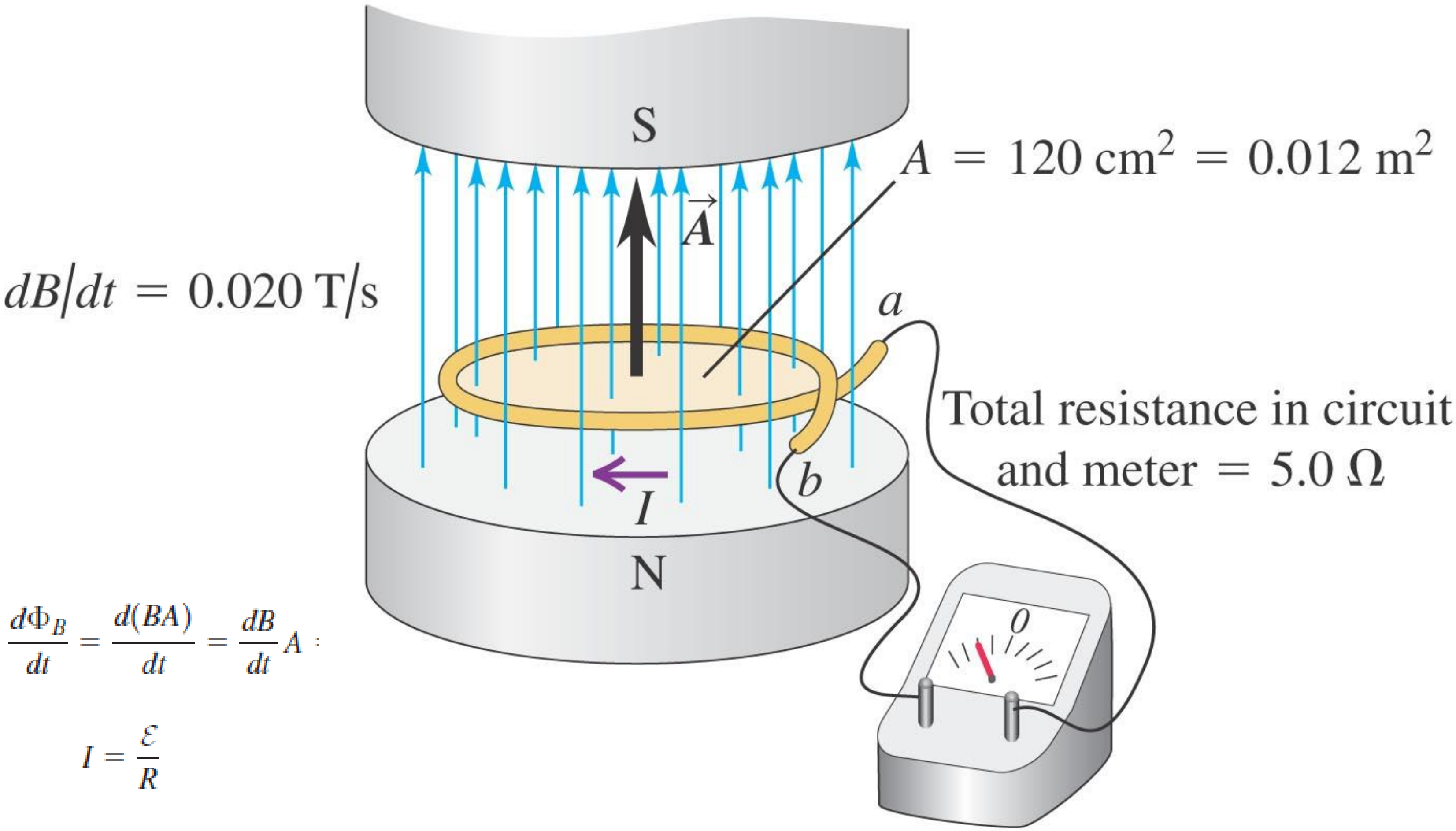
Chapter 29

Electromagnetic Induction

Emf and the current induced in a loop

- Follow Example 29.1 using Figure 29.5 below.



$$\frac{d\Phi_B}{dt} = \frac{d(BA)}{dt} = \frac{dB}{dt}A$$

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

Goals for Chapter 29

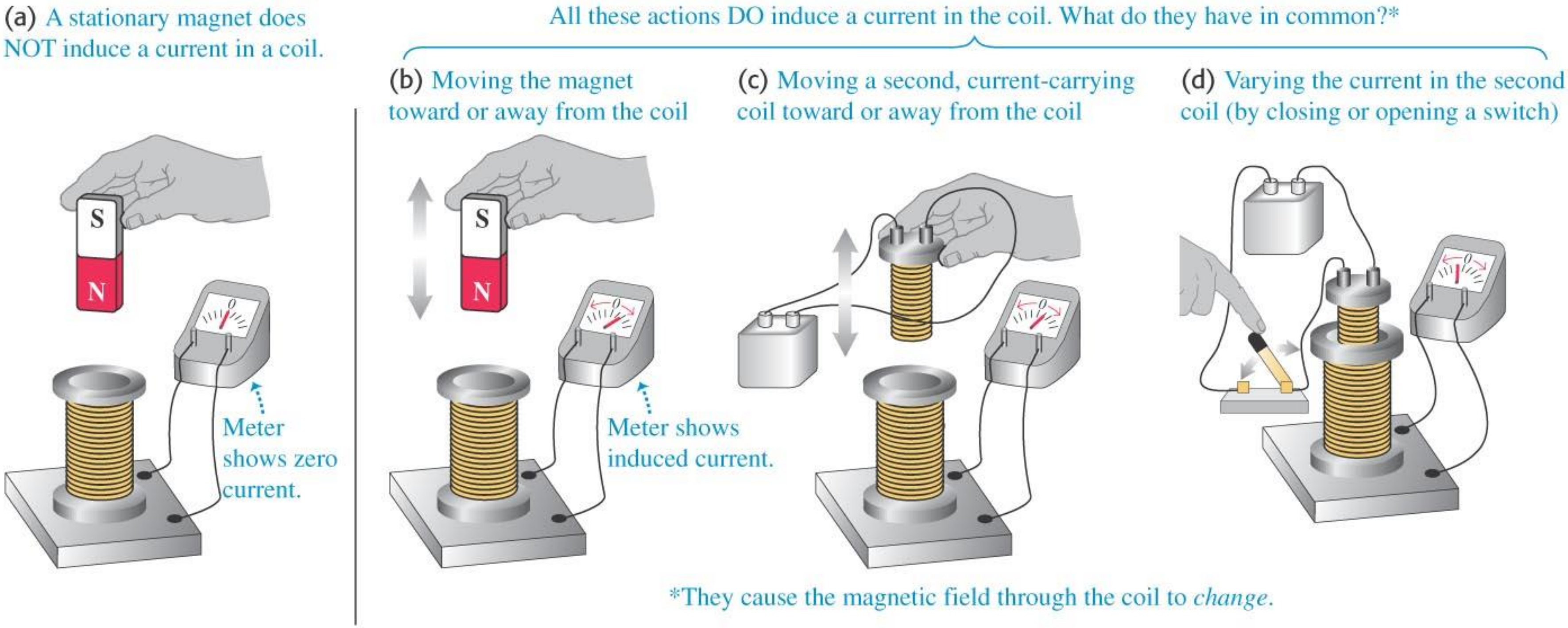
- To examine experimental evidence that a changing magnetic field induces an emf
- To learn how Faraday's law relates the induced emf to the change in flux
- To determine the direction of an induced emf
- To calculate the emf induced by a moving conductor
- To learn how a changing magnetic flux generates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

Introduction

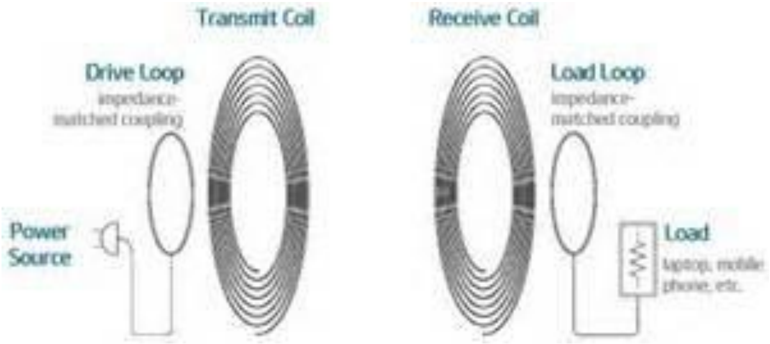
- How is a credit card reader related to magnetism?
- Energy conversion makes use of electromagnetic induction.
- Faraday’s law and Lenz’s law tell us about induced currents.
- Maxwell’s equations describe the behavior of electric and magnetic fields in *any* situation.

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.



