

# Chapter 29

# Electromagnetic Induction

PowerPoint® Lectures for  
*University Physics, Thirteenth Edition*  
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Lectures by Wayne Anderson

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## Goals for Chapter 29

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- To examine experimental evidence that a changing magnetic field induces an emf
- To learn how Faraday's law relates the induced emf to the change in flux
- To determine the direction of an induced emf
- To calculate the emf induced by a moving conductor
- To learn how a changing magnetic flux generates an electric field
- To study the four fundamental equations that describe electricity and magnetism

# Introduction

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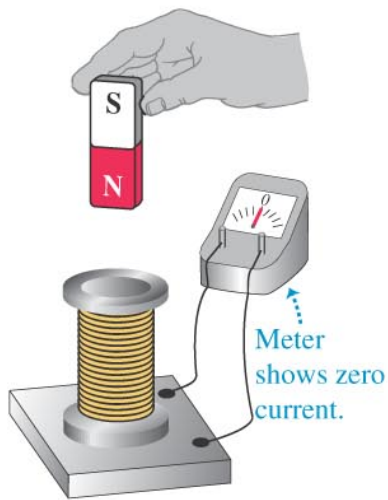
- How is a credit card reader related to magnetism?
- Energy conversion makes use of electromagnetic induction.
- Faraday's law and Lenz's law tell us about induced currents.
- Maxwell's equations describe the behavior of electric and magnetic fields in *any* situation.



# Induced current

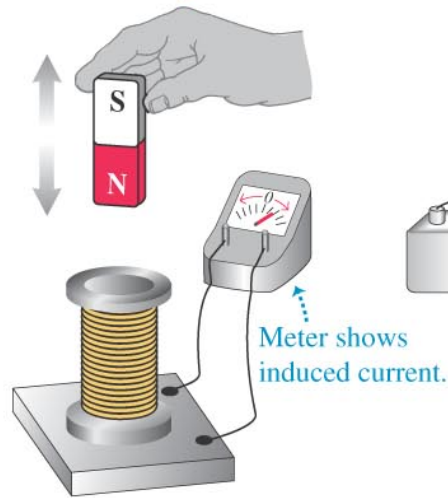
- A changing magnetic flux causes an *induced current*. See Figure 29.1 below.
- The *induced emf* is the corresponding emf causing the current.

(a) A stationary magnet does NOT induce a current in a coil.

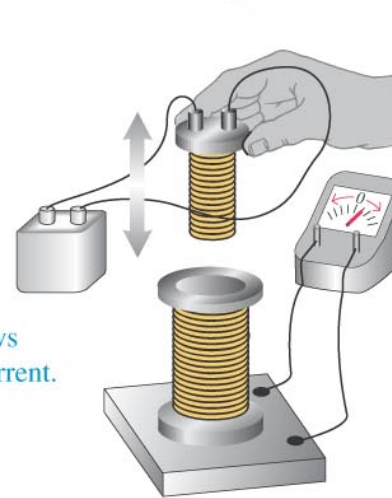


All these actions DO induce a current in the coil. What do they have in common?\*

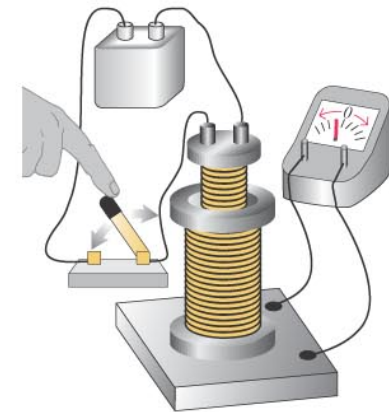
(b) Moving the magnet toward or away from the coil



(c) Moving a second, current-carrying coil toward or away from the coil



(d) Varying the current in the second coil (by closing or opening a switch)

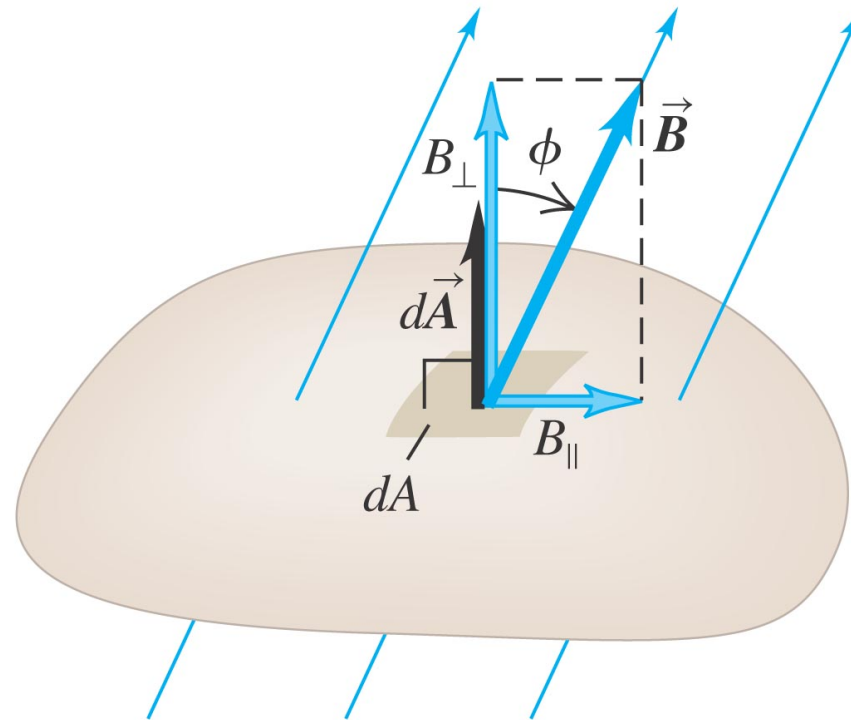


\*They cause the magnetic field through the coil to *change*.

## Magnetic flux through an area element

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- Figure 29.3 below shows how to calculate the magnetic flux through an element of area.



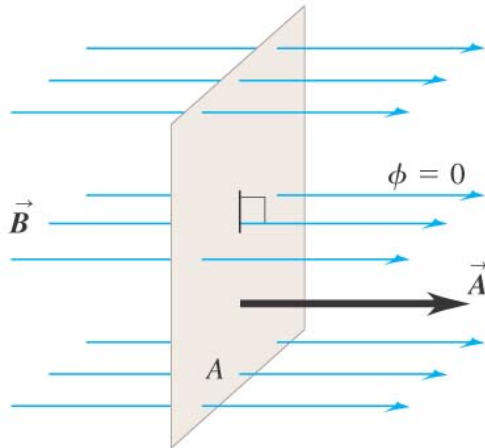
Magnetic flux through element of area  $d\vec{A}$ :  
$$d\Phi_B = \vec{B} \cdot d\vec{A} = B_{\perp} dA = B dA \cos \phi$$

# Faraday's law

- The flux depends on the orientation of the surface with respect to the magnetic field. See Figure 29.4 below.
- *Faraday's law*: The induced emf in a closed loop equals the negative of the time rate of change of magnetic flux through the loop, or  $\mathcal{E} = -d\Phi_B/dt$ .

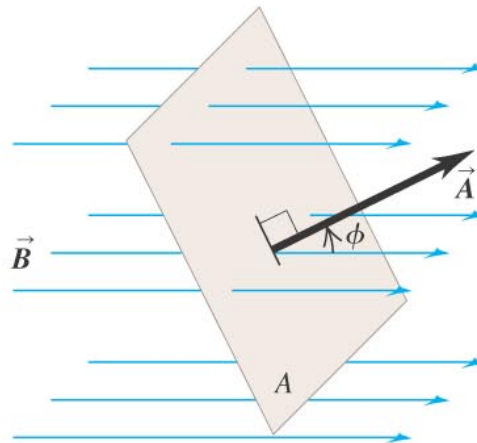
Surface is face-on to magnetic field:

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



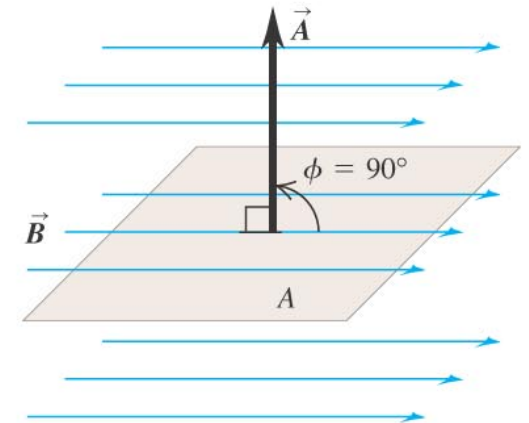
Surface is tilted from a face-on orientation by an angle  $\phi$ :

- The angle between  $\vec{B}$  and  $\vec{A}$  is  $\phi$ .
- The magnetic flux  $\Phi_B = \vec{B} \cdot \vec{A} = BA \cos \phi$ .



