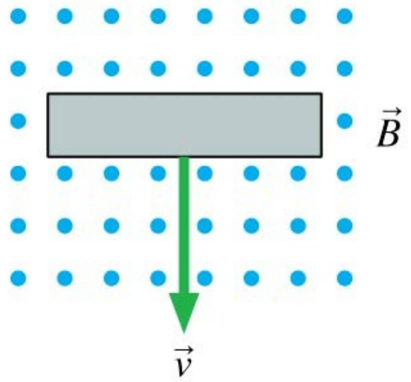
Induced EMF

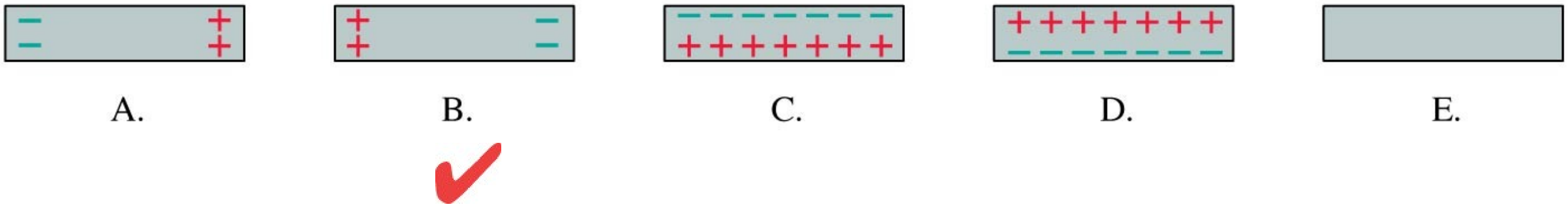


The charge flow continues until the electric and magnetic forces balance. For a positive charge carrier, the upward magnetic force $\vec{F}_B$ is equal to the downward electric force $\vec{F}_E$.

Induced EMF

A metal bar moves through a magnetic field. The induced charges on the bar are





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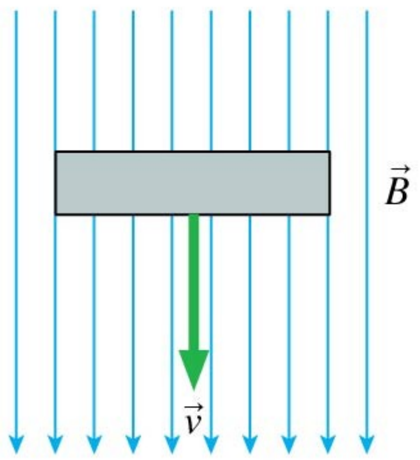
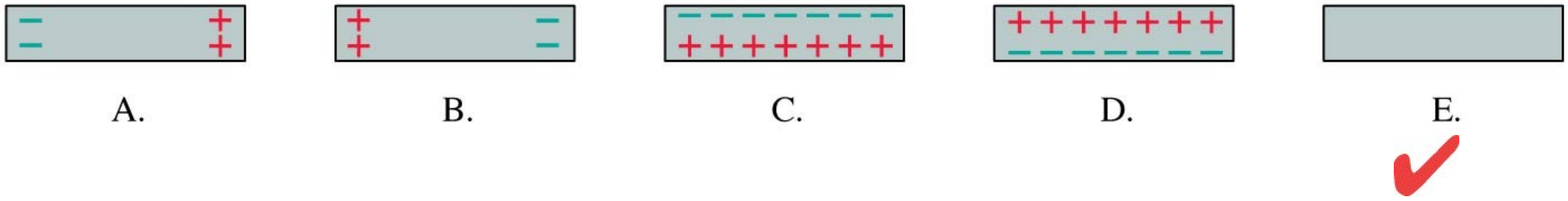




Motional EMF

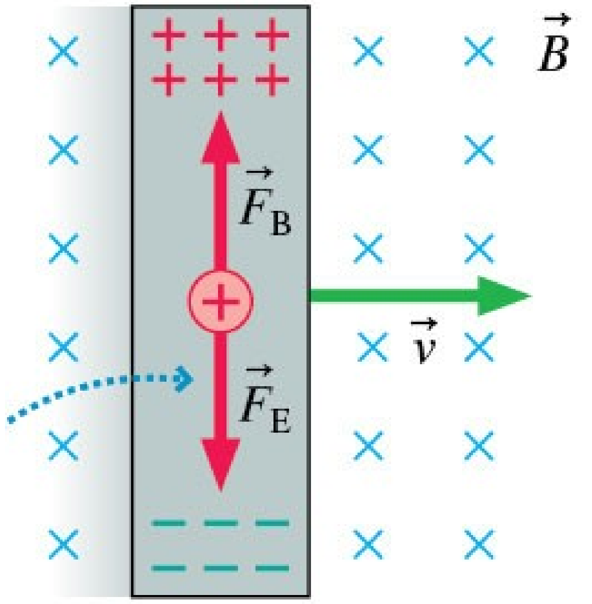
Find the induced voltage:

$$\mathcal{E} = E\ell = \frac{F_E}{q}\ell = \frac{F_B}{q}\ell = \frac{qvB}{q}\ell$$

"motional emf"

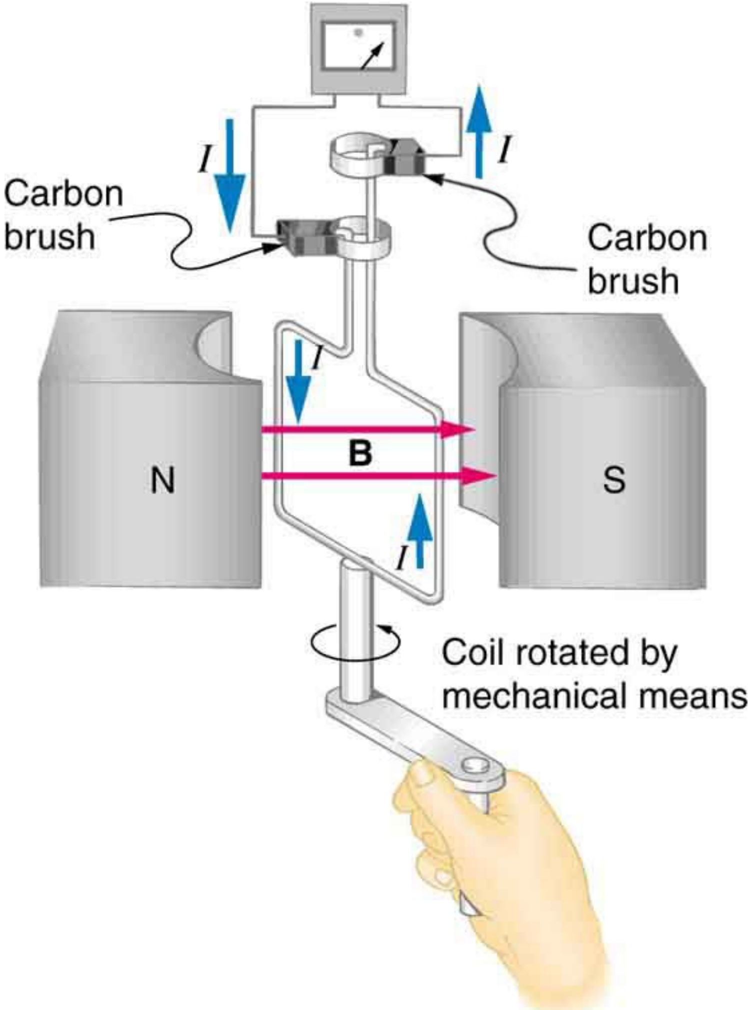
$$\mathcal{E} = Blv$$

voltage induced by motion relative to a magnetic field



Motional EMF

You can generate voltage by moving a wire through a magnetic field.