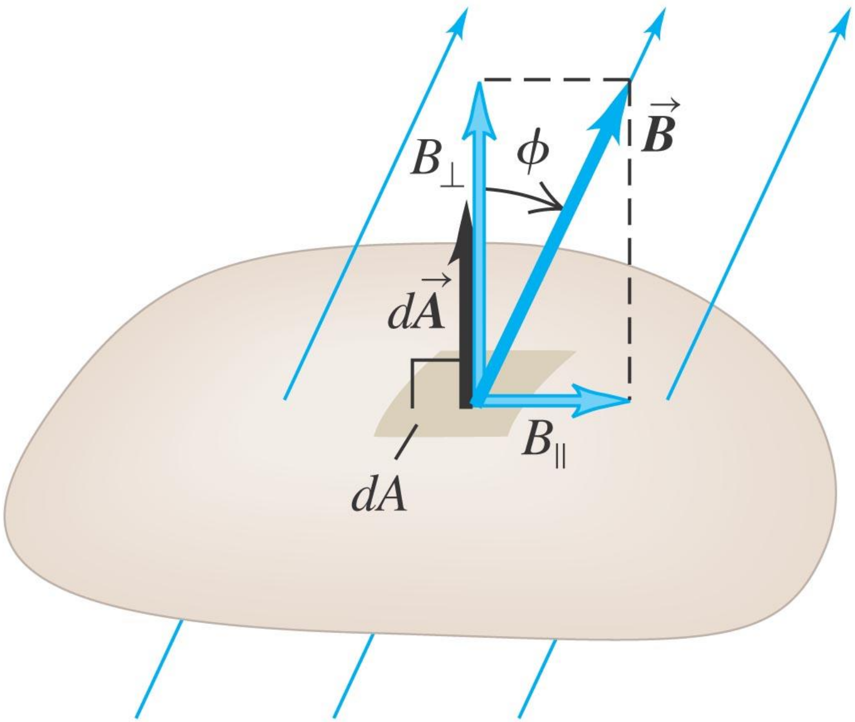
Induced current



Induced current

Magnetic flux through an area element

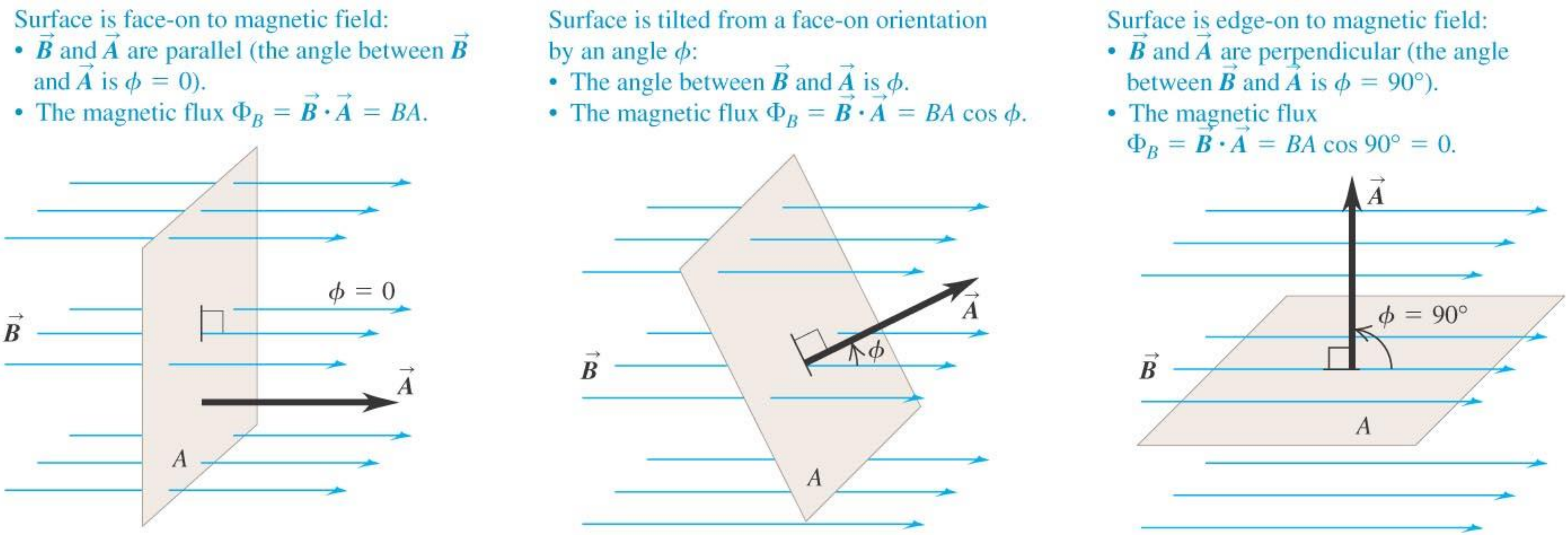
- Figure 29.3 below shows how to calculate the magnetic flux through an element of area.



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 of induction states:

The induced emf in a closed loop equals the negative of the time rate of change of magnetic flux through the loop.

In symbols, Faraday's law is

$$\mathcal{E} = -\frac{d\Phi_B}{dt} \qquad \text{(Faraday's law of induction)} \qquad (29.3)$$

Faraday's law

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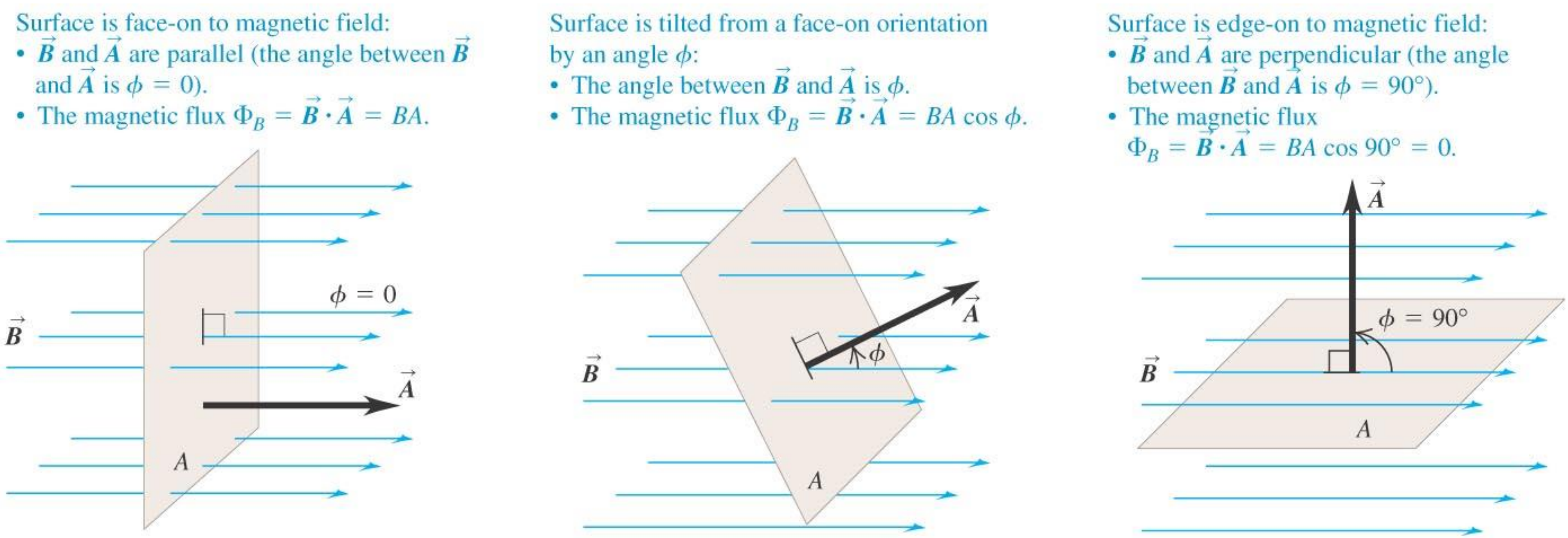
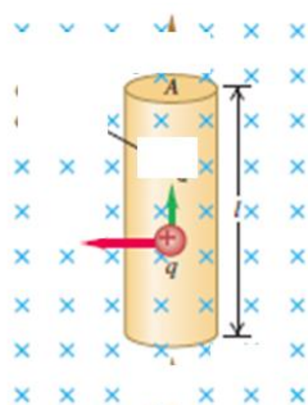
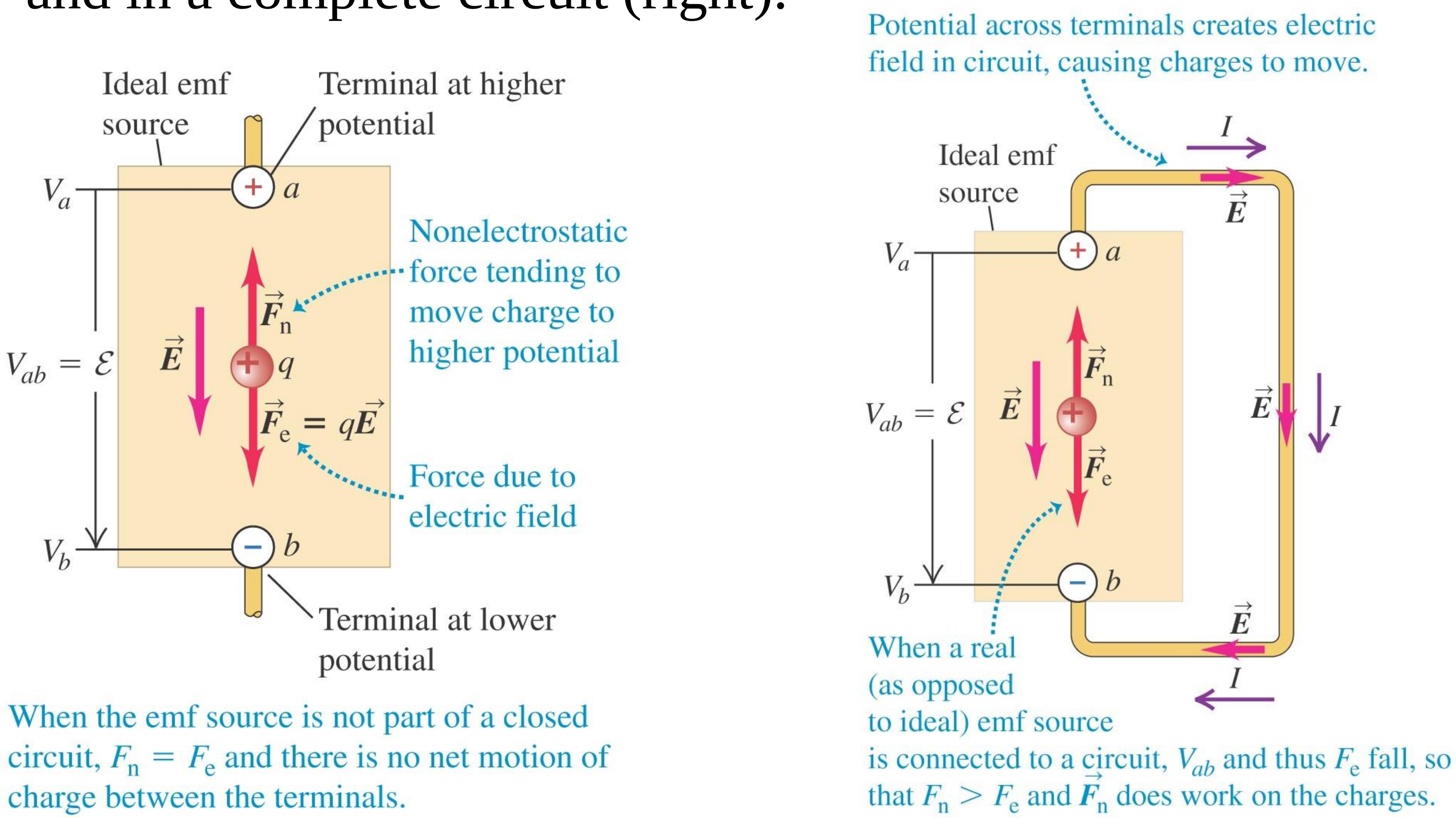