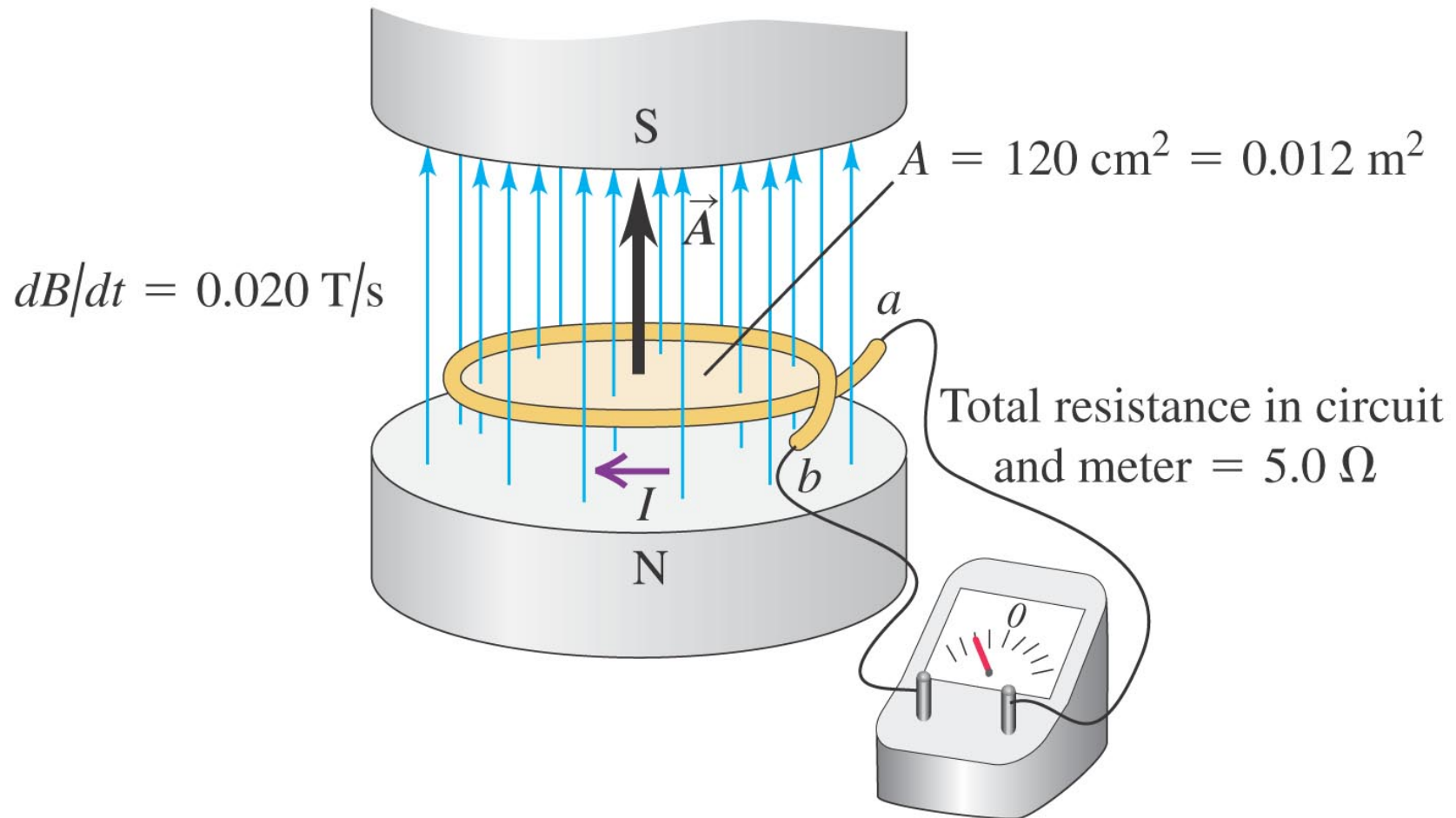
Surface is edge-on to magnetic field:

- $\vec{B}$  and  $\vec{A}$  are perpendicular (the angle between  $\vec{B}$  and  $\vec{A}$  is  $\phi = 90^\circ$ ).
- The magnetic flux  $\Phi_B = \vec{B} \cdot \vec{A} = BA \cos 90^\circ = 0$ .



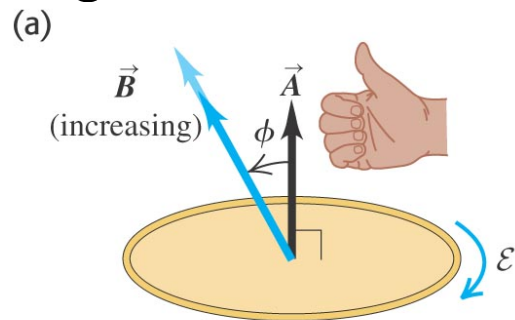
## Emf and the current induced in a loop

- Follow Example 29.1 using Figure 29.5 below.

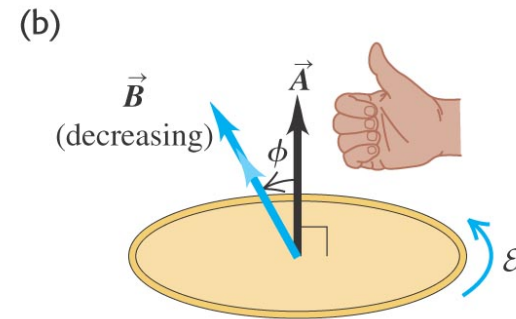


# Direction of the induced emf

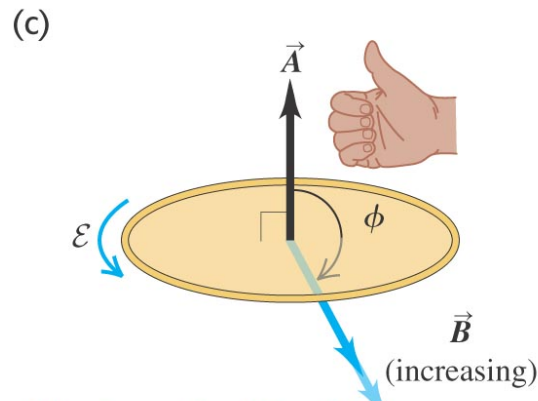
- Follow the text discussion on the direction of the induced emf, using Figure 29.6 below.



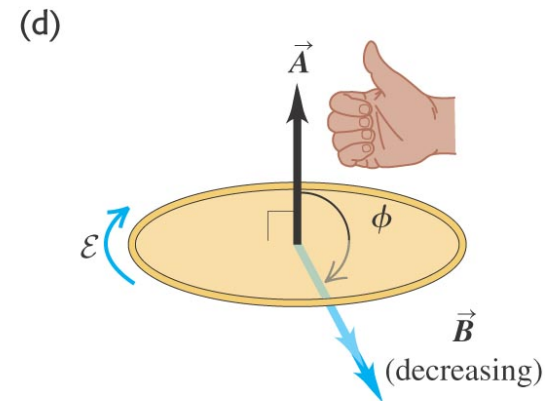
- Flux is positive ( $\Phi_B > 0$ ) ...
- ... and becoming more positive ( $d\Phi_B/dt > 0$ ).
- Induced emf is negative ( $\mathcal{E} < 0$ ).



- Flux is positive ( $\Phi_B > 0$ ) ...
- ... and becoming less positive ( $d\Phi_B/dt < 0$ ).
- Induced emf is positive ( $\mathcal{E} > 0$ ).



- Flux is negative ( $\Phi_B < 0$ ) ...
- ... and becoming more negative ( $d\Phi_B/dt < 0$ ).
- Induced emf is positive ( $\mathcal{E} > 0$ ).