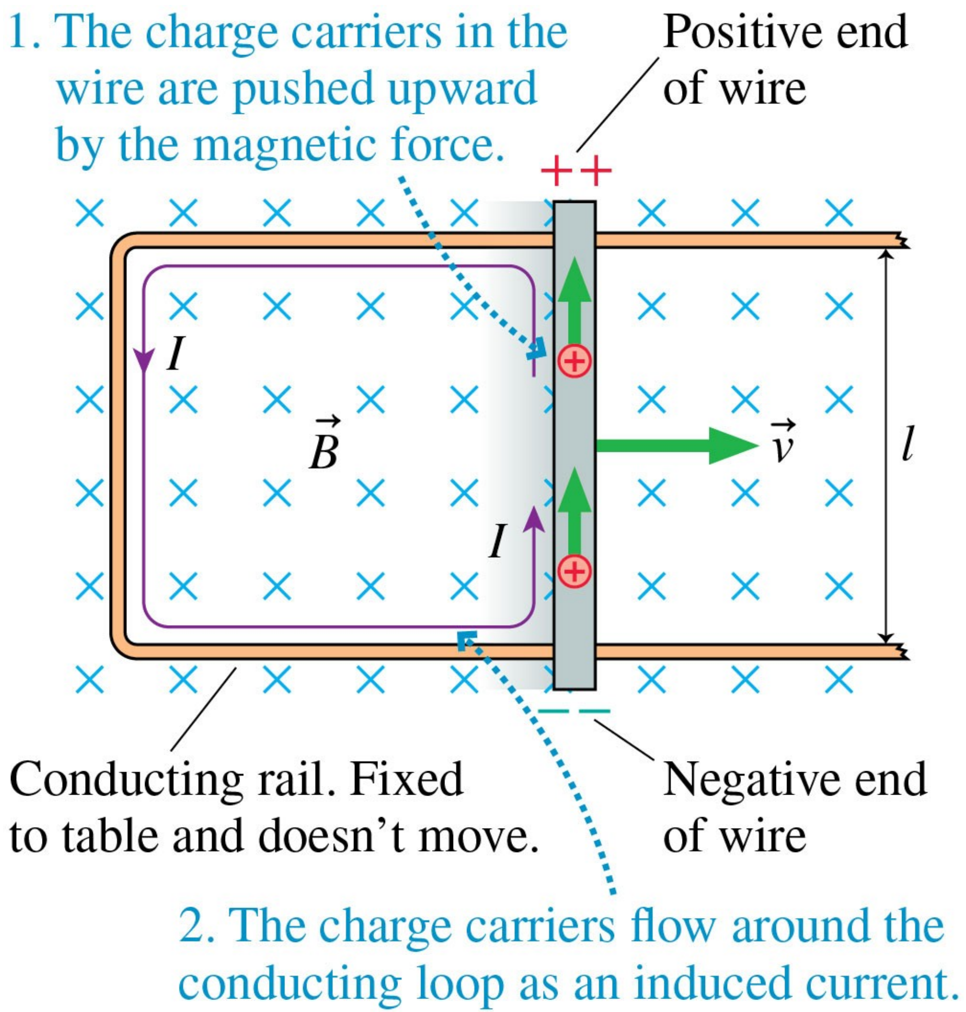


Current Induction

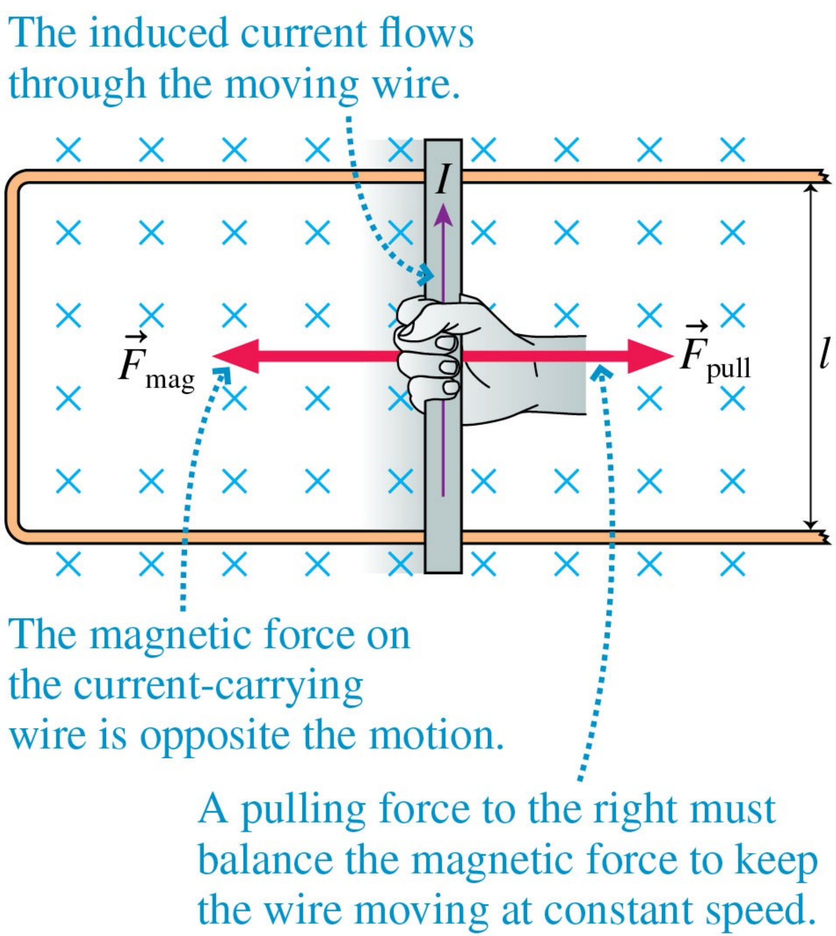
This is not free energy.

The induced current is

$$I = \frac{\mathcal{E}}{R} = \frac{vlB}{R}$$



Current Induction



- To keep the wire moving at a constant speed v, we must apply a pulling force

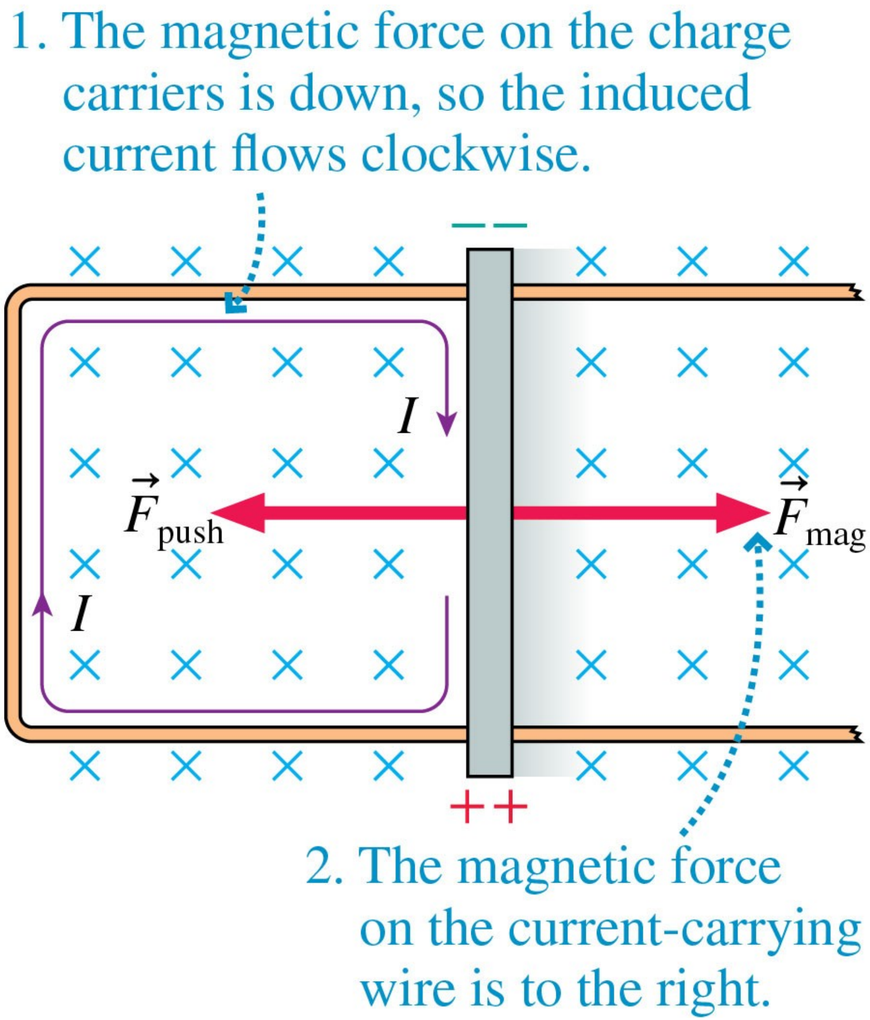
$$F = BI\ell = B\left(\frac{B\ell v}{R}\right)\ell = \frac{B^2\ell^2 v}{R}$$

- This pulling force does work at a rate

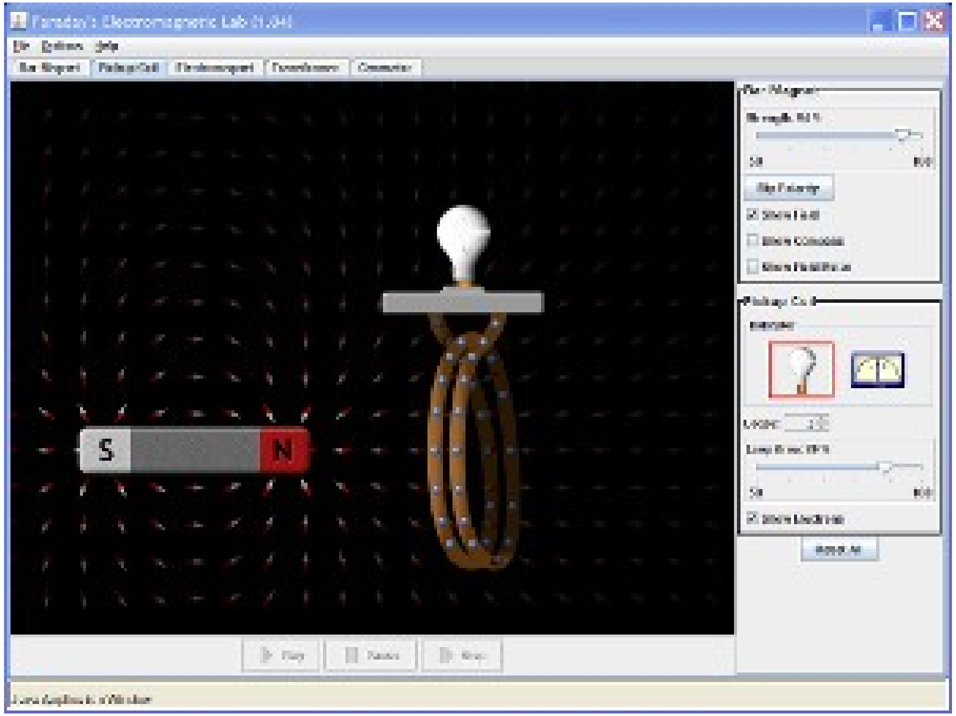
$$P_{\text{input}} = F_{\text{pull}}v = \frac{v^2 l^2 B^2}{R}$$

lec

Current Induction



Current Induction

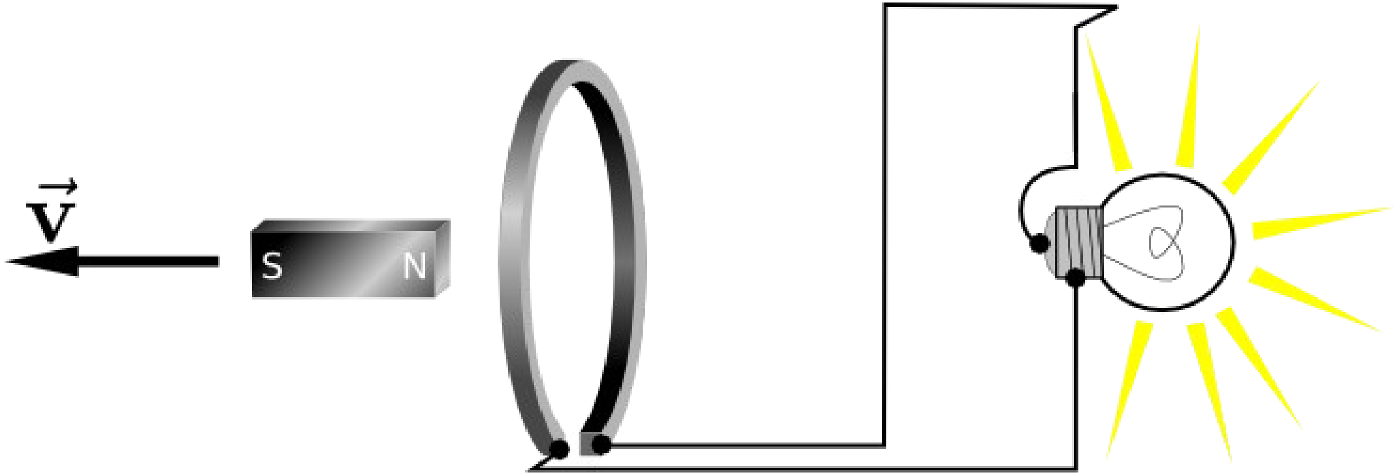


see simulation

Current Induction

What is the ***direction*** of the current through this bulb?