$$\vec{F} = q\vec{v} \times \vec{B}$$

Electromotive force and circuits

- An *electromotive force* (*emf*) makes current flow. In spite of the name, an emf is *not* a force.
- The figures below show a source of emf in an open circuit (left) and in a complete circuit (right).



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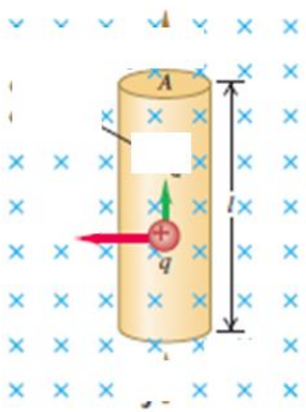
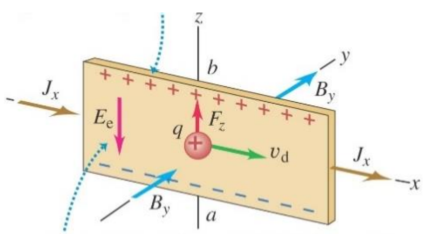
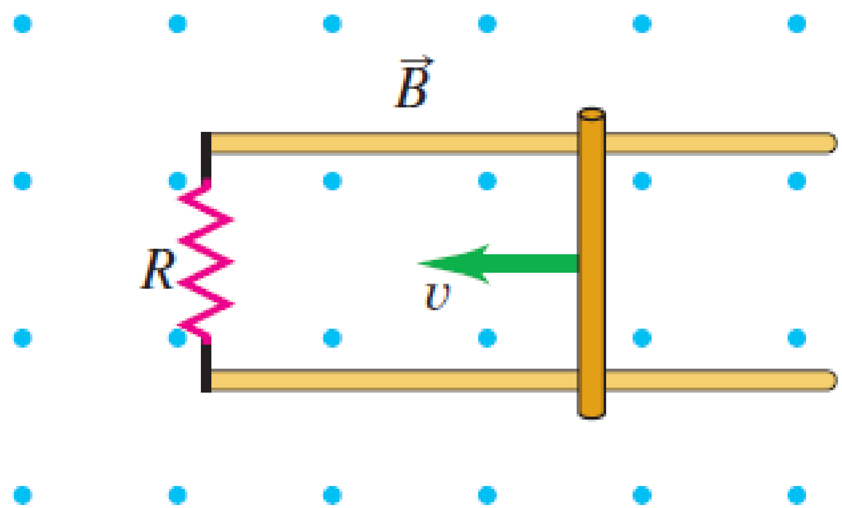
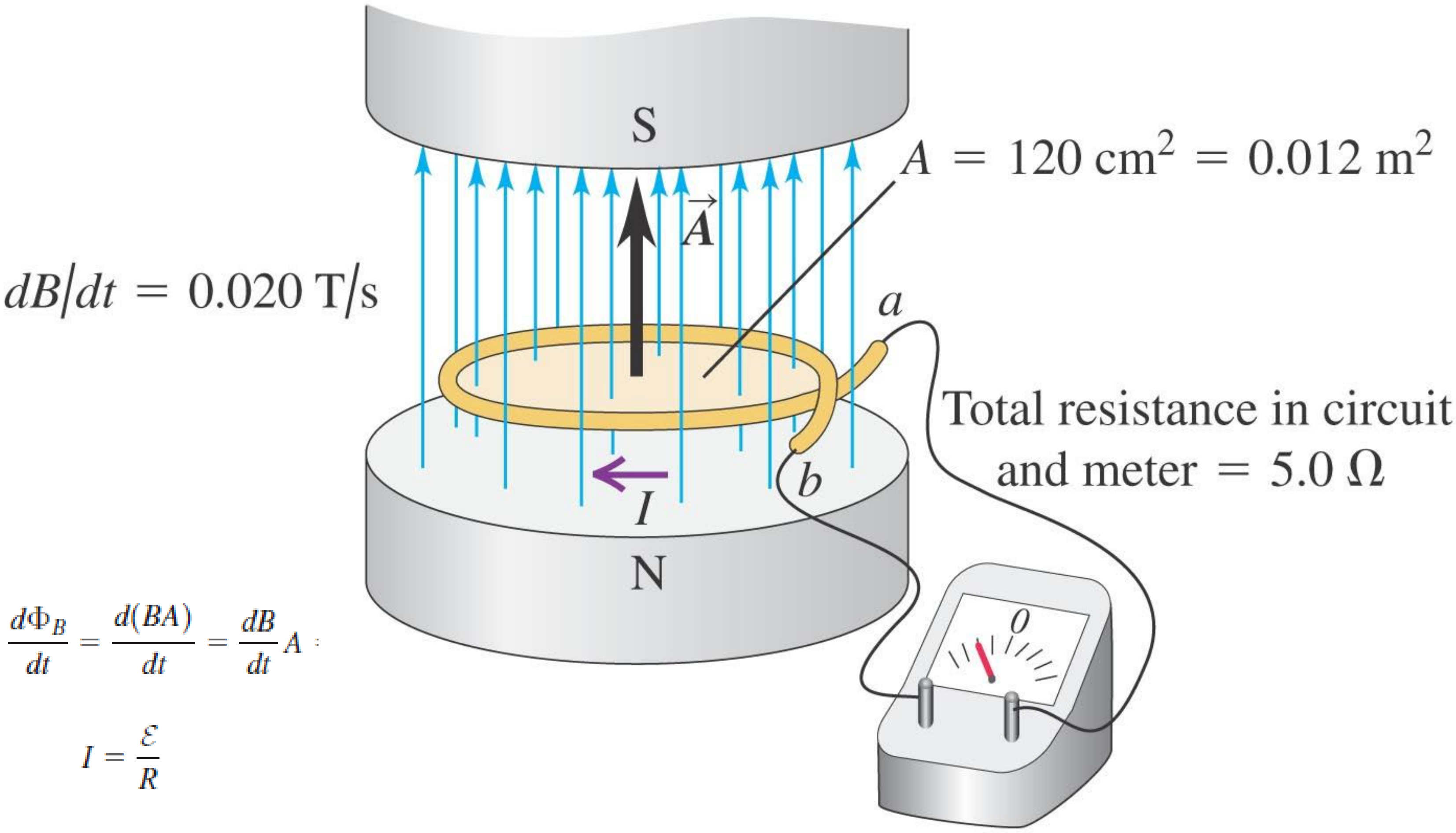






Emf and the current induced in a loop

- Follow Example 29.1 using Figure 29.5 below.