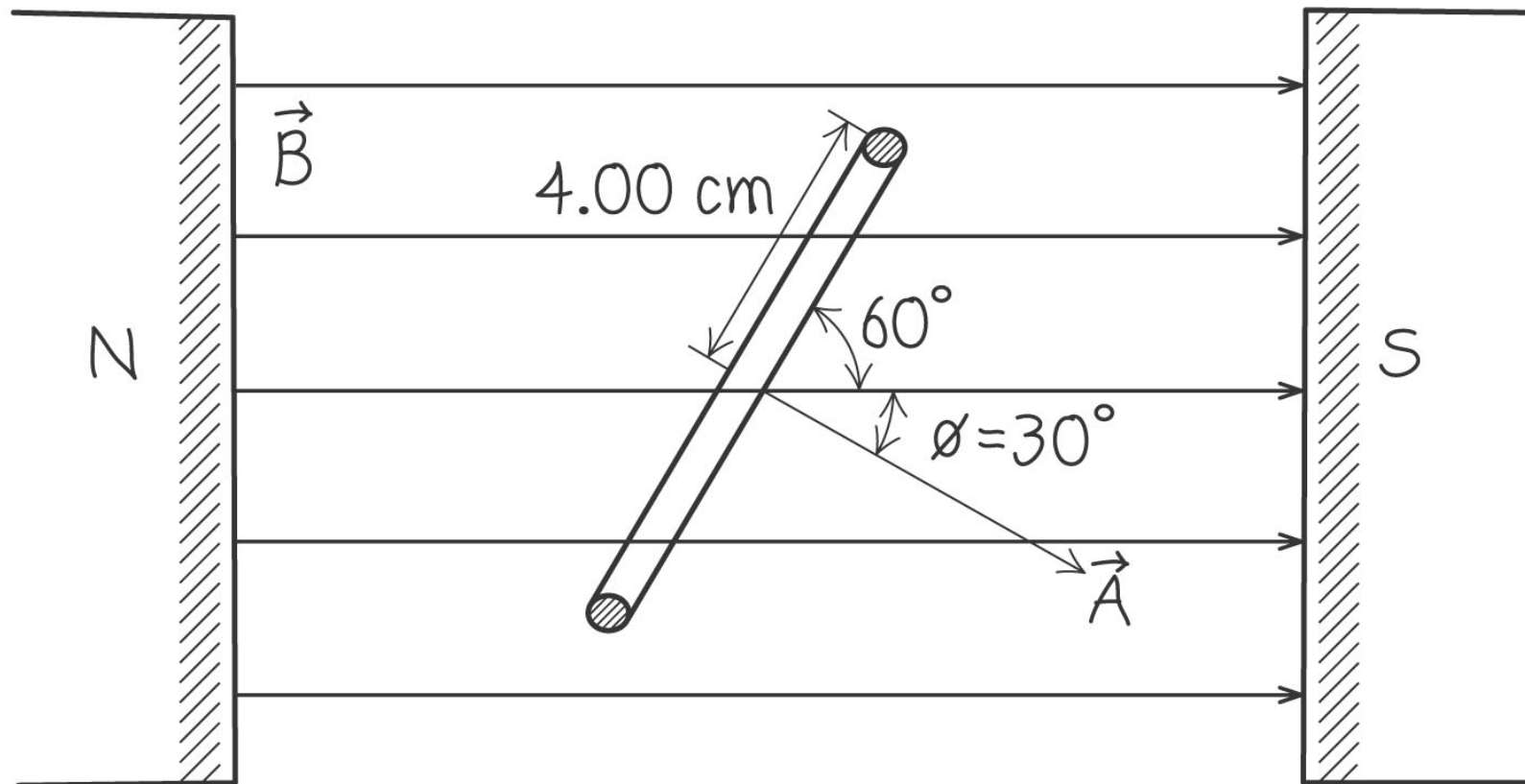
- Flux is negative ( $\Phi_B < 0$ ) ...
- ... and becoming less negative ( $d\Phi_B/dt > 0$ ).
- Induced emf is negative ( $\mathcal{E} < 0$ ).



## Magnitude and direction of an induced emf

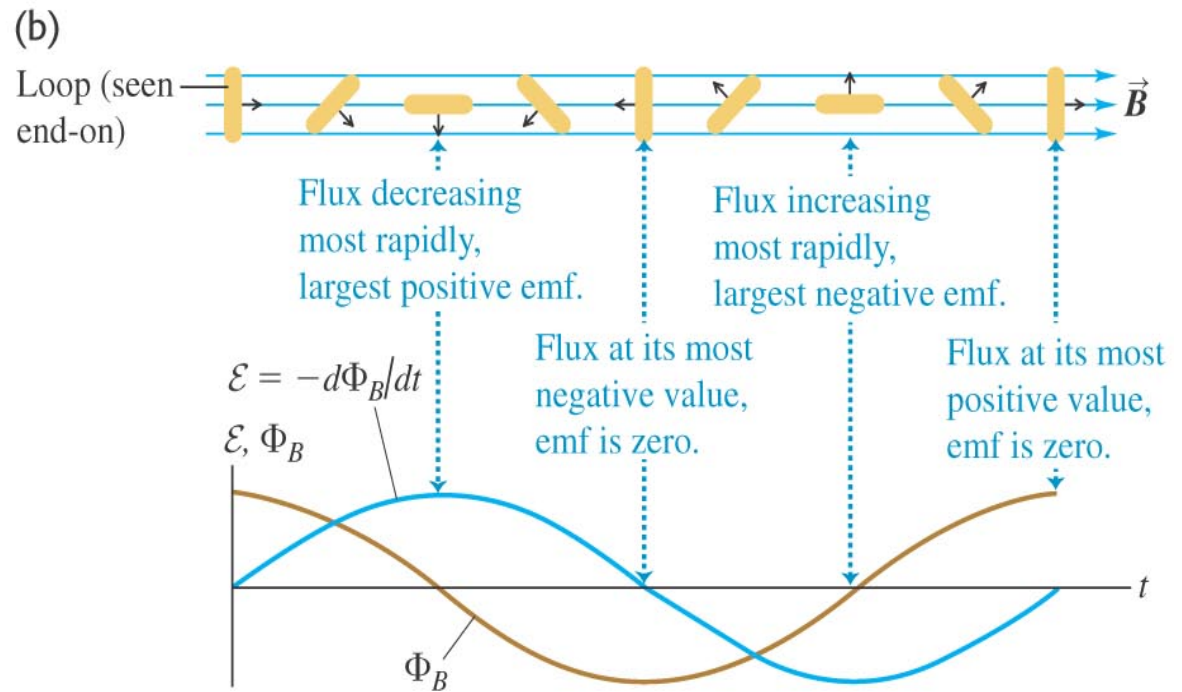
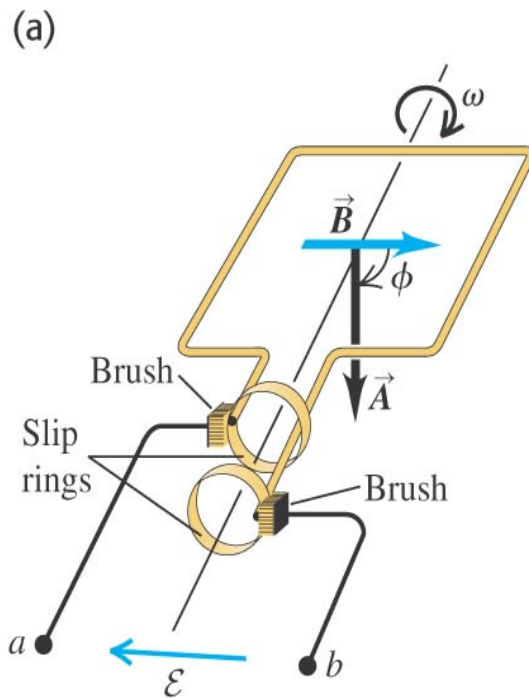
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- Read Problem-Solving Strategy 29.1.
- Follow Example 29.2 using Figure 29.7 below.



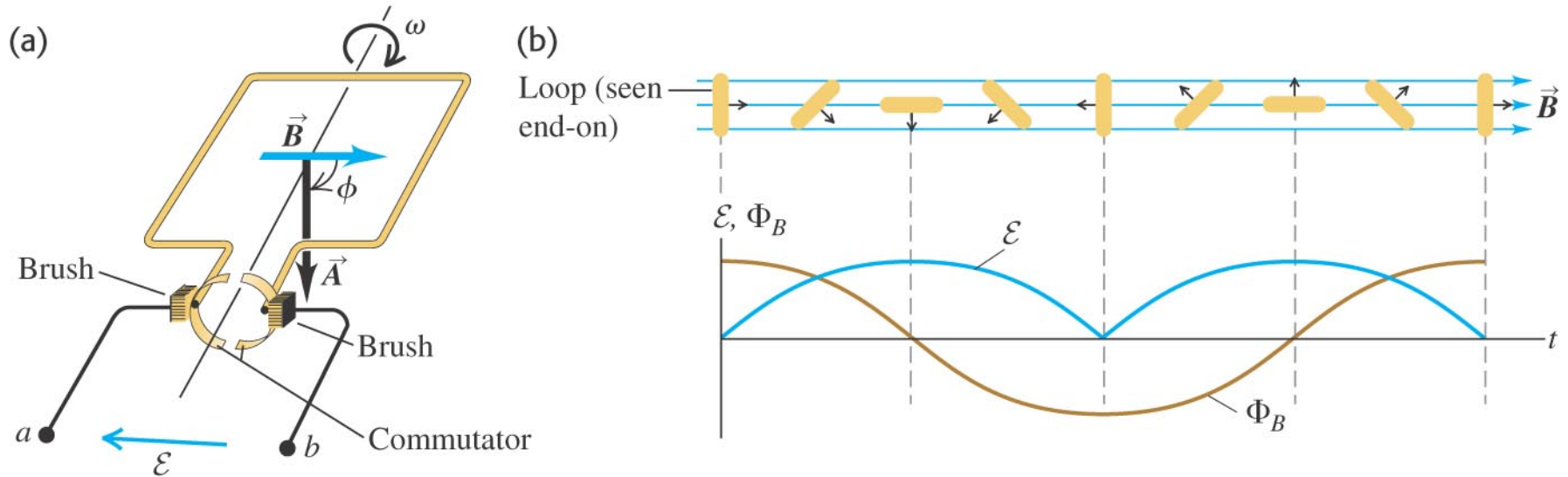
# A simple alternator

- Follow Example 29.3 using Figures 29.8 (below) and 29.9 (right).