- there will be a current in the loop
- the loop current will create its own magnetic field
- if the work done in moving the magnet goes into light energy of the bulb, should the magnets attract or repel?



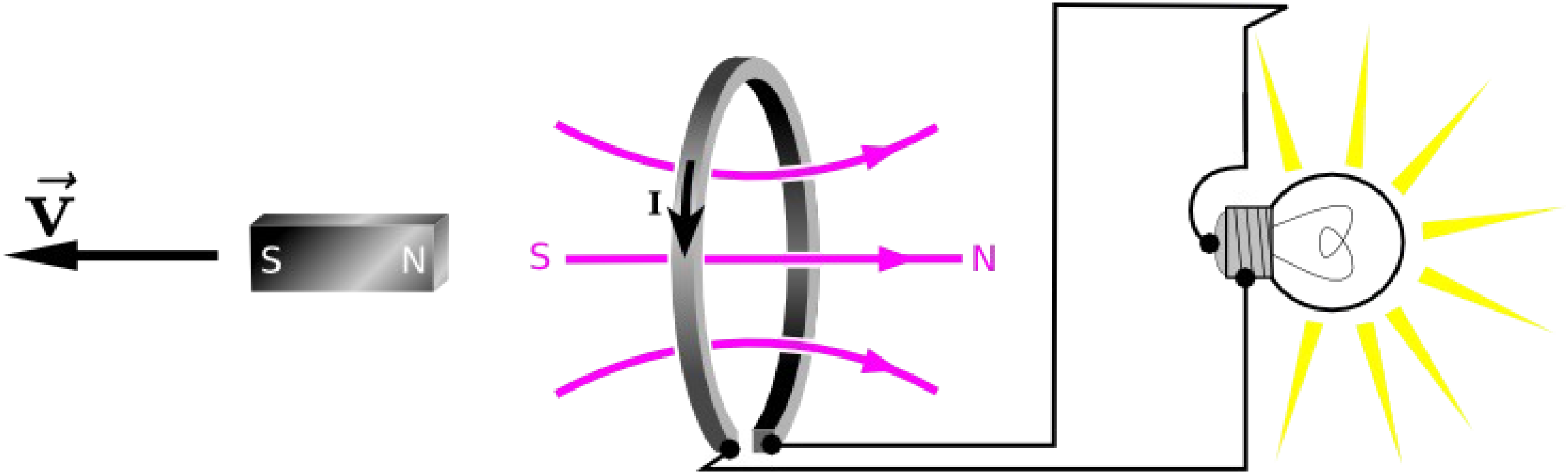
Current Induction

What is the direction of the current through this bulb?

- Should the magnets attract or repel?

  They must ***attract***.

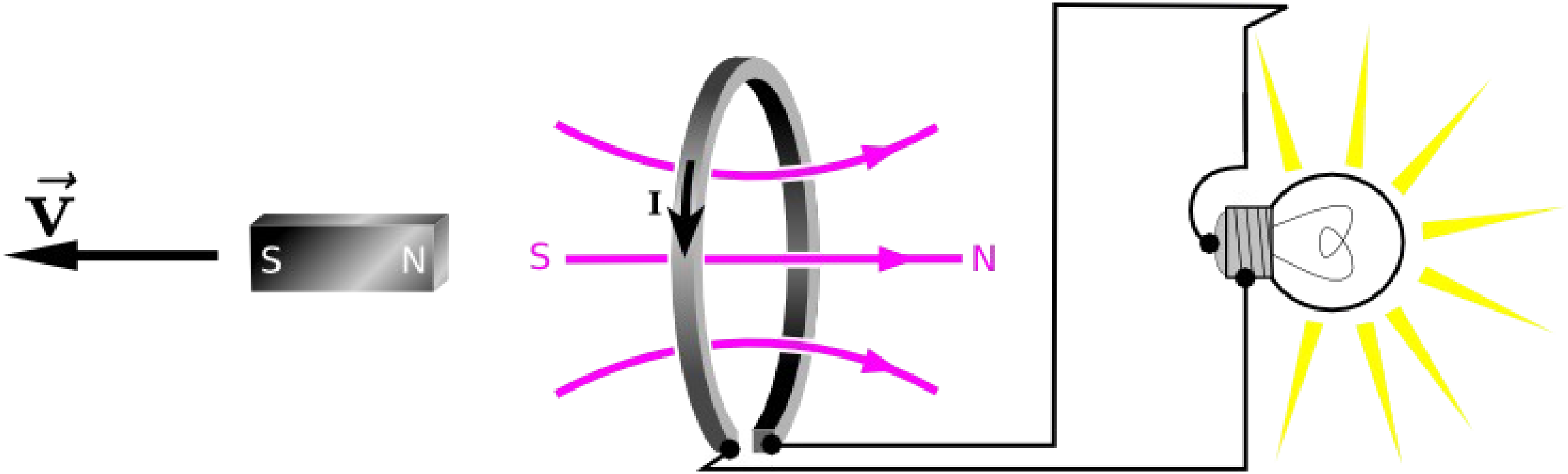
  Otherwise you get free energy (violating conservation of energy).



Current Induction

What is the direction of the current through this bulb?

Current must be **up** through bulb



Current Induction

Faraday's Law

A changing magnetic field through a wire loop will induce a current

Lenz's Law

Induced current will create its own magnetic field that *opposes the change* in the external field

Lenz's Law

Induced current will create its own magnetic field

that ***opposes the change*** in the external field.

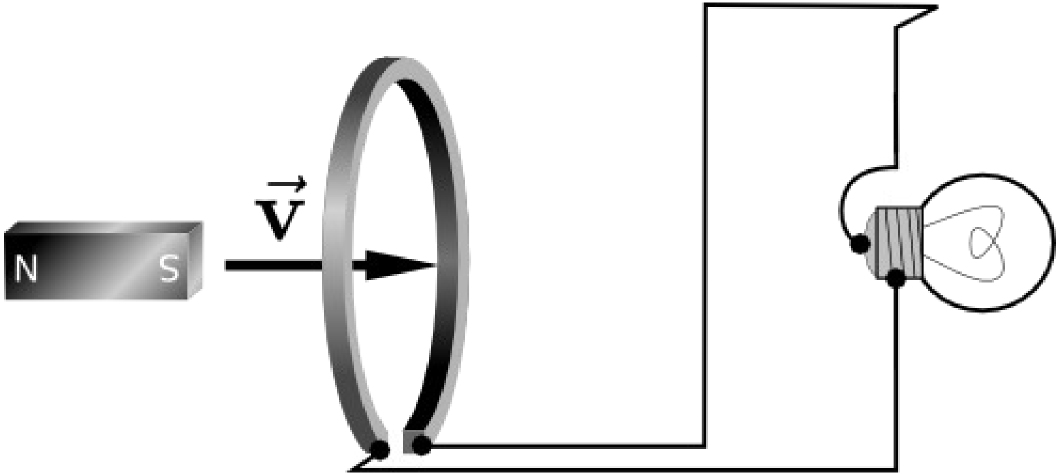
- What is the direction of the (external) magnetic field in the loop?
- Is this field increasing or decreasing in strength?
- What is the direction of magnetic field created by the current in the loop (to oppose the change)?
- What current is required to create this field?

Lenz’s Law

A bulb is illuminated by rapidly bringing a magnet closer to a loop.

What is the direction of the bar magnet's field in the loop?

A. left
B. right
C. up
D. down

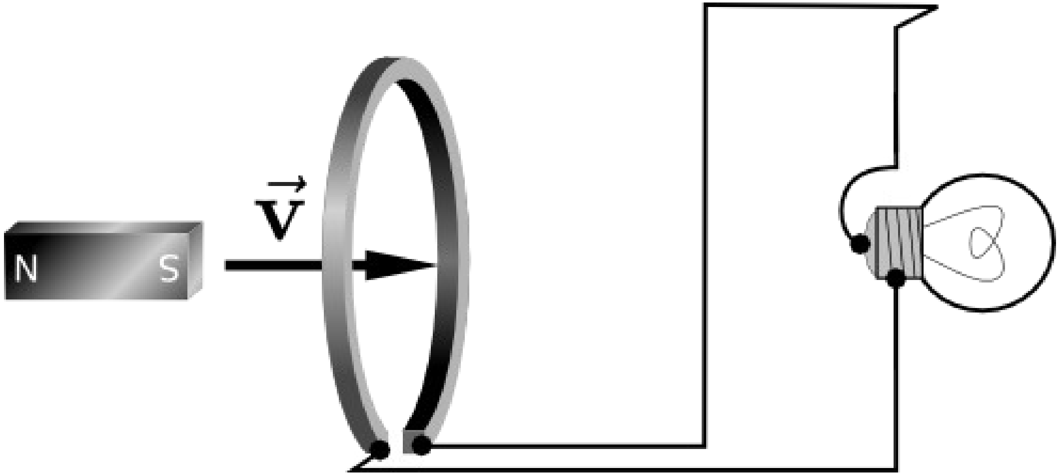


Lenz's Law

A bulb is illuminated by rapidly bringing a magnet closer to a loop.

Is the field in the loop increasing or decreasing in strength?

A. increasing
B. decreasing
C. constant

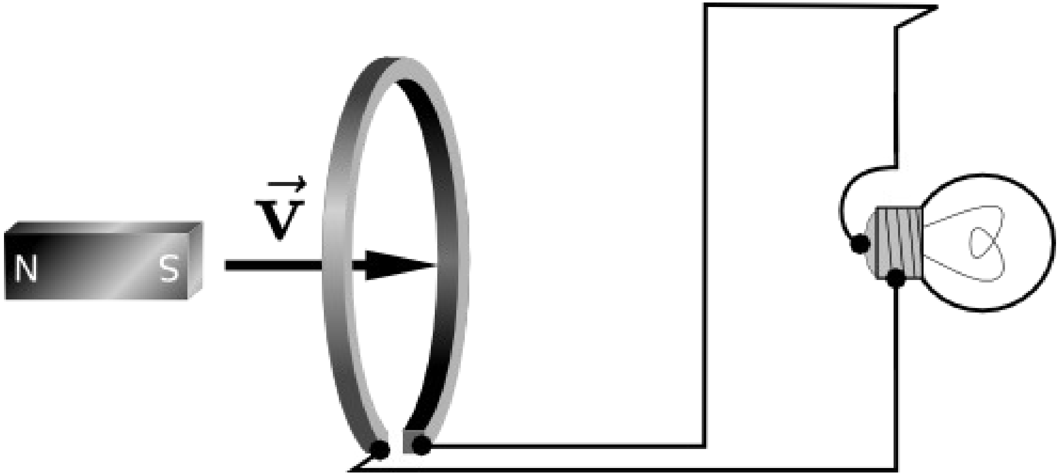


Lenz's Law

A bulb is illuminated by rapidly bringing a magnet closer to a loop.