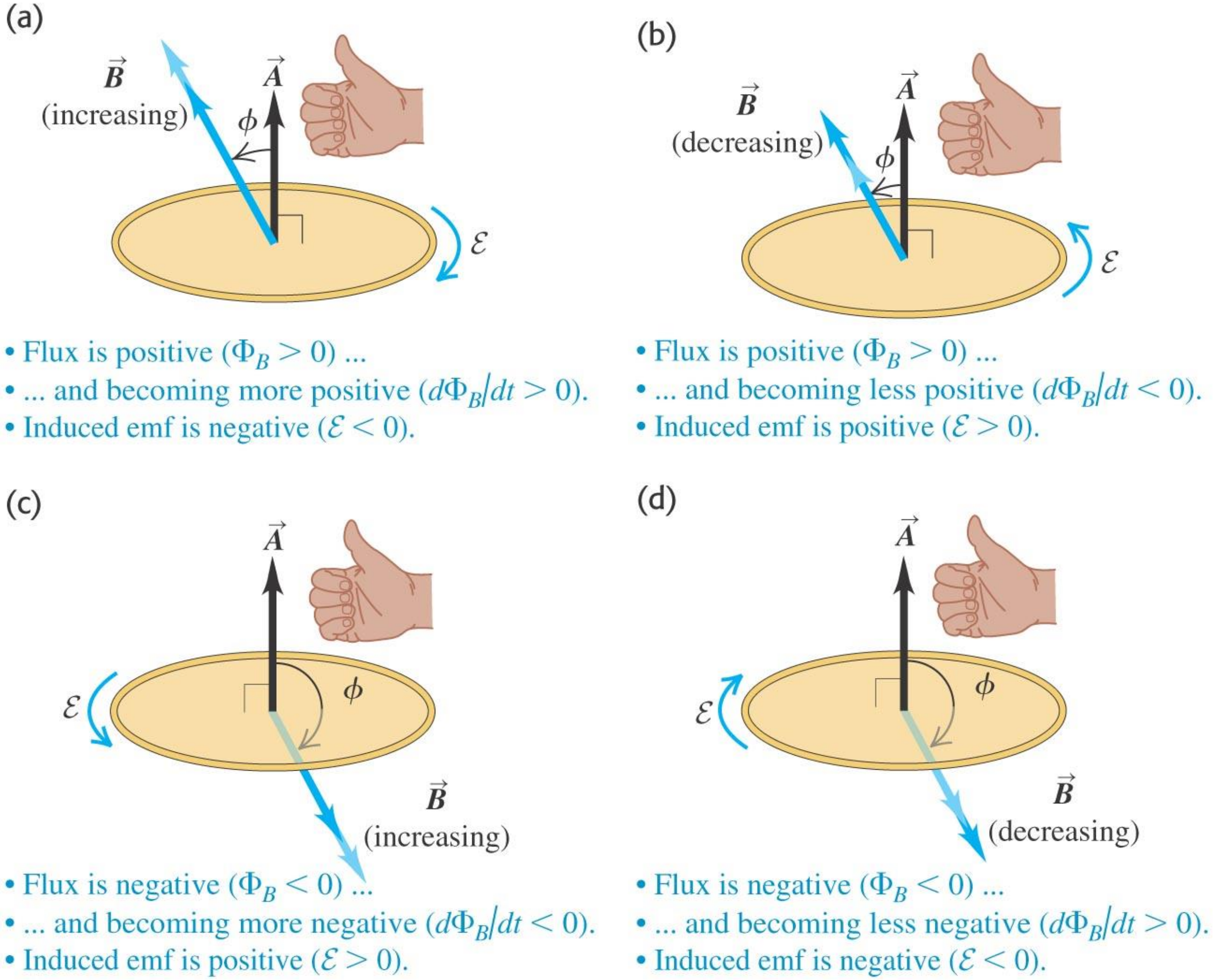


$$\frac{d\Phi_B}{dt} = \frac{d(BA)}{dt} = \frac{dB}{dt}A$$

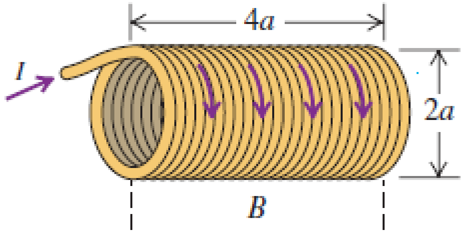
$$I = \frac{\mathcal{E}}{R}$$

Direction of the induced emf

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



induced emf

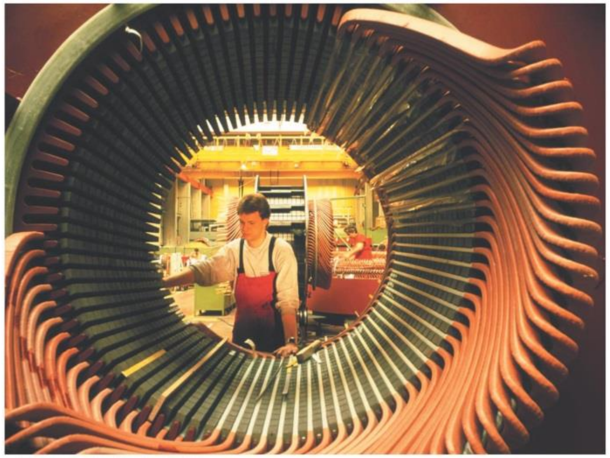


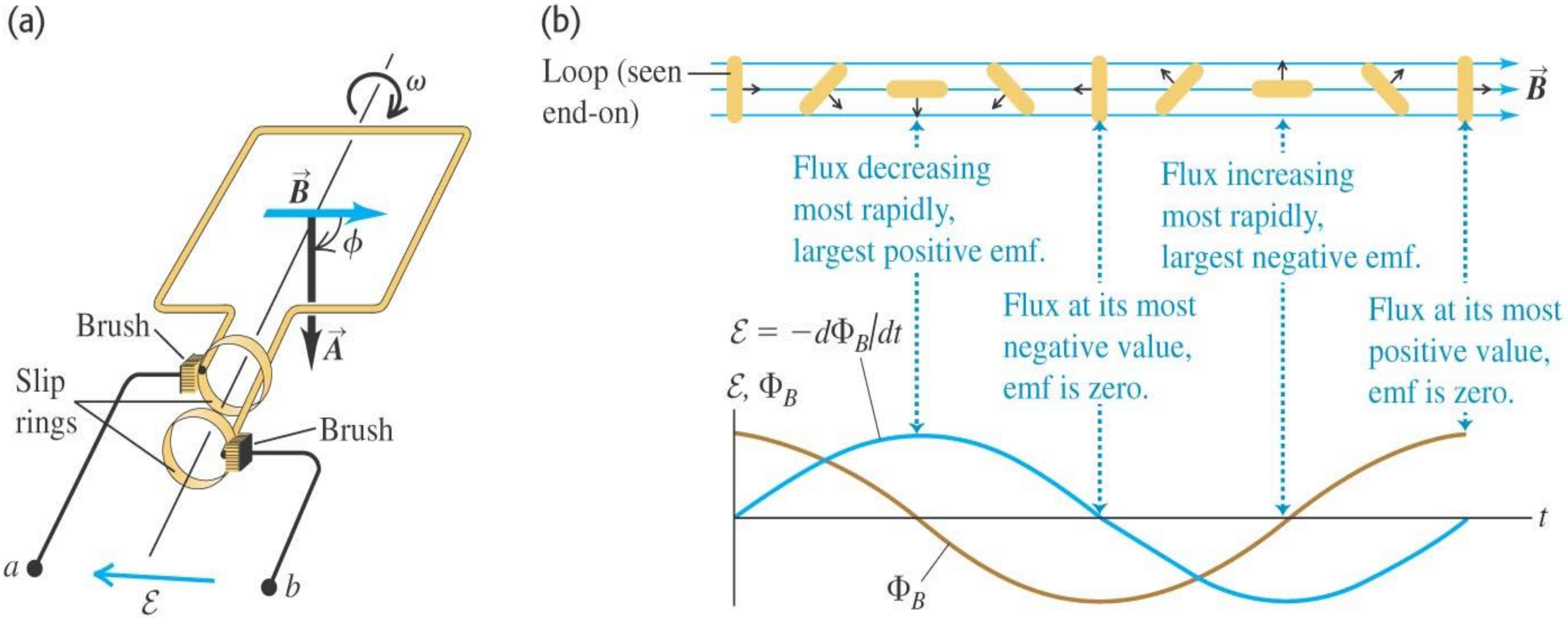
$$\mathcal{E} = -N\frac{d\Phi_B}{dt}$$

A simple alternator

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

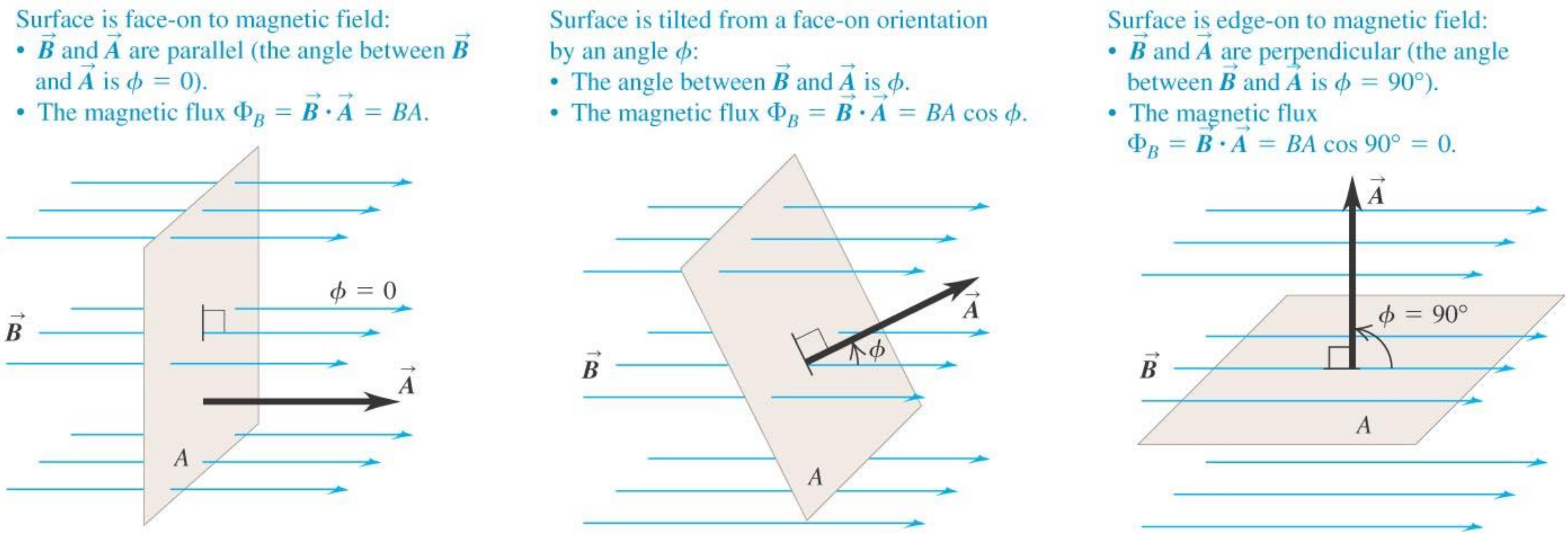
$$\mathcal{E} = -\frac{d\Phi_B}{dt} = -\frac{d}{dt}(BA\cos\omega t) = \omega BA\sin\omega t$$





Faraday's law