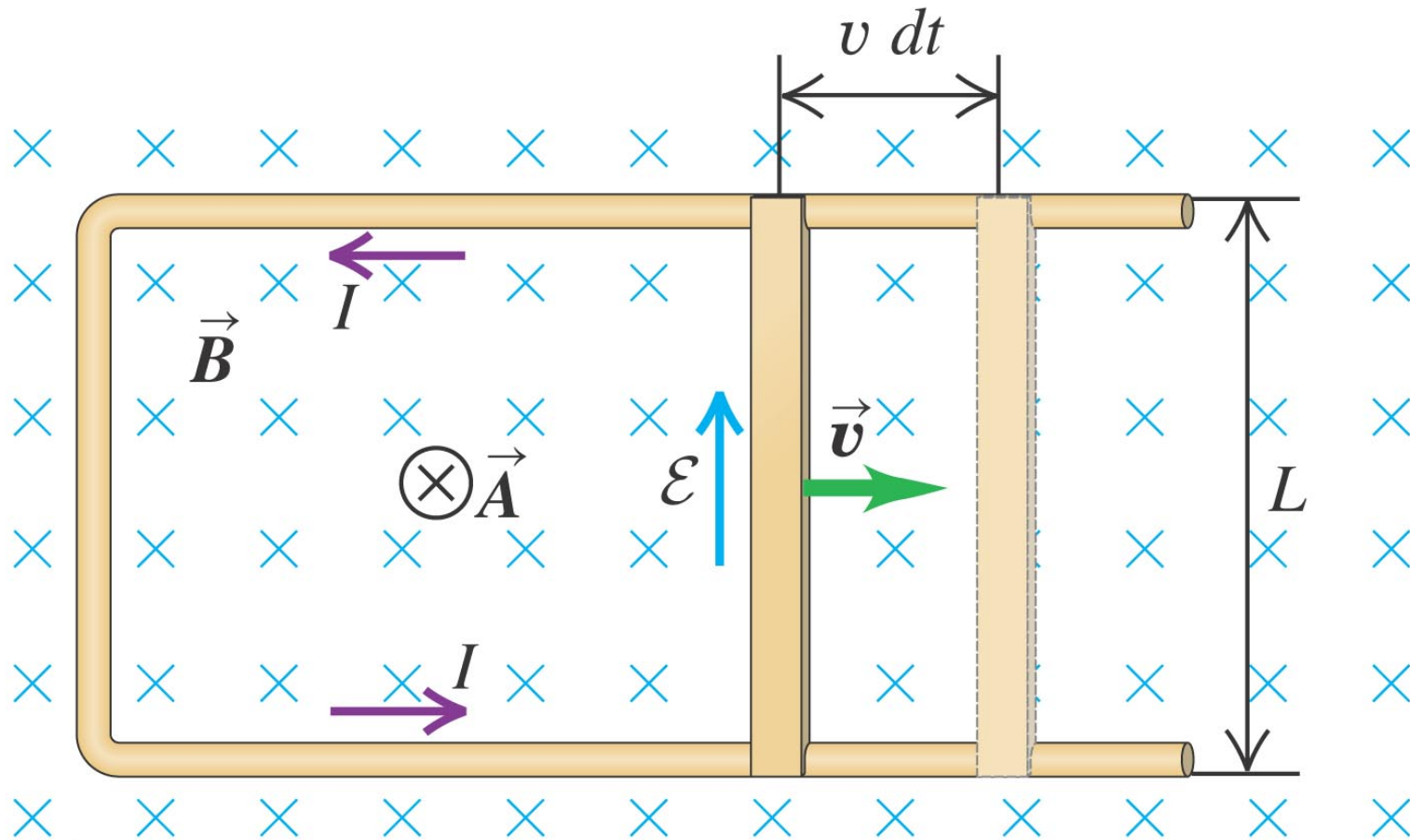
# DC generator and back emf in a motor

- Follow Example 29.4 using Figure 29.10 below.



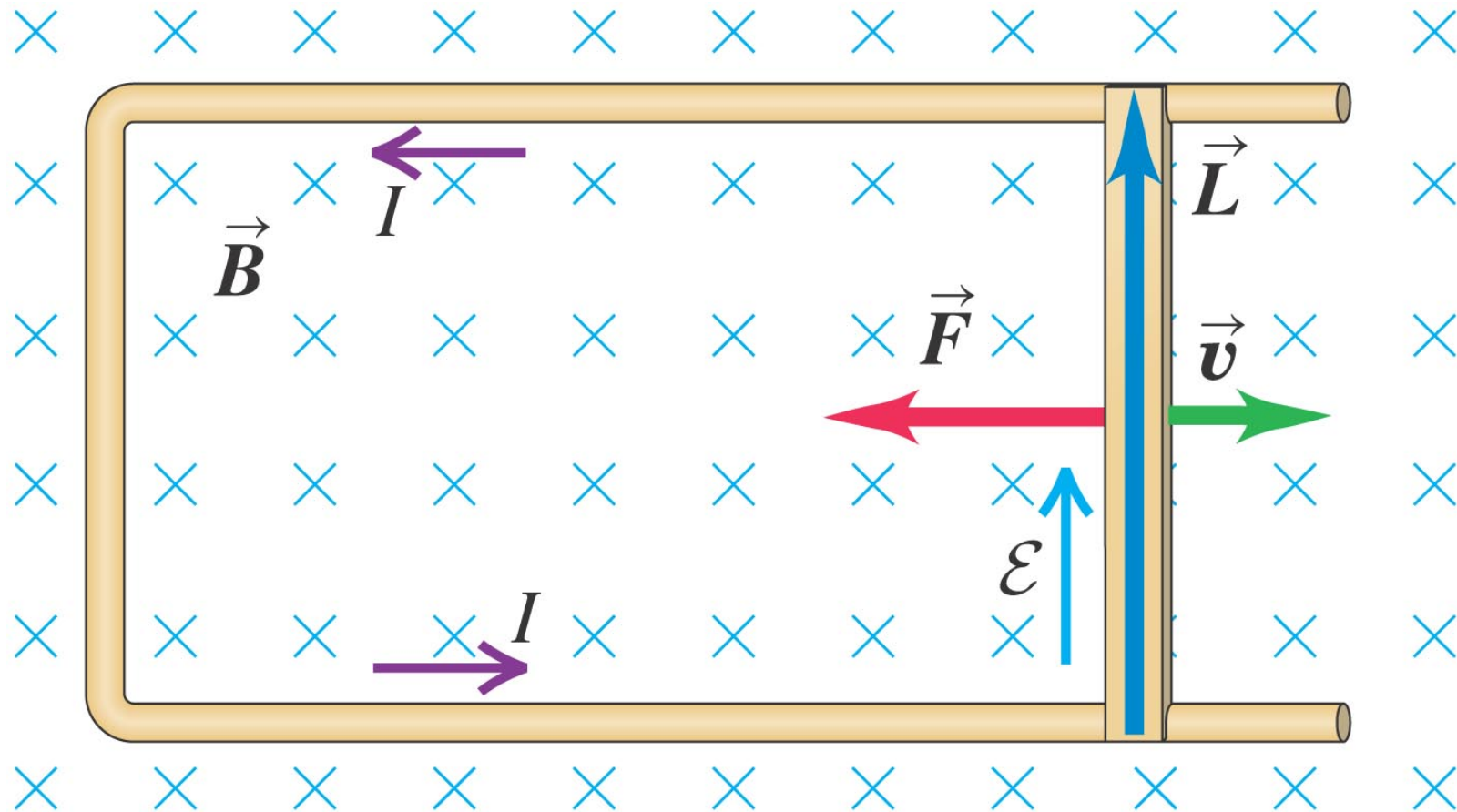
## Slidewire generator

- Follow Example 29.5 using Figure 29.11 below.



## Work and power in the slidewire generator

- Follow Example 29.6 using Figure 29.12 below.



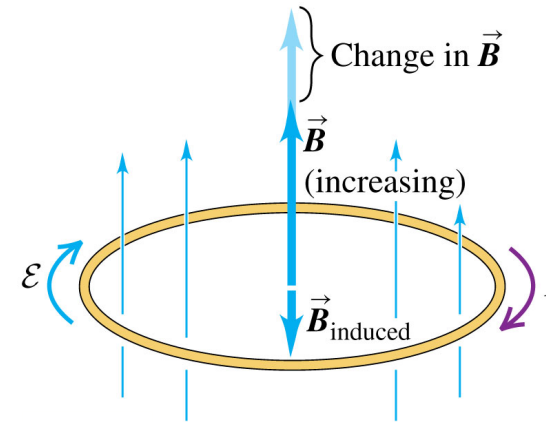
## Lenz's law

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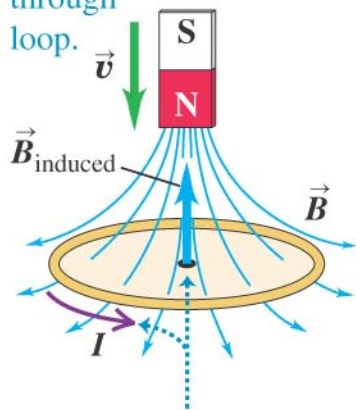
- *Lenz's law*: The direction of any magnetic induction effect is such as to oppose the cause of the effect.
- Follow Conceptual Example 29.7.

# Lenz's law and the direction of induced current

- Follow Example 29.8 using Figures 29.13 (right) and 29.14 (below).

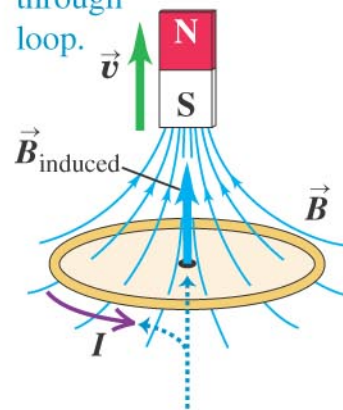


(a) Motion of magnet causes increasing downward flux through loop.