What is the direction of magnetic field created by the current in the loop?

A. left
B. right
C. up
D. down

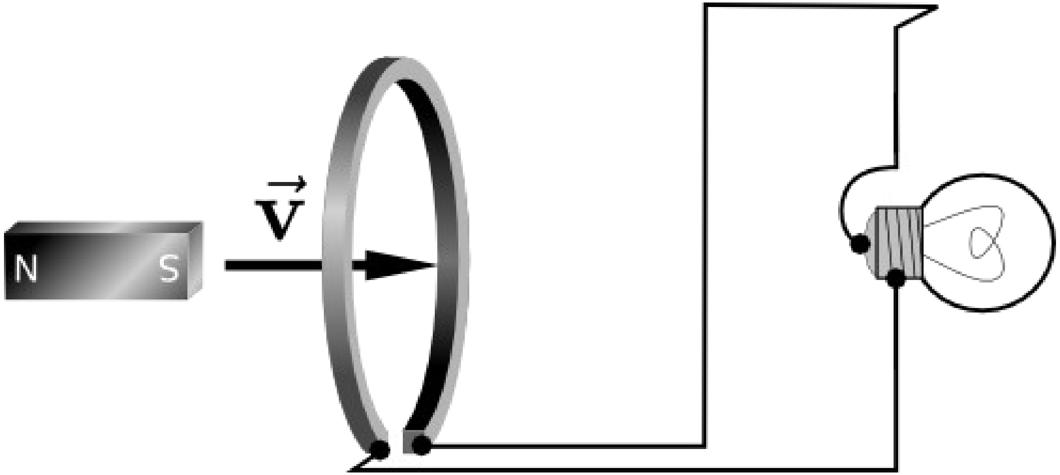


Lenz's Law

A bulb is illuminated by rapidly bringing a magnet closer to a loop.

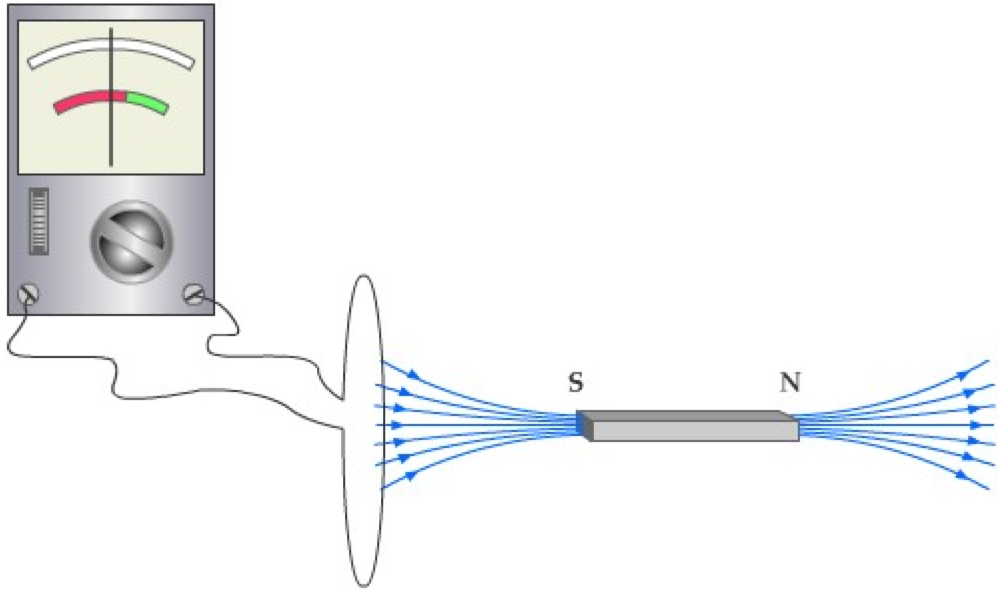
What is the direction of current through the bulb?

A. up
B. down

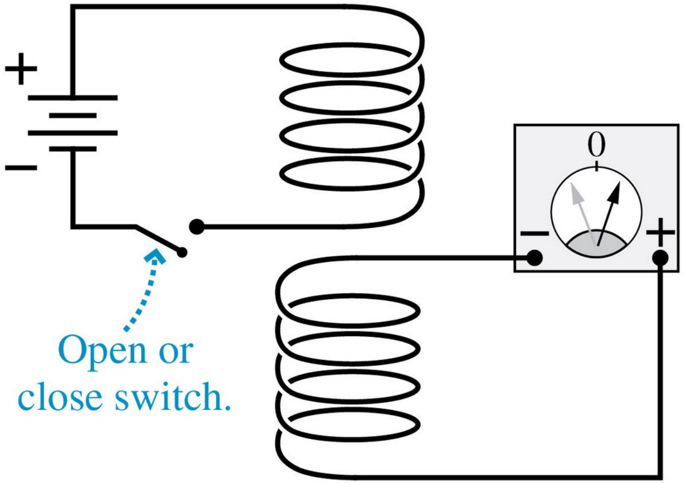


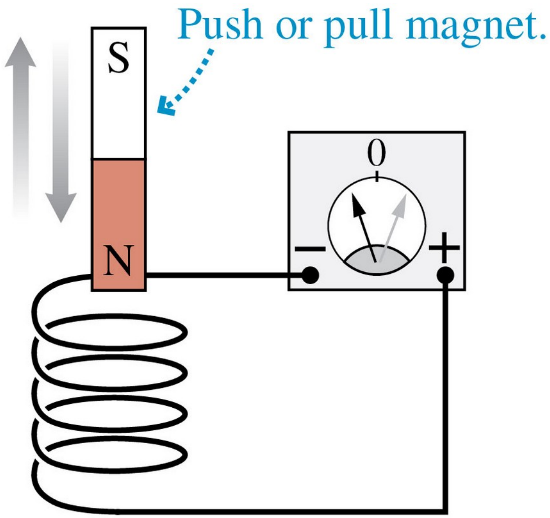
Lenz’s Law

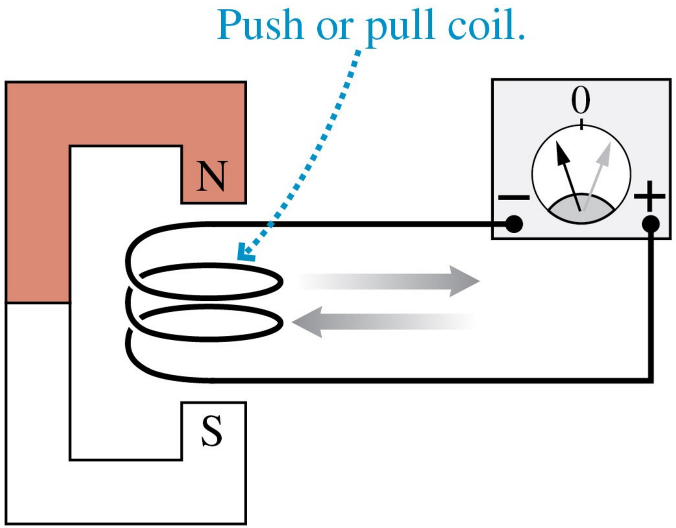
Try to predict the direction of the current when you move the magnet...



Current Induction







Current Induction

Faraday's Law

A changing magnetic field through a wire loop will induce a current.

The current comes from the induced voltage given by

$$\mathcal{E} = -\frac{d\Phi_{\mathrm{m}}}{dt}$$

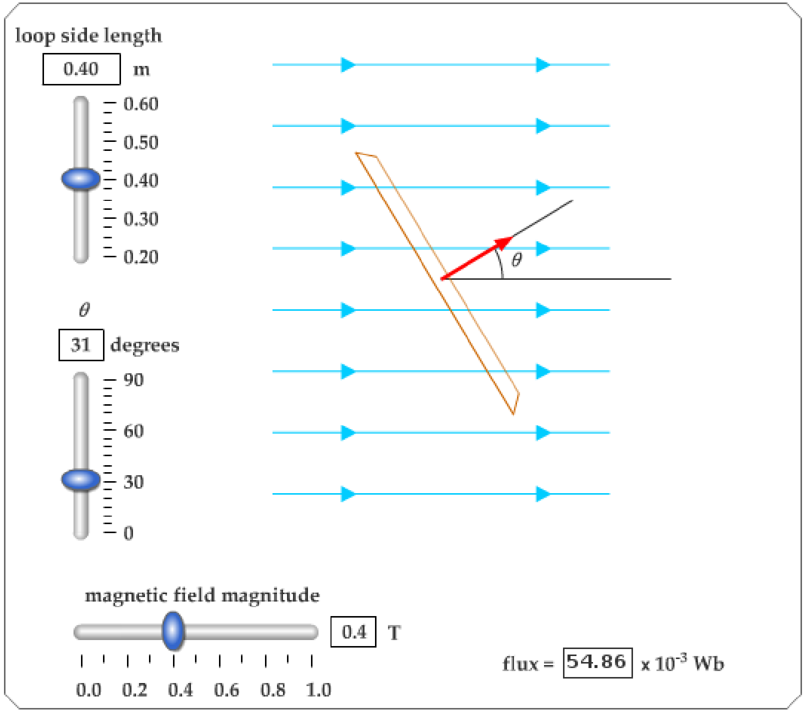
Magnetic Field Flux

- field flux (Φ) is the amount of field that "flows" through a loop of area A:

$$\Phi_{\mathrm{m}} = \int_{\mathrm{area}} \vec{B} \cdot d\vec{A}$$

- field flux (Φ) depends on the strength of the field (B), the area of the loop (A), and the angle between the normal and field (θ)