- The flux depends on the orientation of the surface with respect to the magnetic field. See Figure 29.4 below.



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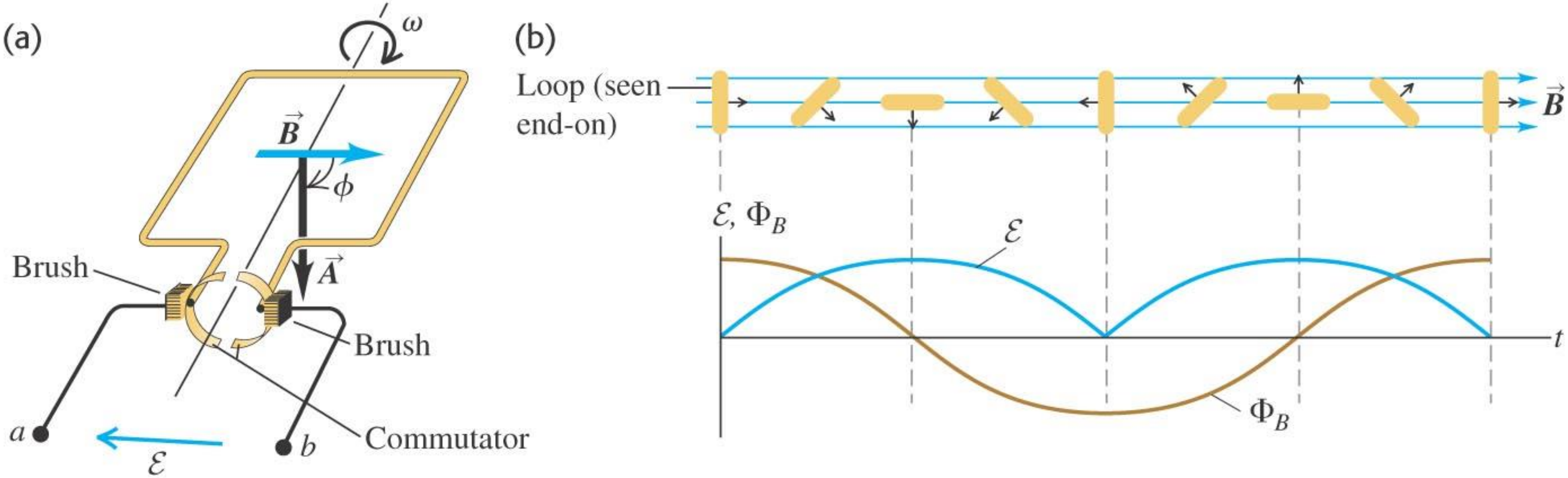
The induced emf in a closed loop equals the negative of the time rate of change of magnetic flux through the loop.

In symbols, Faraday's law is

$$\mathcal{E} = -\frac{d\Phi_B}{dt} \qquad \text{(Faraday's law of induction)} \qquad (29.3)$$

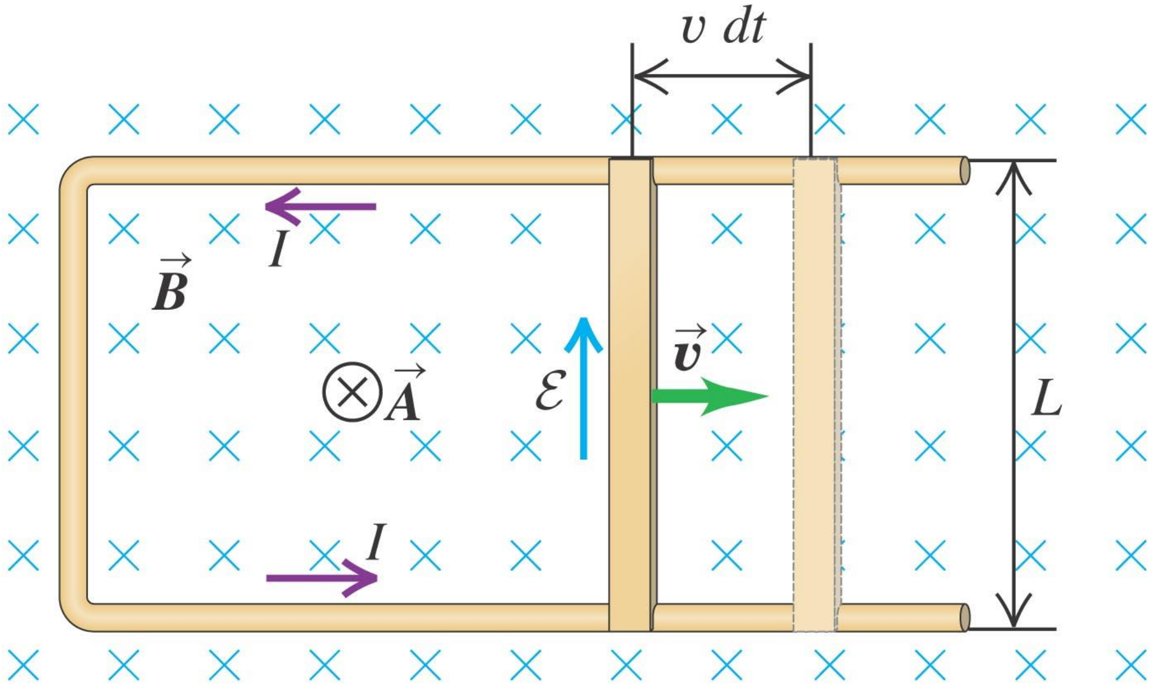
DC generator and back emf in a motor

- Follow Example 29.4 using Figure 29.10 below.



Slidewire generator

- Follow Example 29.5 using Figure 29.11 below.