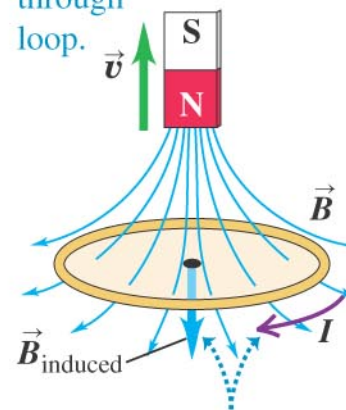


The induced magnetic field is *upward* to oppose the flux change. To produce this induced field, the induced current must be *counterclockwise* as seen from above the loop.

(b) Motion of magnet causes decreasing upward flux through loop.

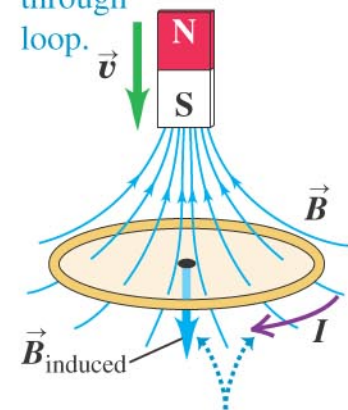


(c) Motion of magnet causes decreasing downward flux through loop.



The induced magnetic field is *downward* to oppose the flux change. To produce this induced field, the induced current must be *clockwise* as seen from above the loop.

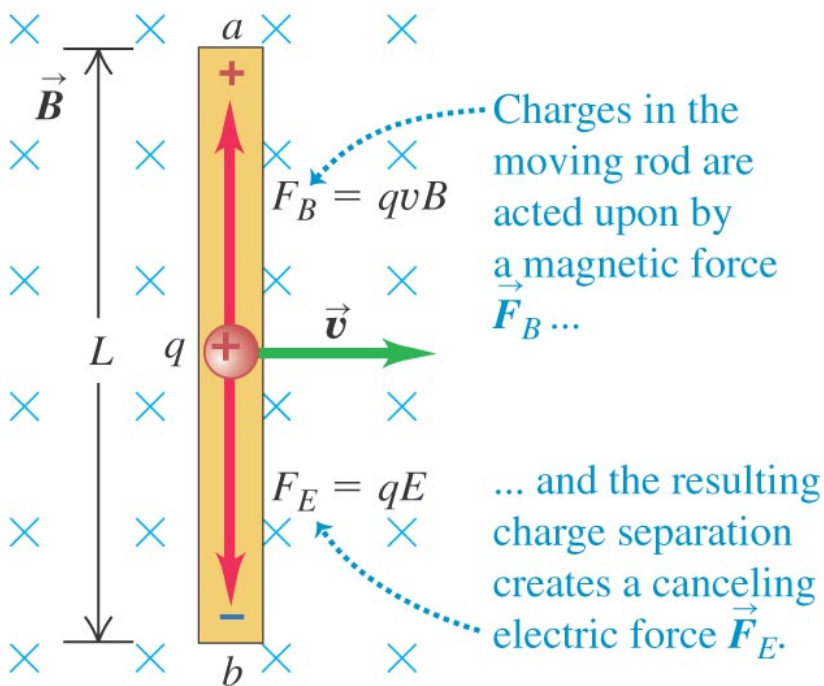
(d) Motion of magnet causes increasing upward flux through loop.



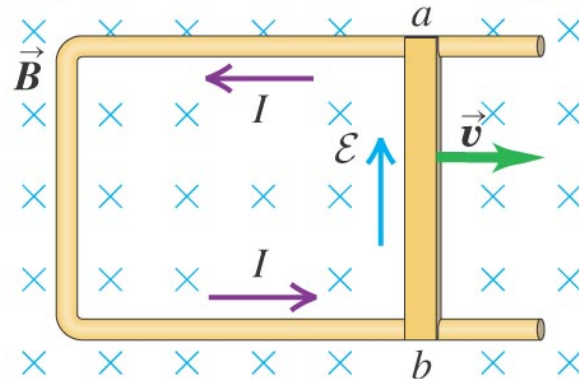
# Motional electromotive force

- The *motional electromotive force* across the ends of a rod moving perpendicular to a magnetic field is  $\mathcal{E} = vBL$ . Figure 29.15 below shows the direction of the induced current.
- Follow the general form of motional emf in the text.

(a) Isolated moving rod



(b) Rod connected to stationary conductor

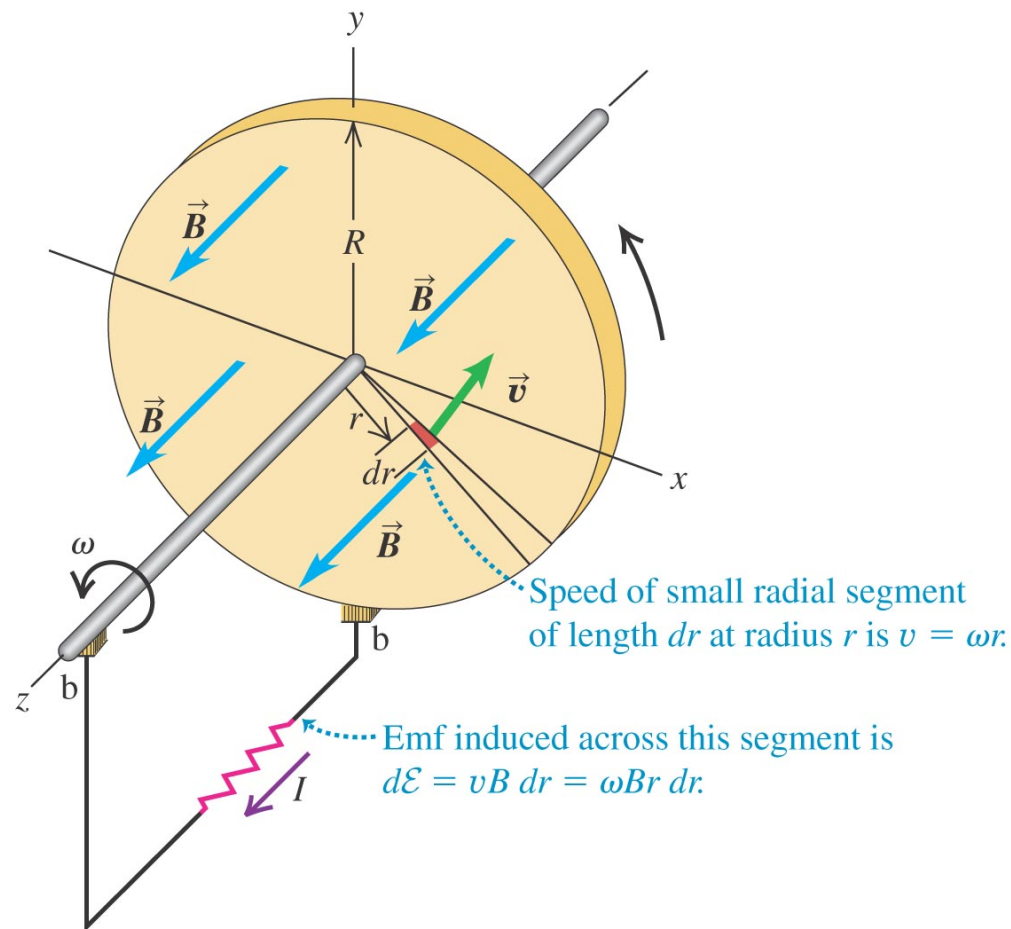


The motional emf  $\mathcal{E}$  in the moving rod creates an electric field in the stationary conductor.



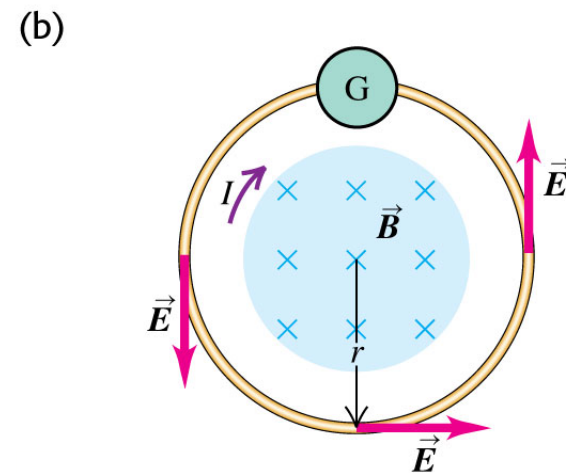
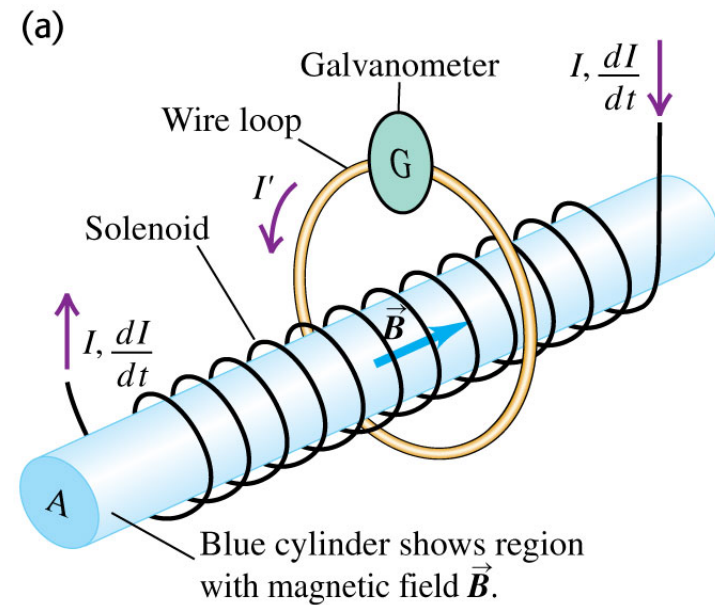
## A slidewire generator and a dynamo

- Follow Example 29.9 for the slidewire generator.
- Follow Example 29.10 for the Faraday disk dynamo, using Figure 29.16 below.