- units of Φ: Weber
  1 Wb = 1 T·m^2



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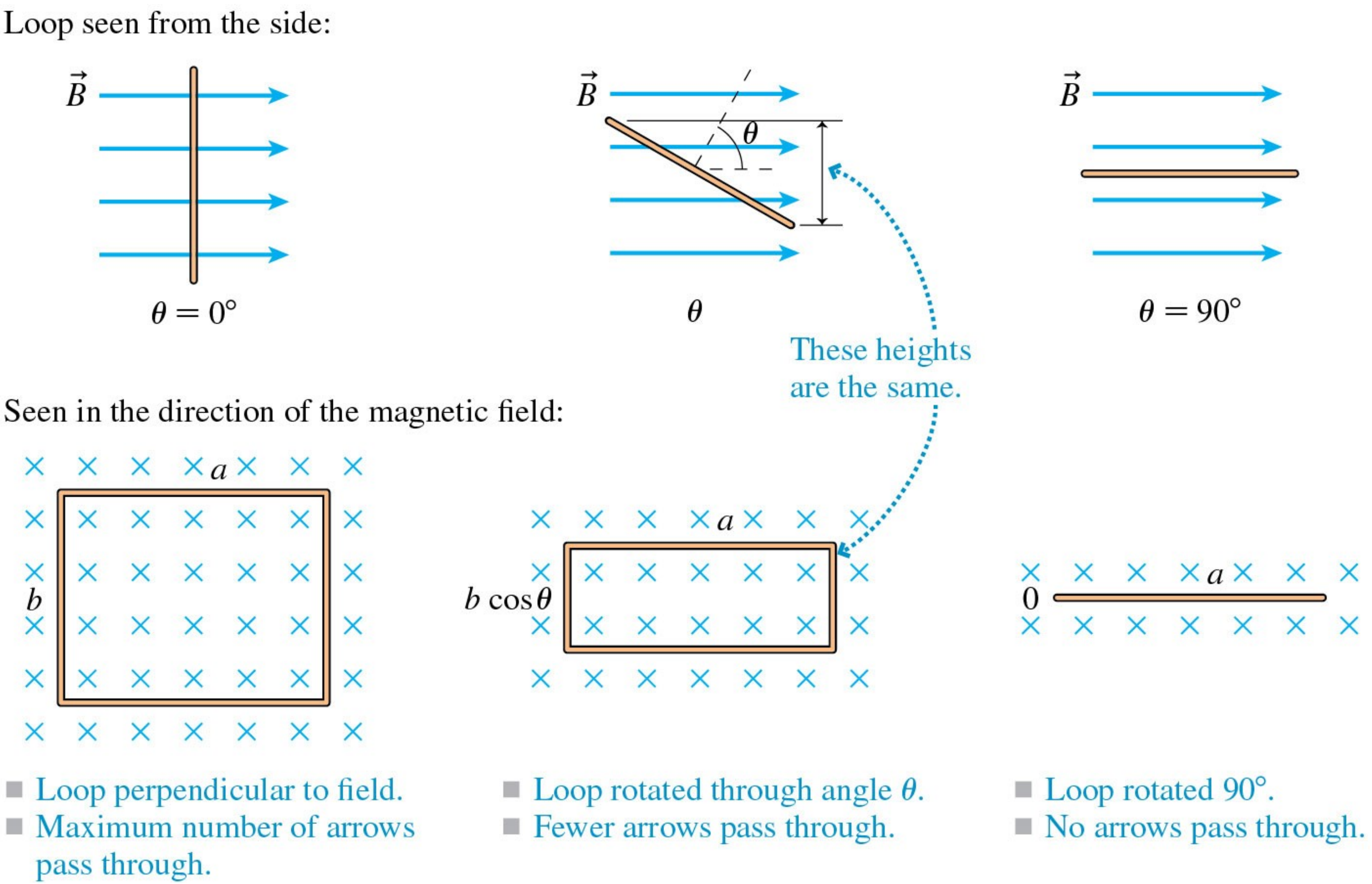

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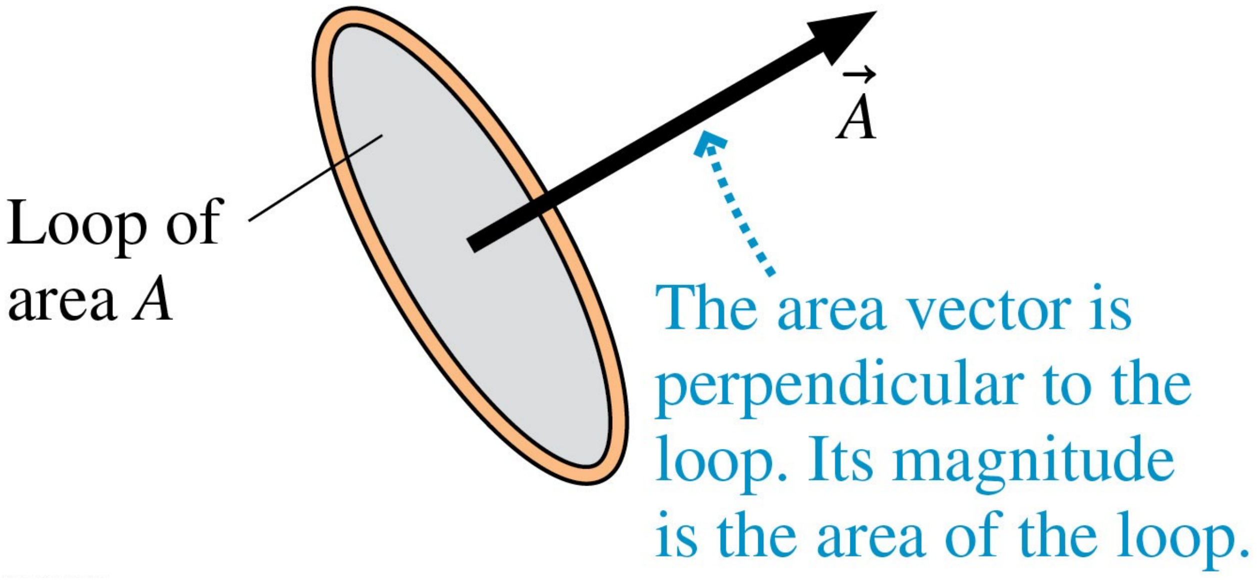
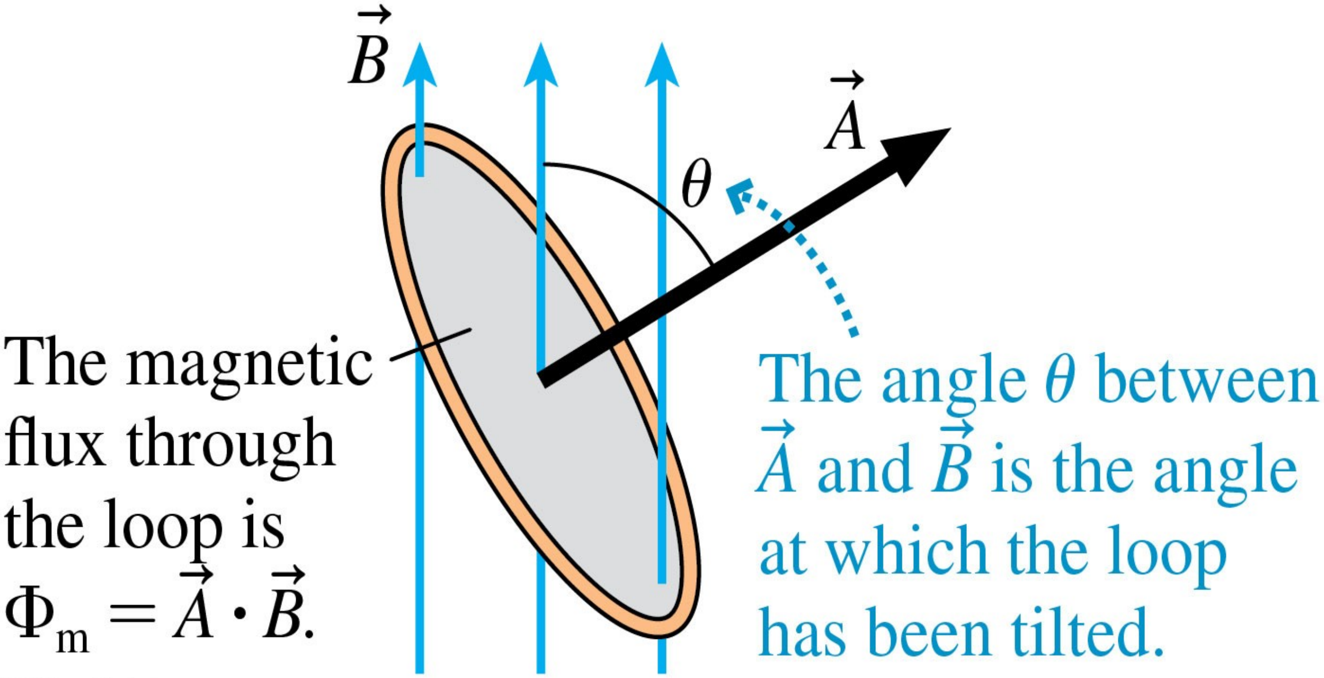


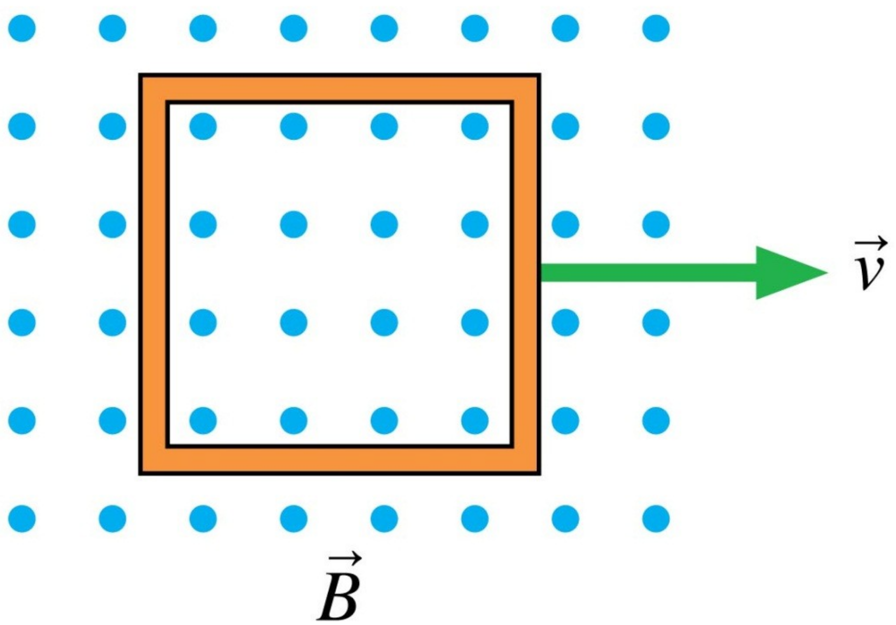
Magnetic Flux



Magnetic Flux

The metal loop is being pulled through a uniform magnetic field. Is the magnetic flux through the loop changing?