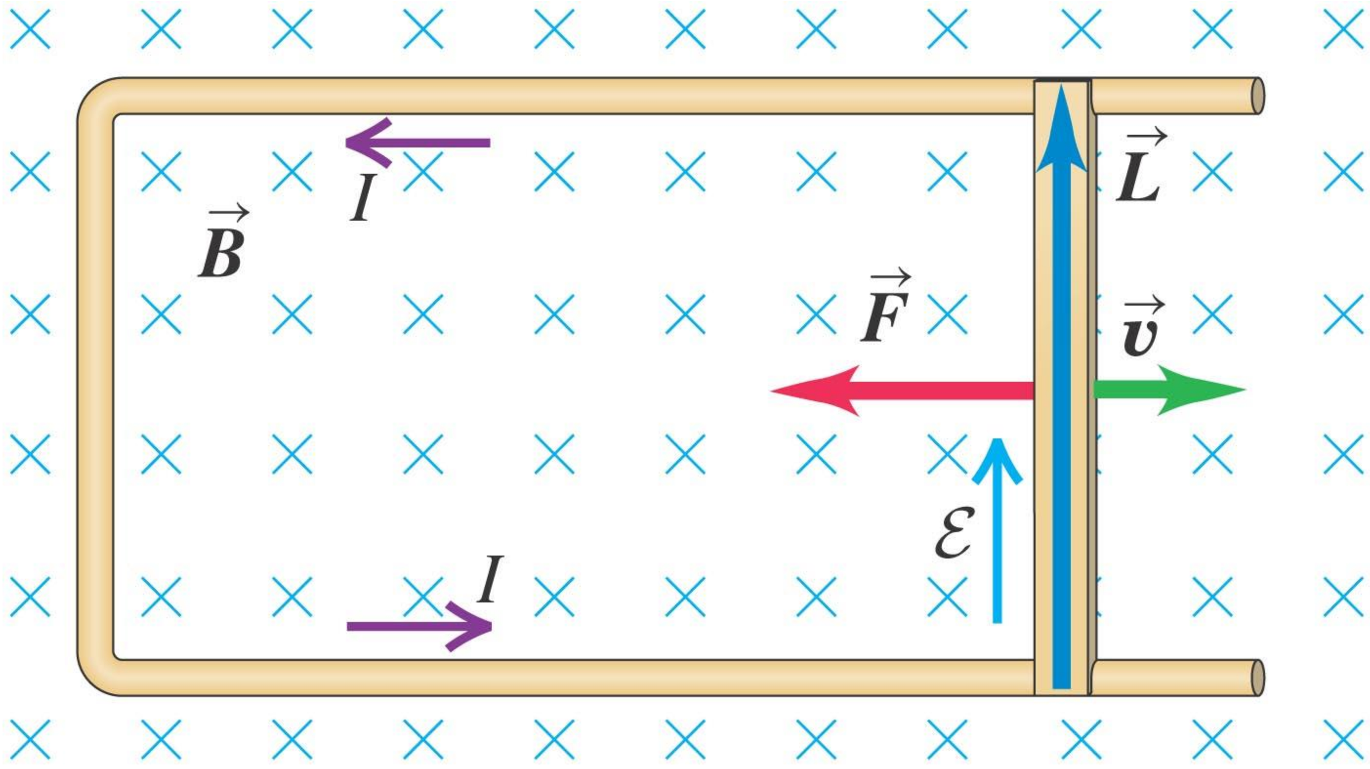


$$\mathcal{E} = -\frac{d\Phi_B}{dt} = -B\frac{dA}{dt}$$

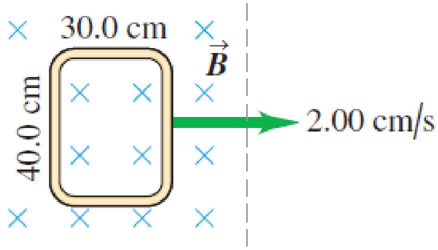
$$\mathcal{E} = -B\frac{Lv\,dt}{dt} = -BLv$$

Work and power in the slidewire generator

- Follow Example 29.6 using Figure 29.12 below.



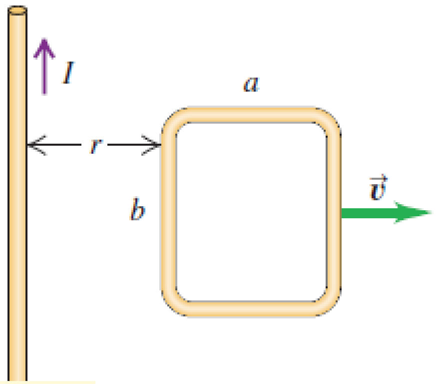
$$d\vec{F} = I\,d\vec{l} \times \vec{B}$$

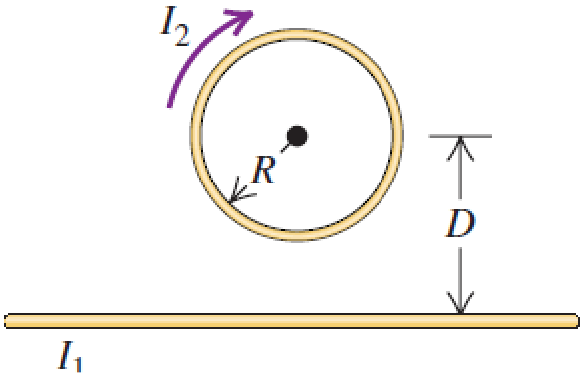


Work and power in the slidewire generator

- Follow Example 29.6 using Figure 29.12 below.

Figure **P29.53**





$$B = \frac{\mu_0 I}{2\pi r}$$

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

$$d\vec{F} = I\, d\vec{l} \times \vec{B}$$

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

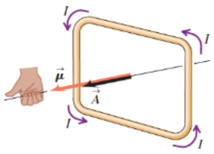
The direction of any magnetic induction effect is such as to oppose the cause of the effect.

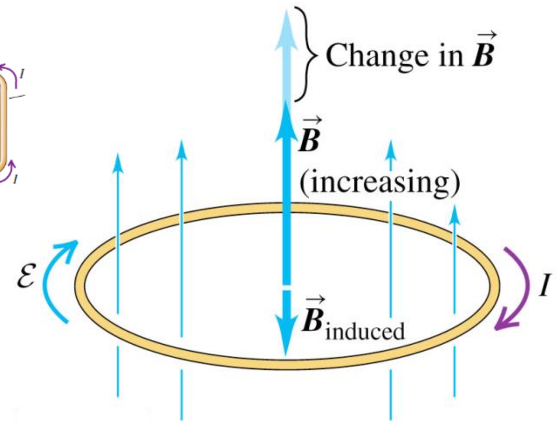
Lenz's law

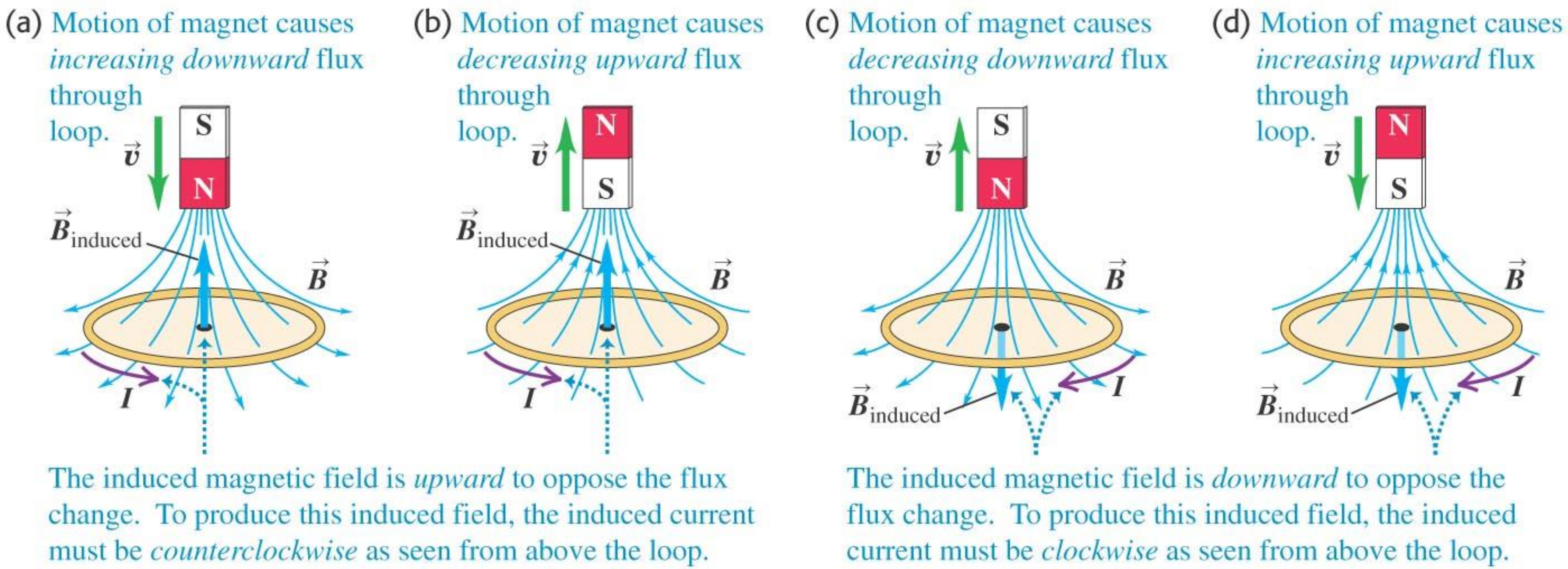
- *Lenz's law*: The direction of any magnetic induction effect is such as to ***oppose*** the cause of the effect.