# Induced electric fields

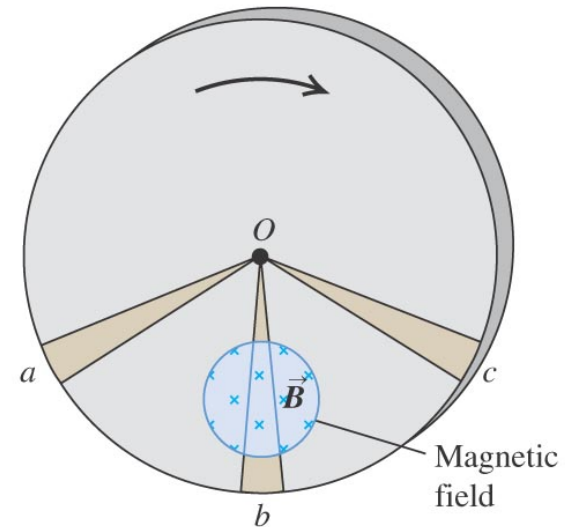
- Changing magnetic flux causes an *induced electric field*.
- See Figure 29.17 at the right to see the induced electric field for a solenoid.
- Follow the text discussion for Faraday's law restated in terms of the induced electric field.
- Follow Example 29.11 using Figure 29.17.



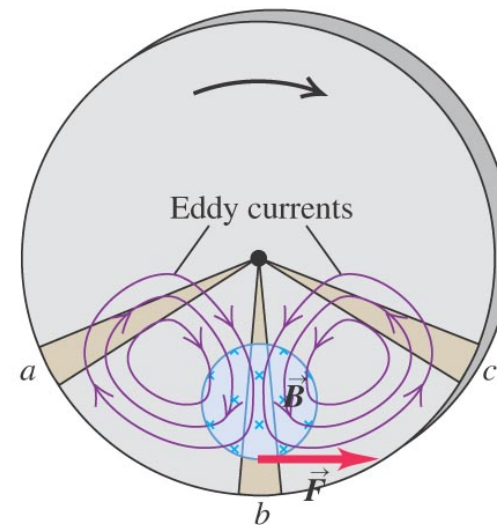
# Eddy currents

- Follow the text discussion of *eddy currents*, using Figure 29.19 at the right.