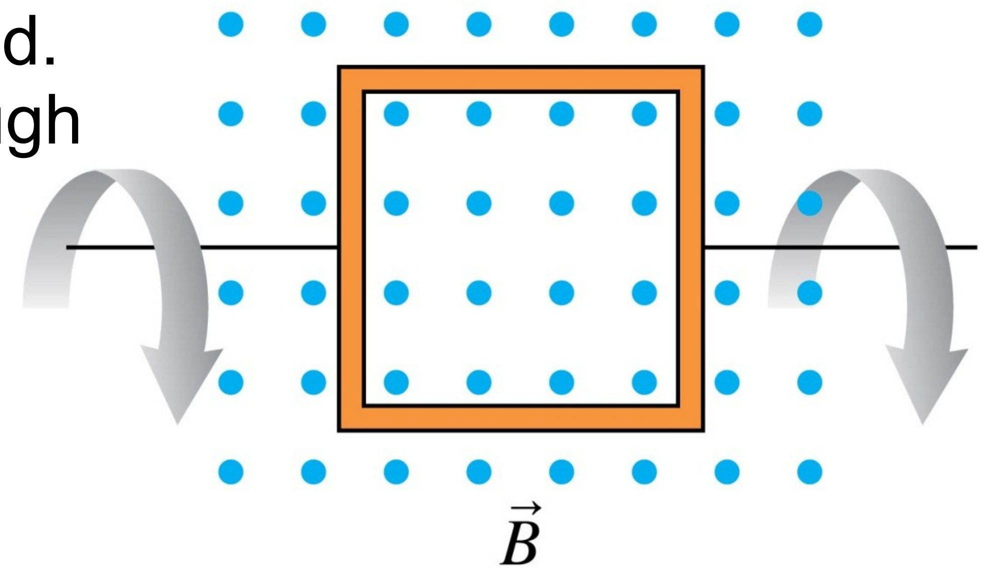
A. Yes
B. No ✔



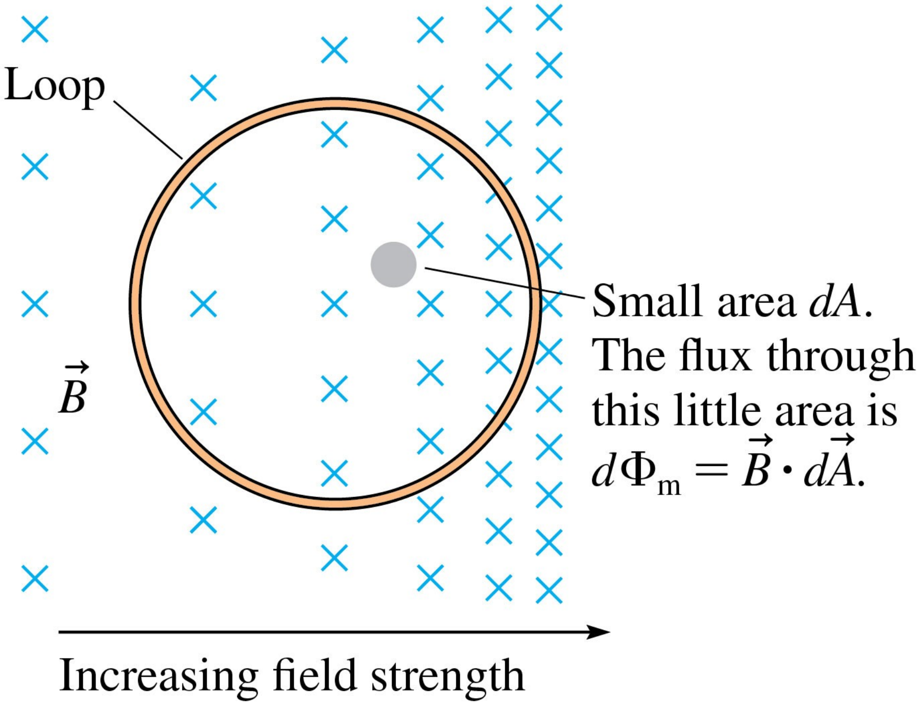
Magnetic Flux

The metal loop is rotating in a uniform magnetic field. Is the magnetic flux through the loop changing?

✔ A. Yes
B. No



Magnetic Flux

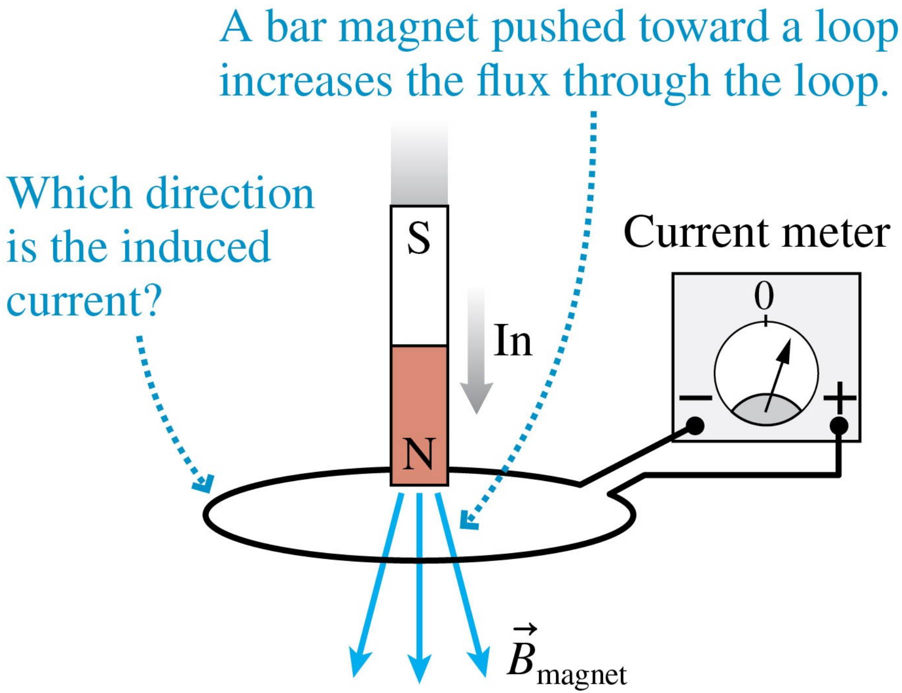


The total magnetic flux through the loop is found with an *area integral*:

$$\Phi_m = \int_{area} \vec{B} \cdot d\vec{A}$$

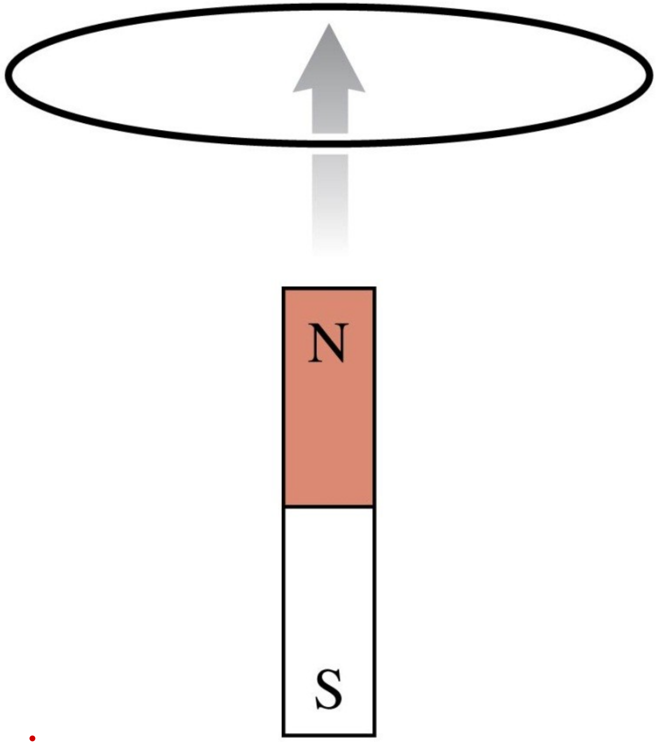
Lenz’s Law

Lenz’s law There is an induced current in a closed, conducting loop if and only if the magnetic flux through the loop is changing. The direction of the induced current is such that the induced magnetic field opposes the *change* in the flux.



Lenz's Law

The bar magnet is pushed toward the center of a wire loop. Which is true?



✔ A. There is a clockwise induced current in the loop.

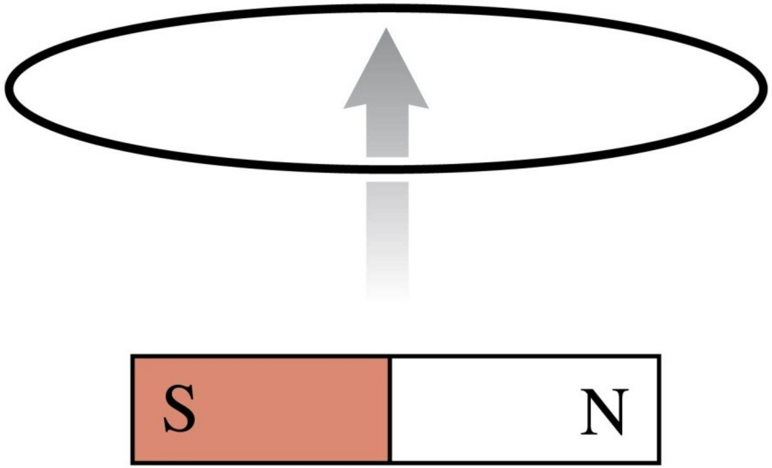
B. There is a counterclockwise induced current in the loop.

C. There is no induced current in the loop.

1. Upward flux from magnet is increasing.
2. To oppose the increase, the field of the induced current points down.
3. From the right-hand rule, a downward field needs a cw current.

Lenz's Law

The bar magnet is pushed toward the center of a wire loop. Which is true?