Lenz's law and the direction of induced current

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

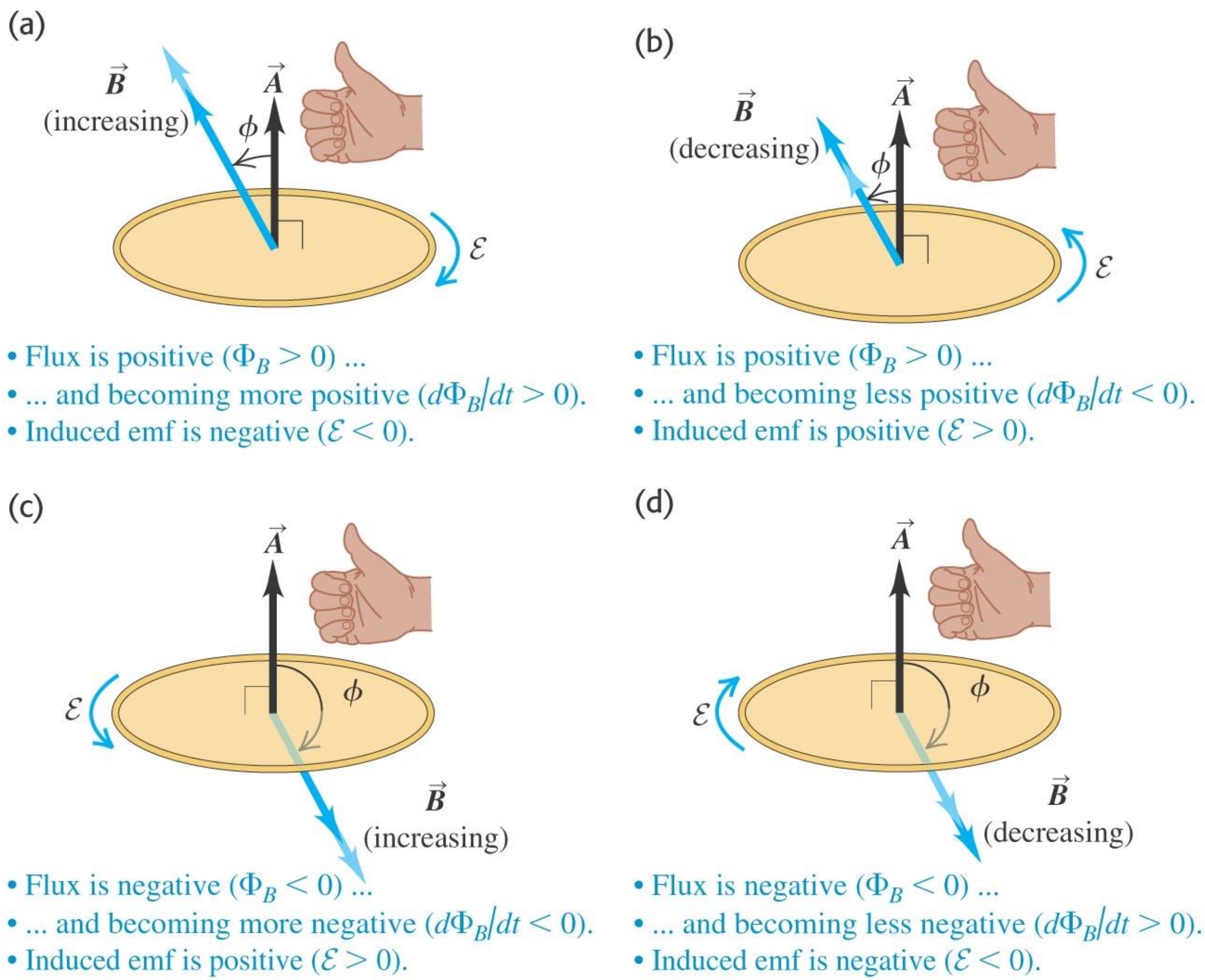






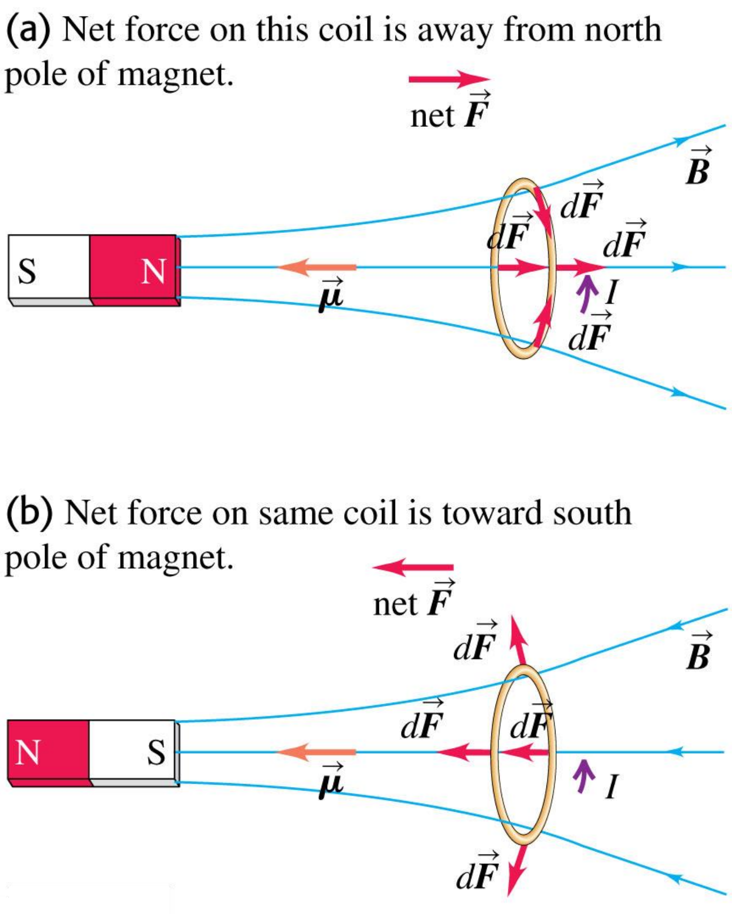
What about F?

Lenz’s law and the direction of induced current



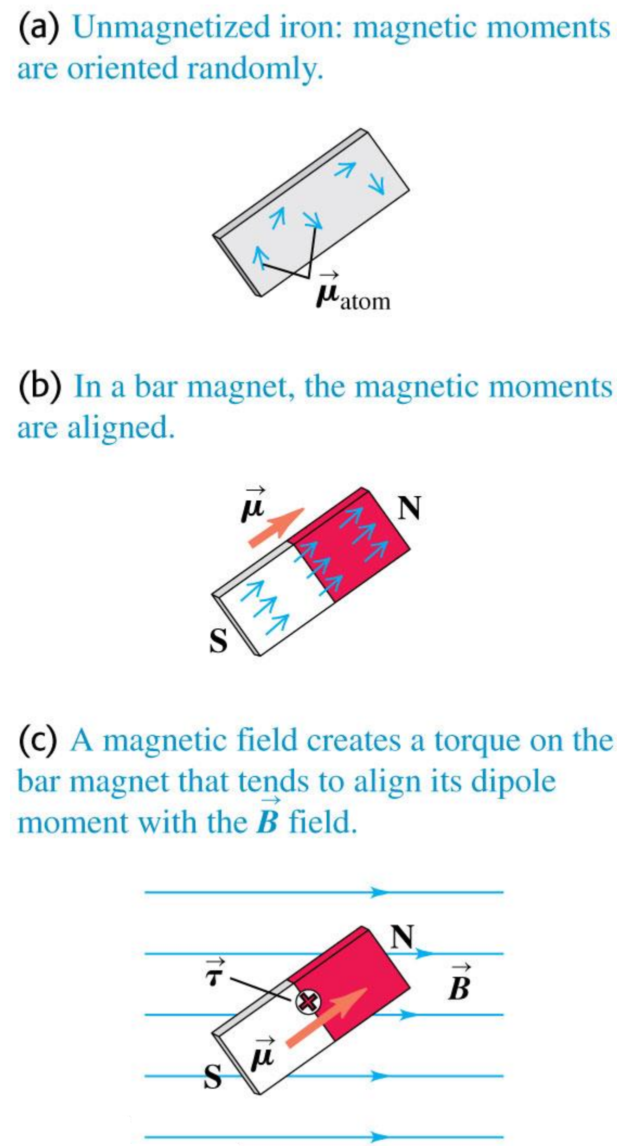
How magnets work

- Follow the discussion in the text of magnetic dipoles and how magnets work. Use Figures 27.36 (below) and 27.37 (right).



(a) Net force on this coil is away from north pole of magnet.

(b) Net force on same coil is toward south pole of magnet.