(a) Metal disk rotating through a magnetic field

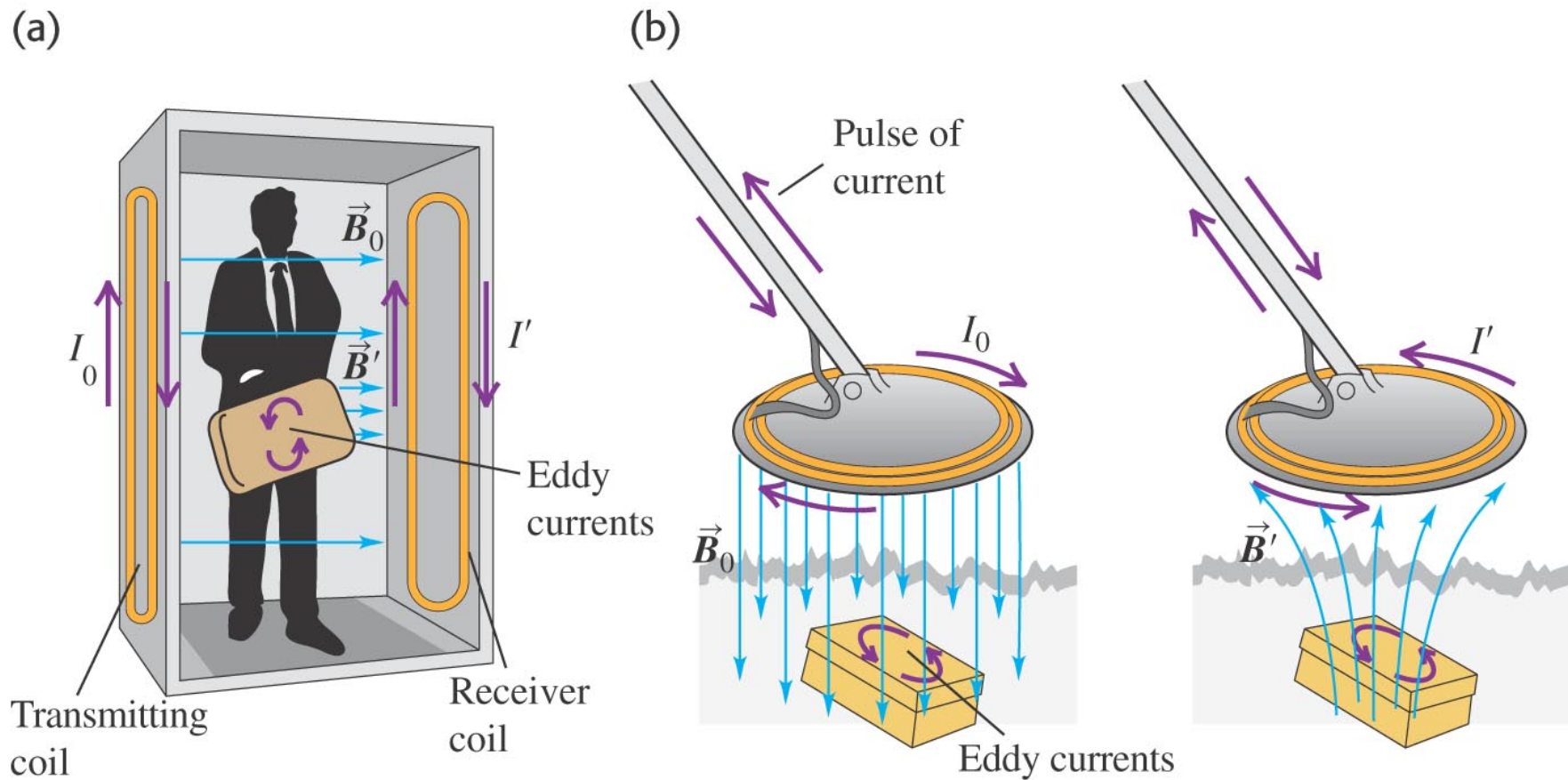


(b) Resulting eddy currents and braking force



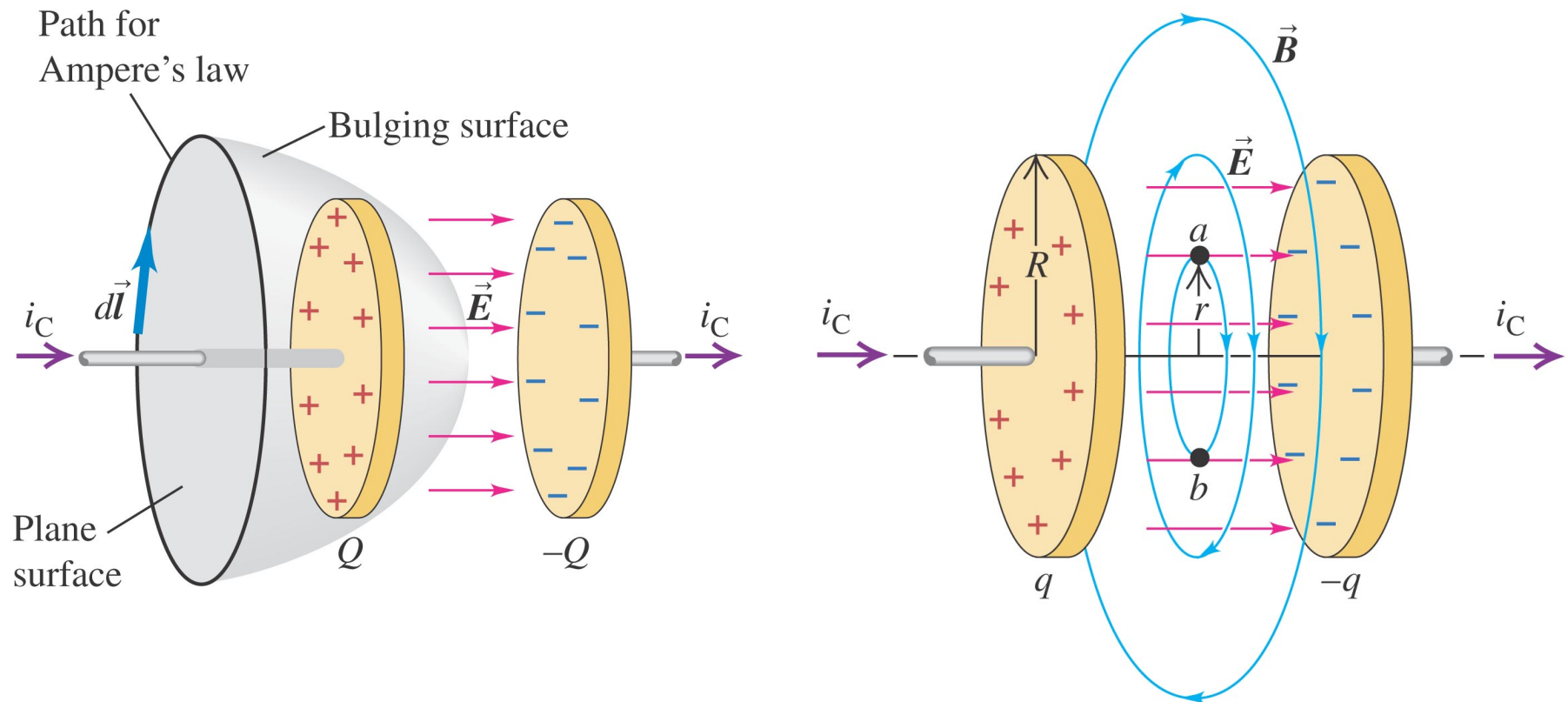
## Using eddy currents

- Figure 29.20 below illustrates an airport metal detector and a portable metal detector, both of which use eddy currents in their design.



# Displacement current

- Follow the text discussion displacement current using Figures 29.21 and 29.22 below.



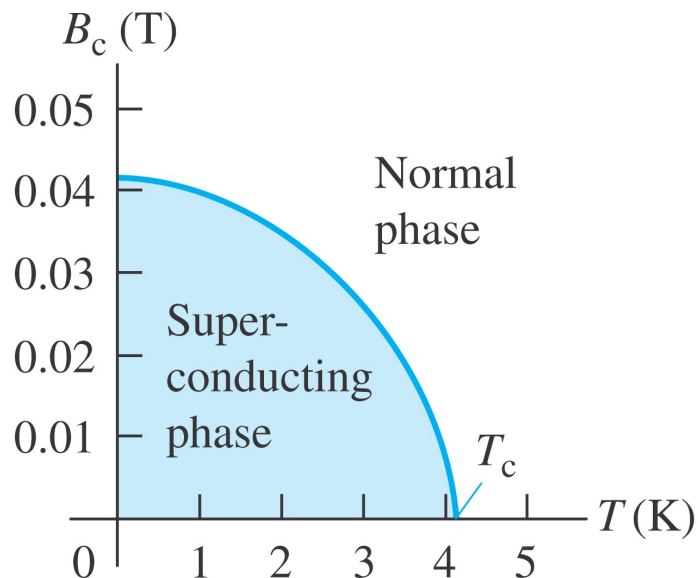
# Maxwell's equations

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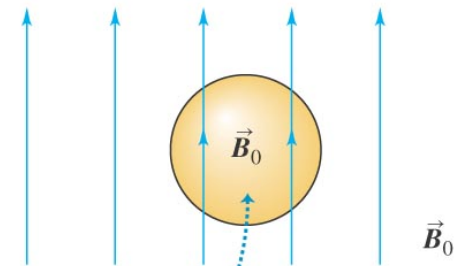
- *Maxwell's equations* consist of
  - ✓ Gauss's law for the electric field
  - ✓ Gauss's law for the magnetic field
  - ✓ Ampere's law
  - ✓ Faraday's law.
- Follow the text discussion for the mathematical form of these four fundamental laws.

# Superconductivity

- When a superconductor is cooled below its *critical temperature*, it loses all electrical resistance.
- Follow the text discussion using Figures 29.23 (below) and 29.24 (right).

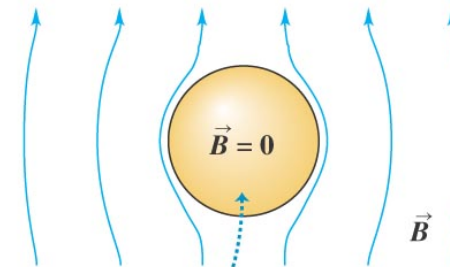


(a) Superconducting material in an external magnetic field  $\vec{B}_0$  at  $T > T_c$ .



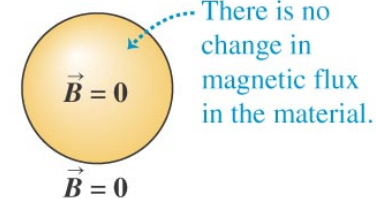
The field inside the material is very nearly equal to  $\vec{B}_0$ .

(b) The temperature is lowered to  $T < T_c$ , so the material becomes superconducting.



Magnetic flux is expelled from the material, and the field inside it is zero (Meissner effect).

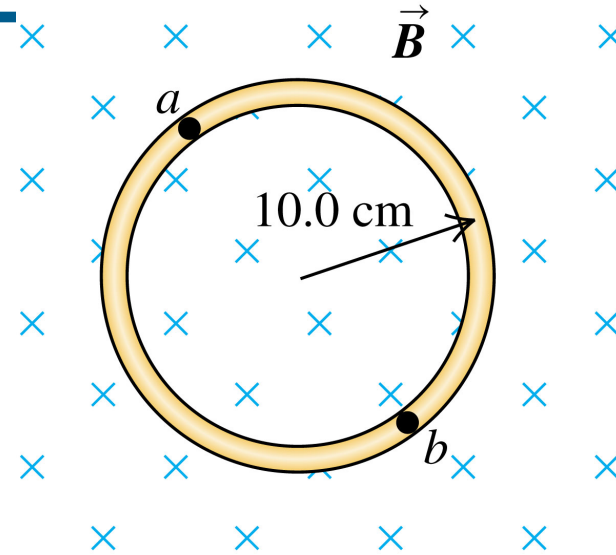
(c) When the external field is turned off at  $T < T_c$ , the field is zero everywhere.



There is no change in magnetic flux in the material.

## 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,

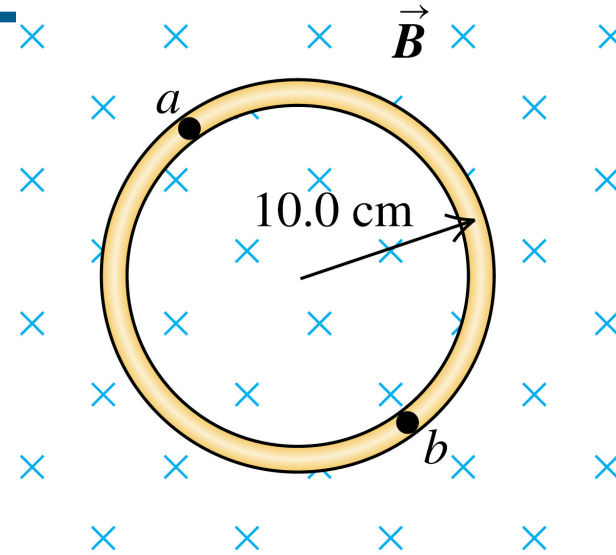


- A. the induced emf is clockwise.
- B. the induced emf is counterclockwise.
- C. the induced emf is zero.
- D. The answer depends on the strength of the field.



## Q29.2

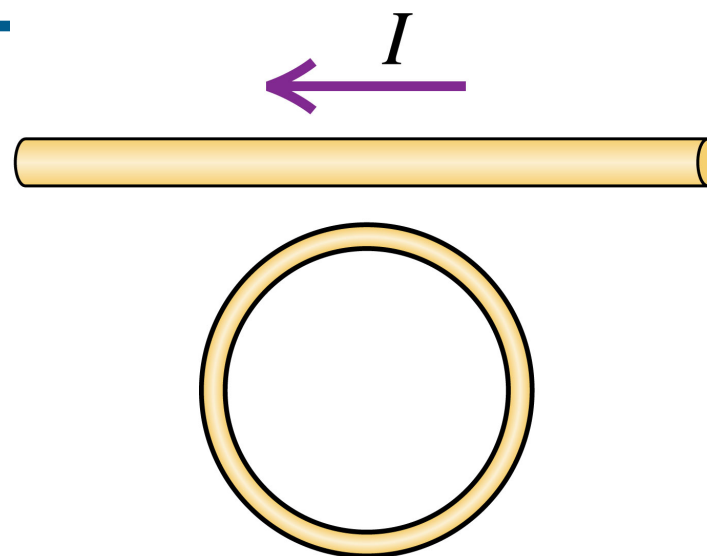
A circular loop of wire is in a region of spatially uniform magnetic field. The magnetic field is directed into the plane of the figure. If the magnetic field magnitude is *decreasing*,



- A. the induced emf is clockwise.
- B. the induced emf is counterclockwise.
- C. the induced emf is zero.
- D. The answer depends on the strength of the field.

### Q29.3

A circular loop of 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?