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Lenz's Law

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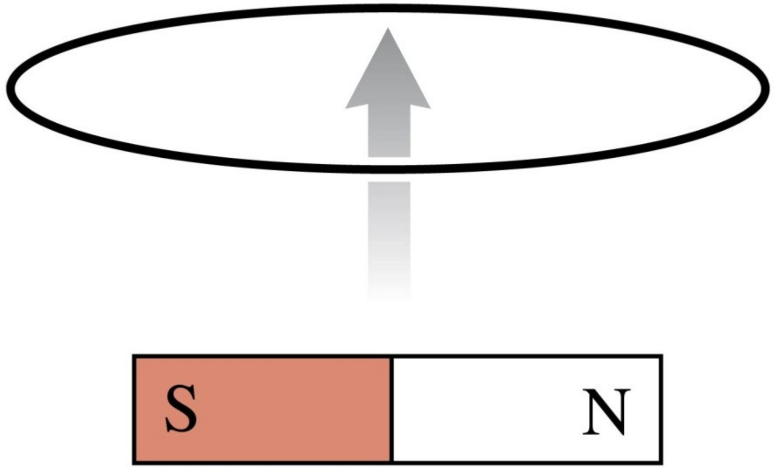


A. There is a clockwise induced current in the loop.

B. There is a counterclockwise induced current in the loop.

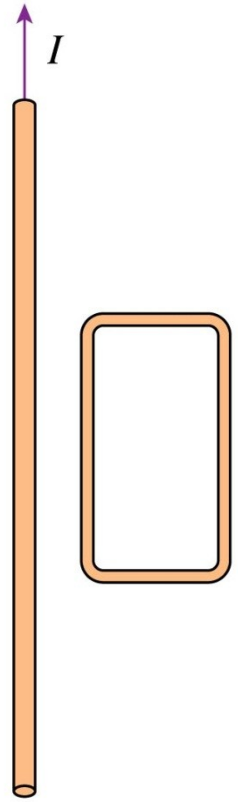
✔ C. **There is no induced current in the loop.**

Magnetic flux is zero, so there's no change of flux.

Lenz’s Law

The current in the straight wire is decreasing. Which is true?

A. There is a clockwise induced current in the loop.
B. There is a counterclockwise induced current in the loop.
C. There is no induced current in the loop.



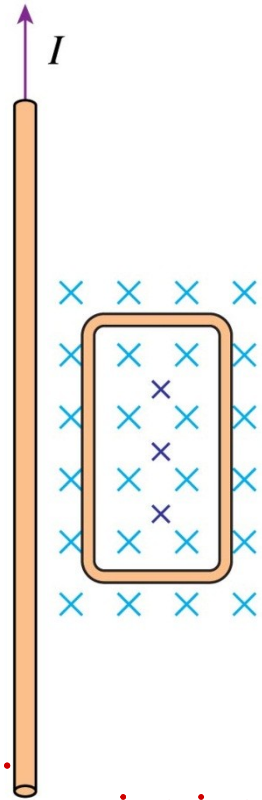
Lenz's Law

The current in the straight wire is decreasing. Which is true?

✔ A. **There is a clockwise induced current in the loop.**

B. There is a counterclockwise induced current in the loop.

C. There is no induced current in the loop.

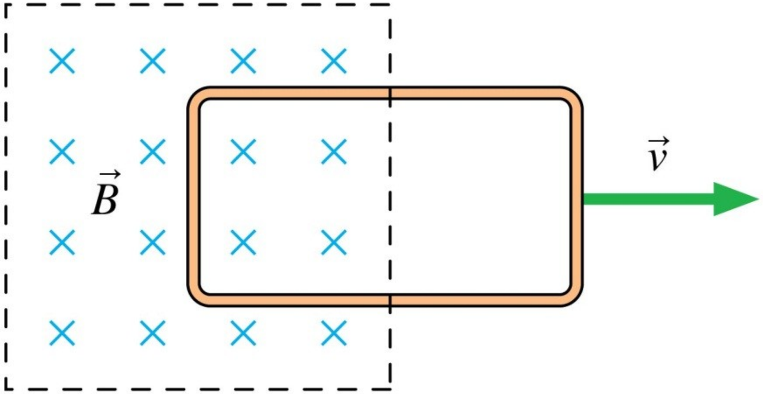


1. The flux from wire's field is <u>into</u> the screen and <u>decreasing</u>.
2. To oppose the <u>decrease</u>, the field of the induced current must point <u>into</u> the screen.
3. From the right-hand rule, an inward field needs a cw current.

Lenz's Law

The magnetic field is confined to the region inside the dashed lines; it is zero outside. The metal loop is being pulled out of the magnetic field. Which is true?

A. There is a clockwise induced current in the loop.
B. There is a counterclockwise induced current in the loop.
C. There is no induced current in the loop.



Lenz's Law

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✔ **A. There is a clockwise induced current in the loop.**

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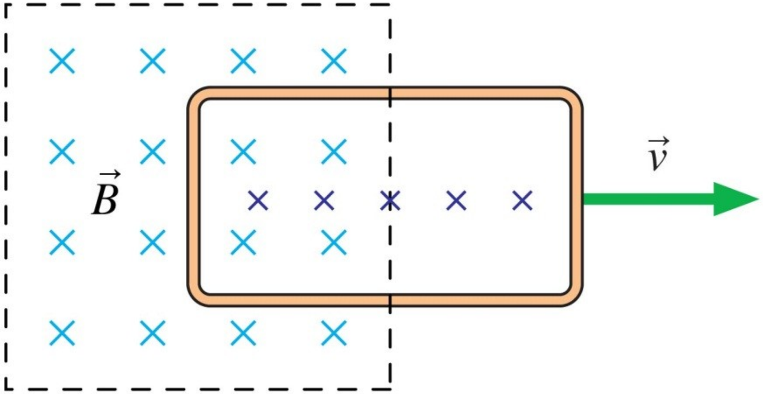
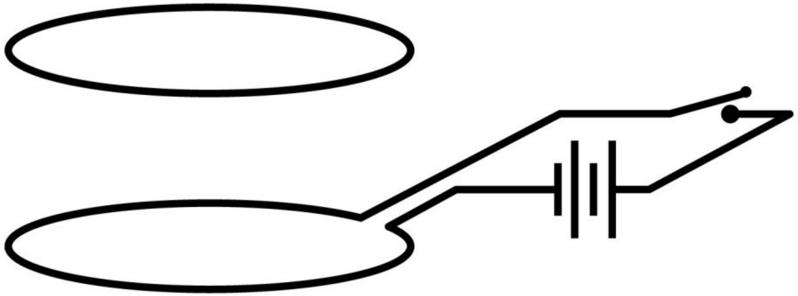


1. The flux through the loop is <u>into</u> the screen and <u>decreasing</u>.
2. To oppose the <u>decrease</u>, the field of the induced current must point <u>into</u> the screen.
3. From the right-hand rule, an inward field needs a cw current.

Lenz's Law

Immediately after the switch is closed, the lower loop exerts _____ on the upper loop.

A. a torque
B. an upward force
C. a downward force
D. no force or torque



Lenz's Law

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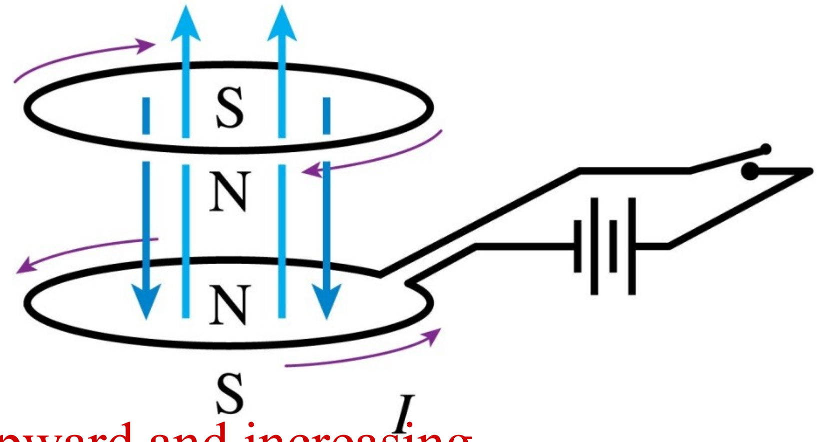
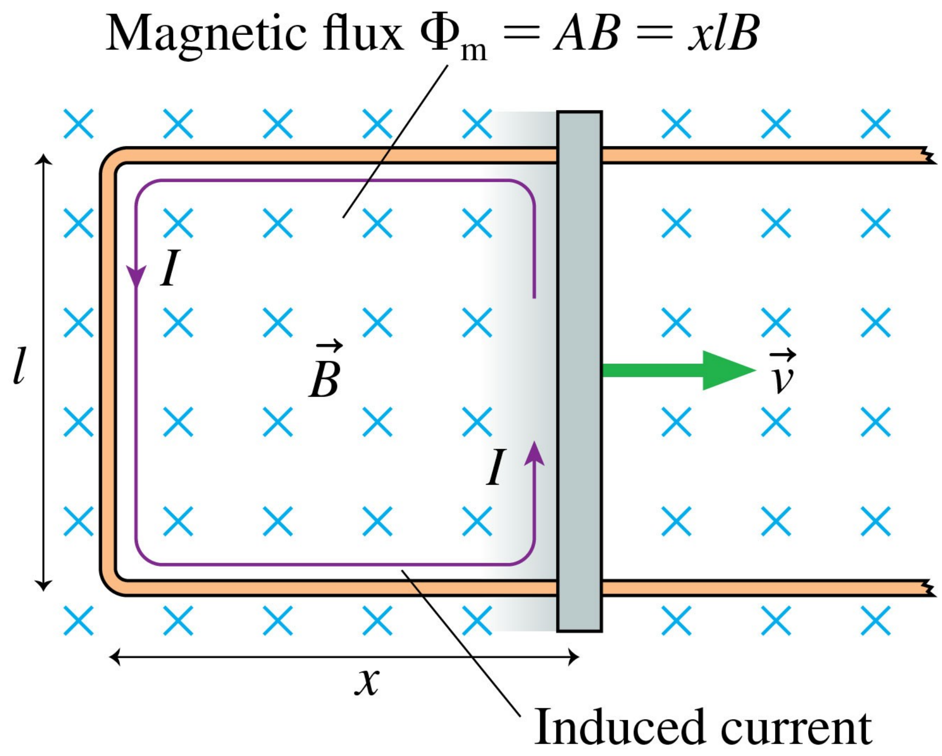


A. a torque
✔ **B. an upward force**
C. a downward force
D. no force or torque

1. The flux through the top loop is upward and increasing.
2. To oppose the increase, the field of the induced current must point downward.
3. From the right-hand rule, a downward field needs a cw current.
4. The ccw current in the lower loop makes the upper face a north pole. The cw induced current in the upper loop makes the lower face a north pole.
5. Facing north poles exert repulsive forces on each other.