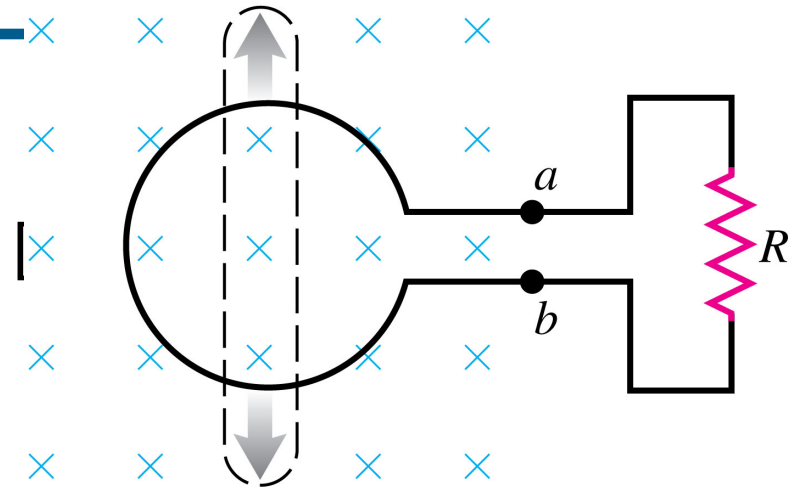


- A. a clockwise current
- B. a counterclockwise current
- C. zero current
- D. not enough information given to decide



### Q29.4

A flexible loop of wire lies in a uniform magnetic field of magnitude  $B$  directed into the plane of the picture. The loop is pulled as shown, reducing its area.



The induced current

- A. flows downward through resistor  $R$  and is proportional to  $B$ .
- B. flows upward through resistor  $R$  and is proportional to  $B$ .
- C. flows downward through resistor  $R$  and is proportional to  $B^2$ .
- D. flows upward through resistor  $R$  and is proportional to  $B^2$ .

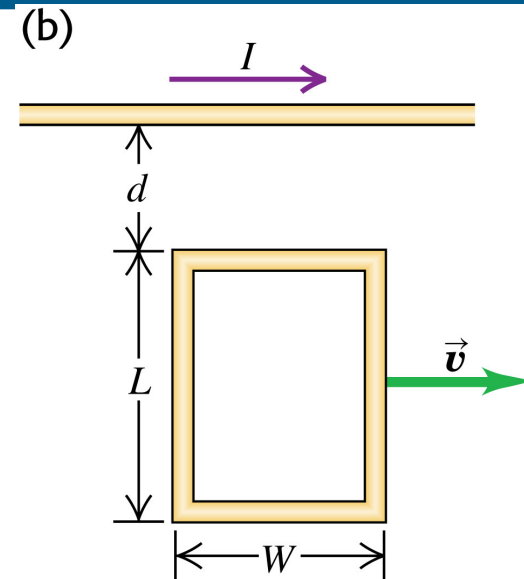
E. none of the above



## Q29.5

The rectangular loop of wire is being moved to the right at constant velocity. A constant current  $I$  flows in the long straight wire in the direction shown. The current induced in the loop is

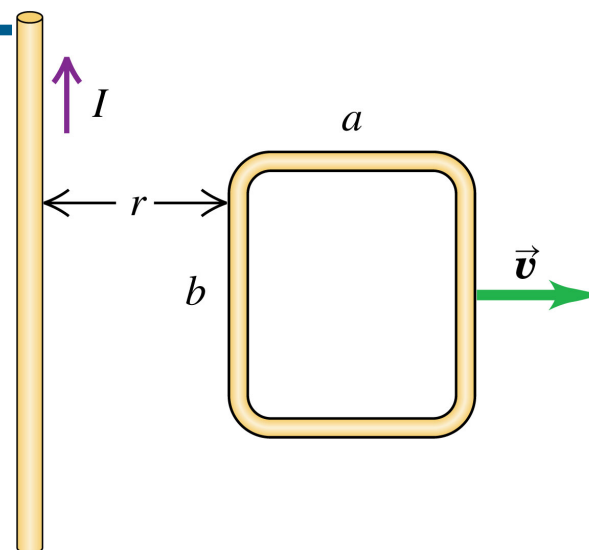
- A. clockwise and proportional to  $I$ .
- B. counterclockwise and proportional to  $I$ .
- C. clockwise and proportional to  $I^2$ .
- D. counterclockwise and proportional to  $I^2$ .
- E. zero.





## Q29.6

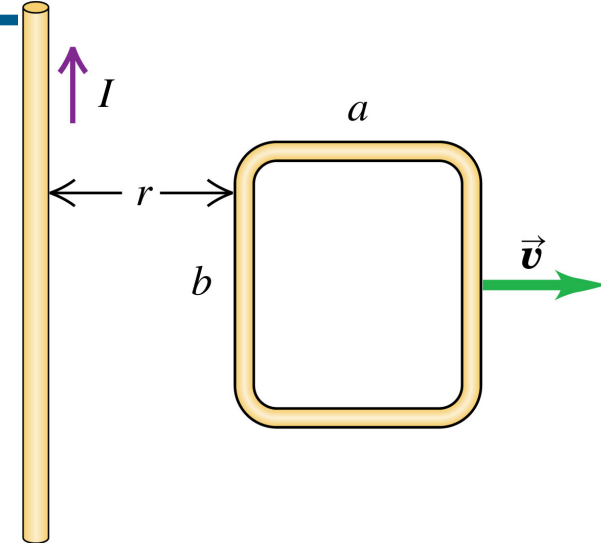
The loop of wire is being moved to the right at constant velocity. A constant current  $I$  flows in the long straight wire in the direction shown. The current induced in the loop is



- A. clockwise and proportional to  $I$ .
- B. counterclockwise and proportional to  $I$ .
- C. clockwise and proportional to  $I^2$ .
- D. counterclockwise and proportional to  $I^2$ .
- E. zero.

## Q29.7

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?

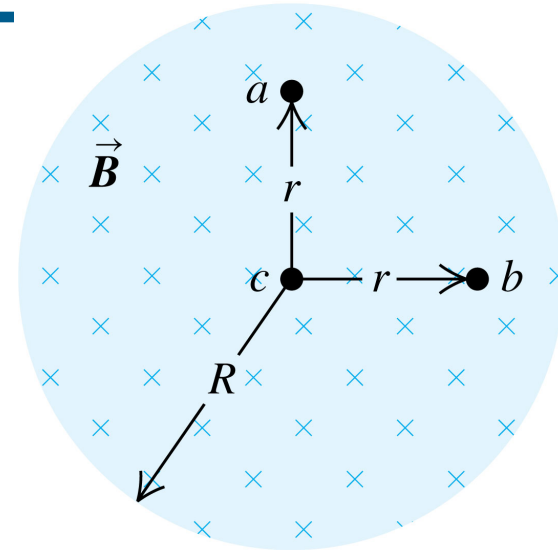


- A. L: to the left; R: to the left
- B. L: to the left; R: to the right
- C. L: to the right; R: to the left
- D. L: to the right; R: to the right



## Q29.8

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*?

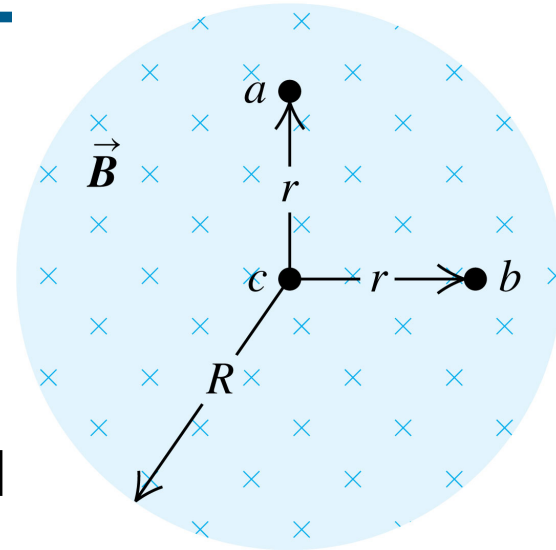
- A. to the left
- B. to the right
- C. straight up
- D. straight down
- E. misleading question—the electric force at this point is zero



## 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 *b*?



- 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

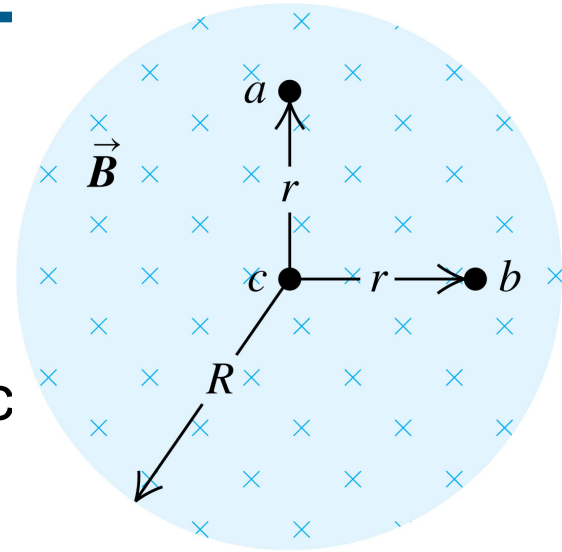


## Q29.10



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 *c* (at the center of the solenoid)?



- 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