Faraday's Law



"motional emf":

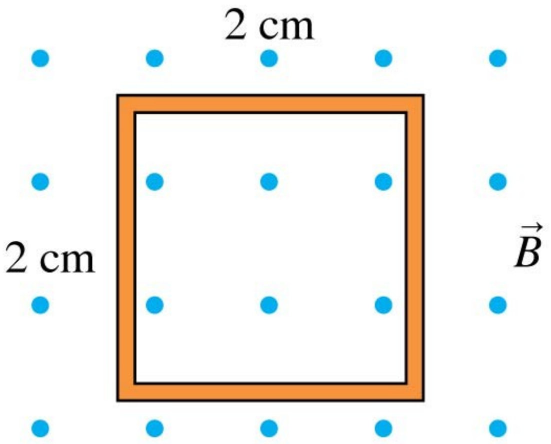
$$\mathcal{E} = Blv$$

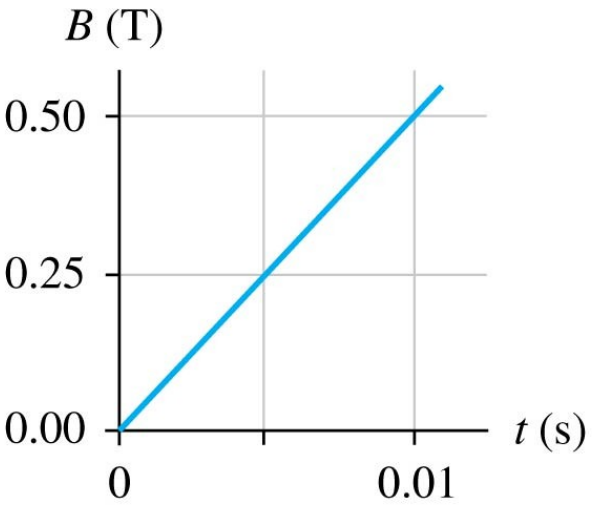
alternatively: $$\mathcal{E} = \left|\frac{d\Phi_m}{dt}\right| = \frac{d}{dt}(xlB) = \frac{dx}{dt}lB = vlB$$

Faraday's Law

The induced emf around this loop is

A. 200 V
B. 50 V
C. 2 V
D. 0.5 V
E. 0.02 V

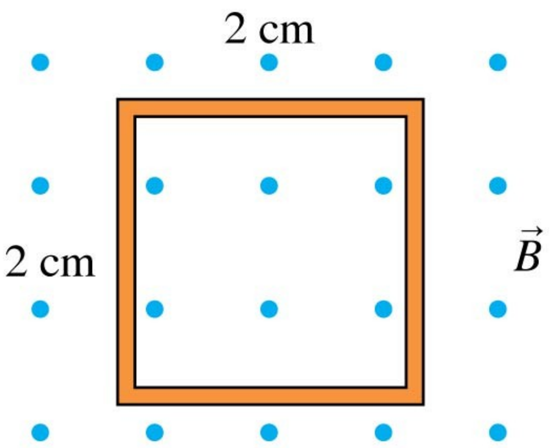


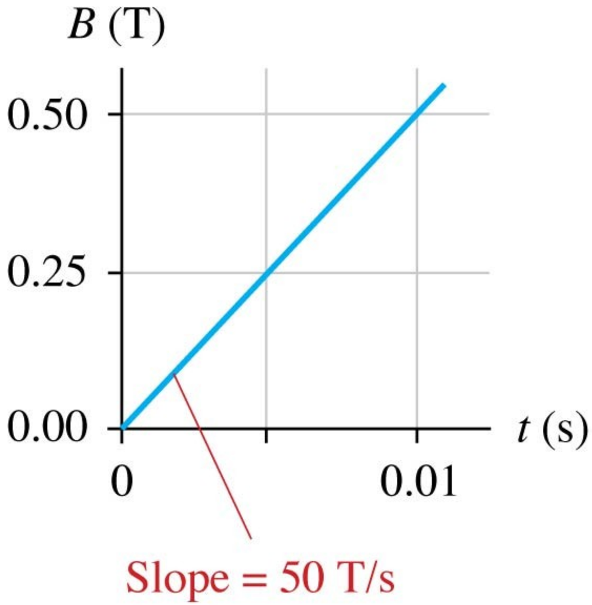


Faraday's Law

The induced emf around this loop is

A. 200 V
B. 50 V
C. 2 V
D. 0.5 V
✔ E. 0.02 V





$$\mathcal{E} = \frac{d\Phi_m}{dt} = A\frac{dB}{dt} = A \times \text{slope of graph}$$

Faraday's Law

- An emf is induced in a conducting loop if the magnetic flux through the loop changes.

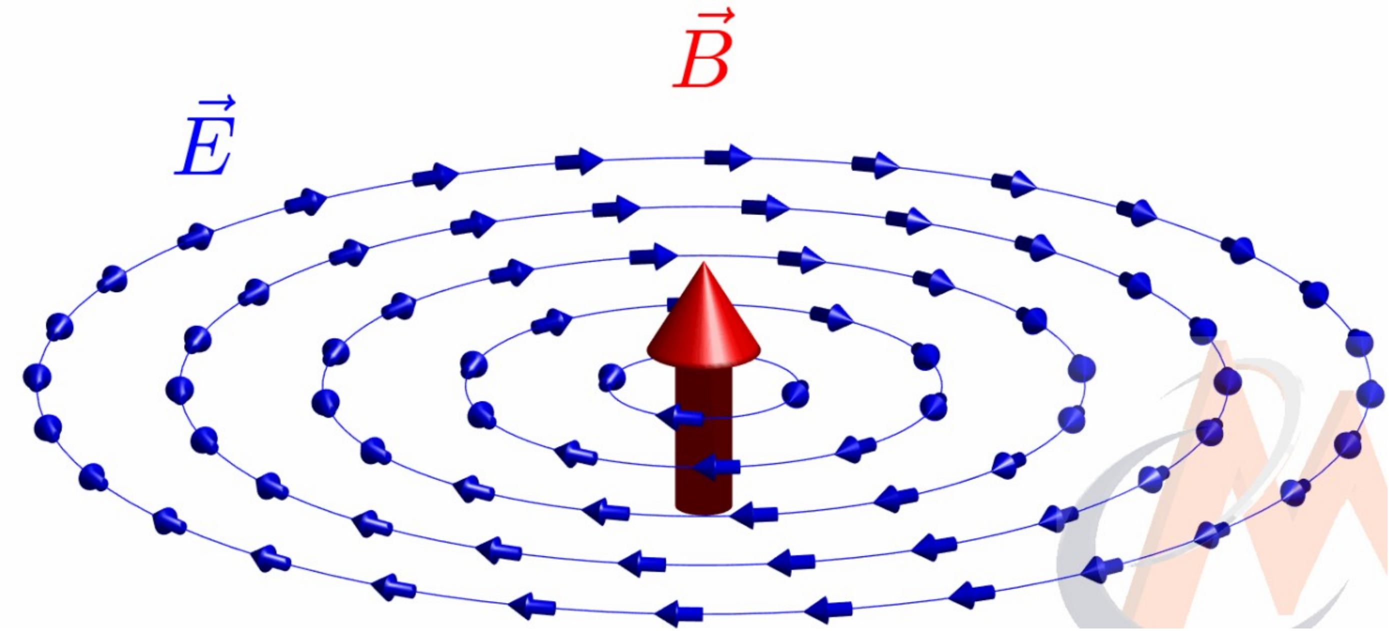
$$\mathcal{E} = -\frac{d\Phi_{\mathrm{m}}}{dt} = \oint \vec{E} \cdot d\vec{\ell}$$

- The direction of the emf is such as to drive an induced current in the direction given by Lenz's law.
- The direction of the area vector (in the flux) agrees with the right-hand circulation of the path integral.

Faraday’s Law

What is actually happening to induce a current?

Whenever a magnetic field changes, an electric field is created that circulates around the *B* field.



https://madisoncollegephysics.net/resources/media/induced_E-field.gif

Faraday's Law

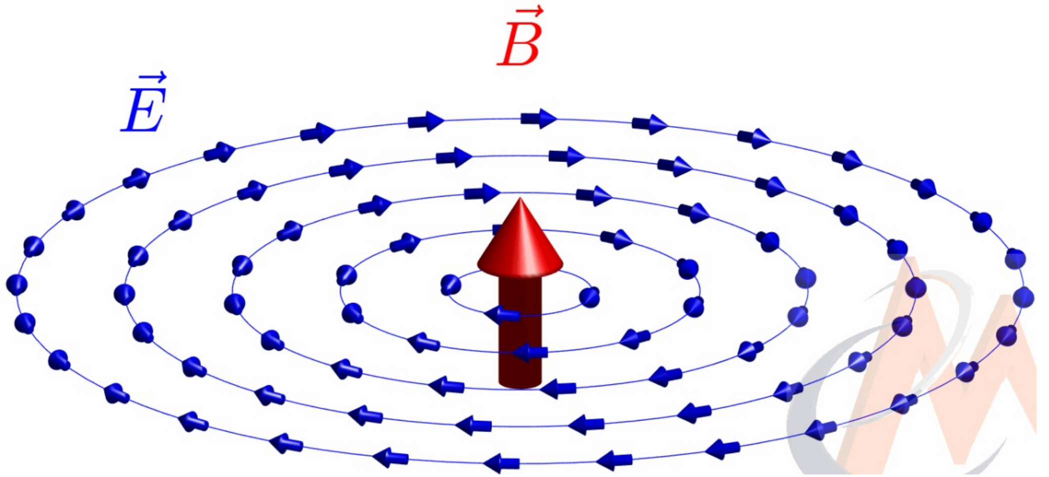
Whenever a magnetic field changes, an electric field is created that circulates around the *B* field.

A "circulating" vector field means a closed path integral

$$\oint \vec{E} \cdot d\vec{\ell}$$ is not zero.

If there is a wire loop here, a current will be induced in it.

But there is a circulating *E* field whether or not there is a wire.



Faraday's Law

The complete statement of Faraday's Law:

$$\oint \vec{E} \cdot d\vec{\ell} = -\frac{d\Phi_{\mathrm{m}}}{dt}$$

where Φ_{m} is the magnetic field flux through the area of the closed path integral:

$$\Phi_{\mathrm{m}} = \int_{\mathrm{area}} \vec{B} \cdot d\vec{A}$$