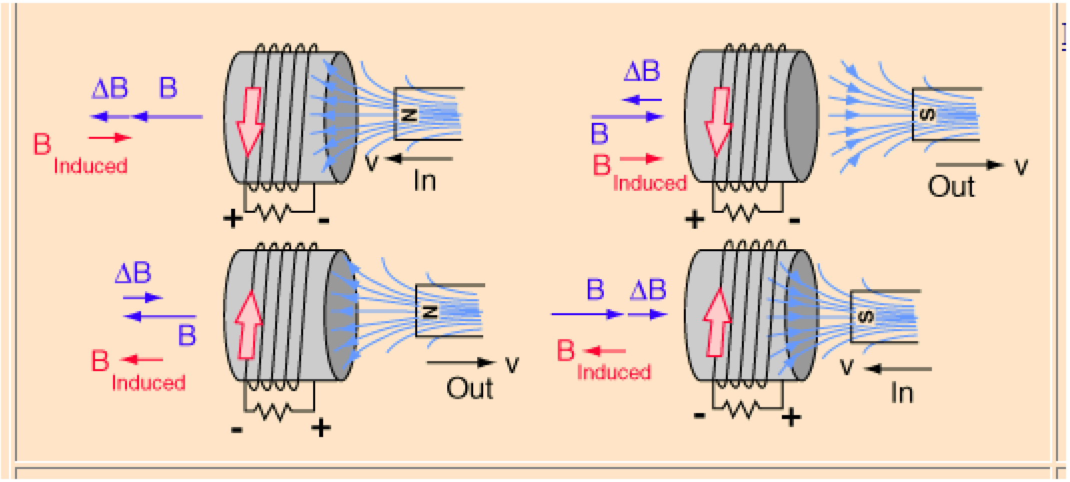


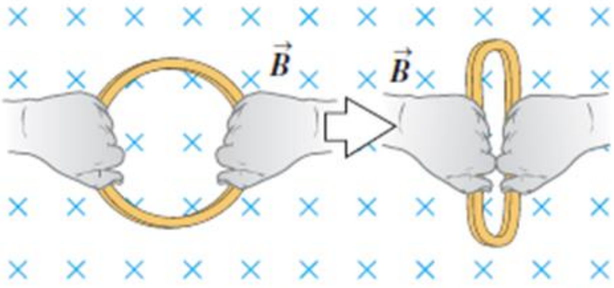
(a) Unmagnetized iron: magnetic moments are oriented randomly.

(b) In a bar magnet, the magnetic moments are aligned.

(c) A magnetic field creates a torque on the bar magnet that tends to align its dipole moment with the $\vec{B}$ field.

Lenz's law and the direction of induced current





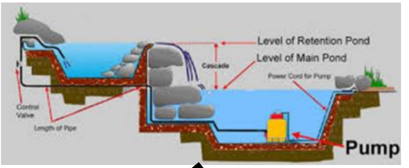
Circular wire coil

Coil squeezed into oval

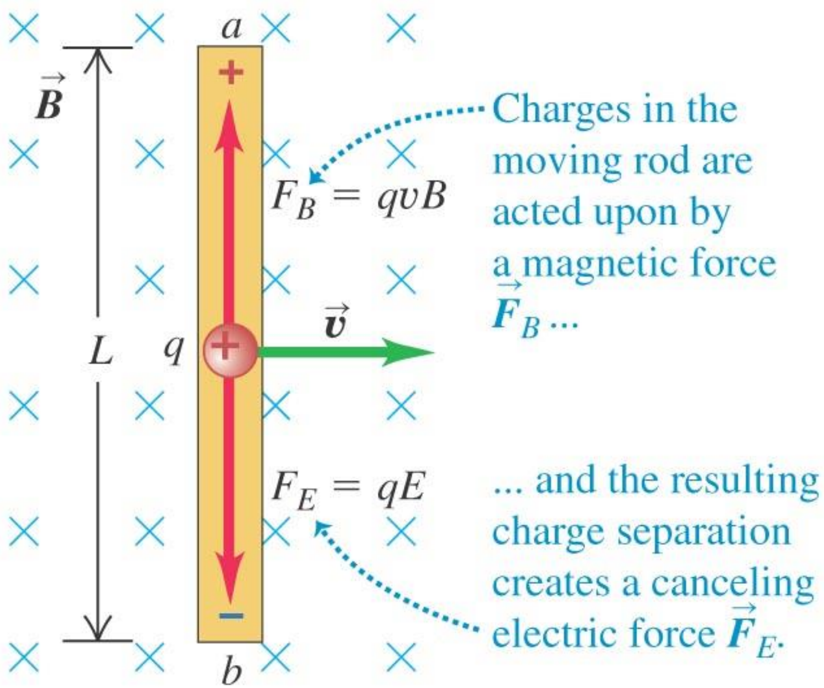
Motional electromotive force

- The *motional electromotive force* across the ends of a rod moving perpendicular to a magnetic field is $\xi = vBL$. Figure 29.15 below shows the direction of the induced current.

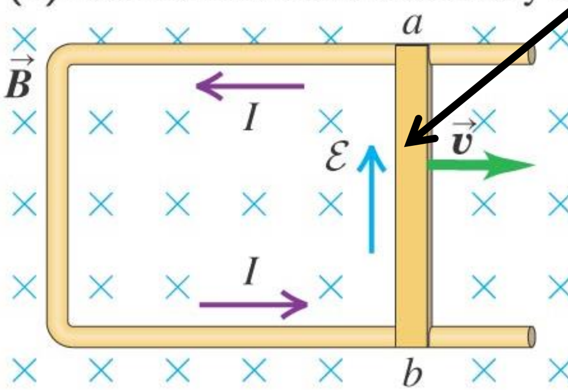
- Follow the general form of motional emf in the text.



(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.

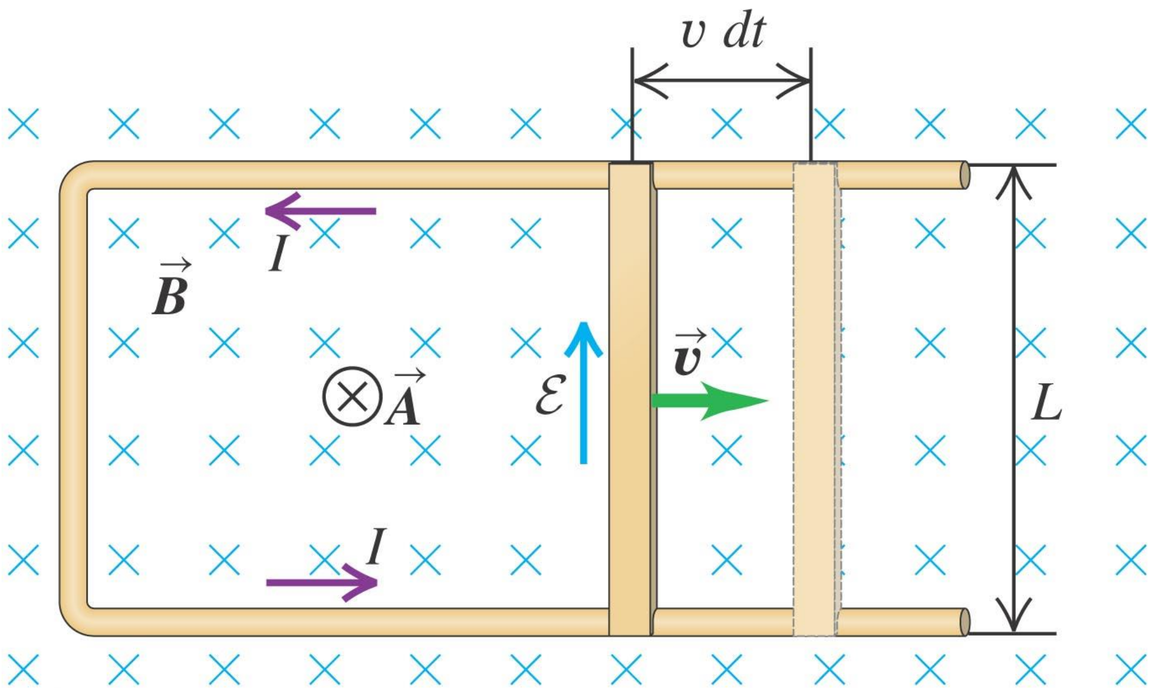
$$qE = qvB$$

$$V_{ab} = EL = vBL$$

$$\mathcal{E} = vBL \quad \text{(motional emf; length and velocity perpendicular to uniform } \vec{B}\text{)}$$

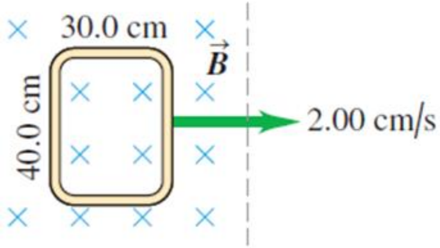
Slidewire generator

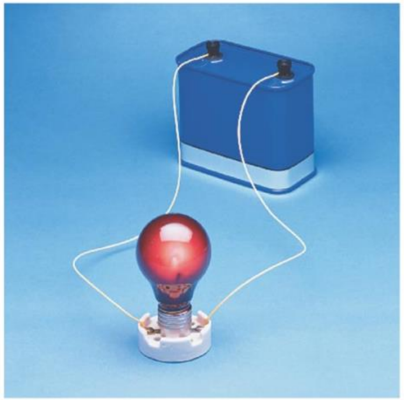
- Follow Example 29.5 using Figure 29.11 below.



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

$$\mathcal{E} = -B\frac{Lv\,dt}{dt} = -BLv$$

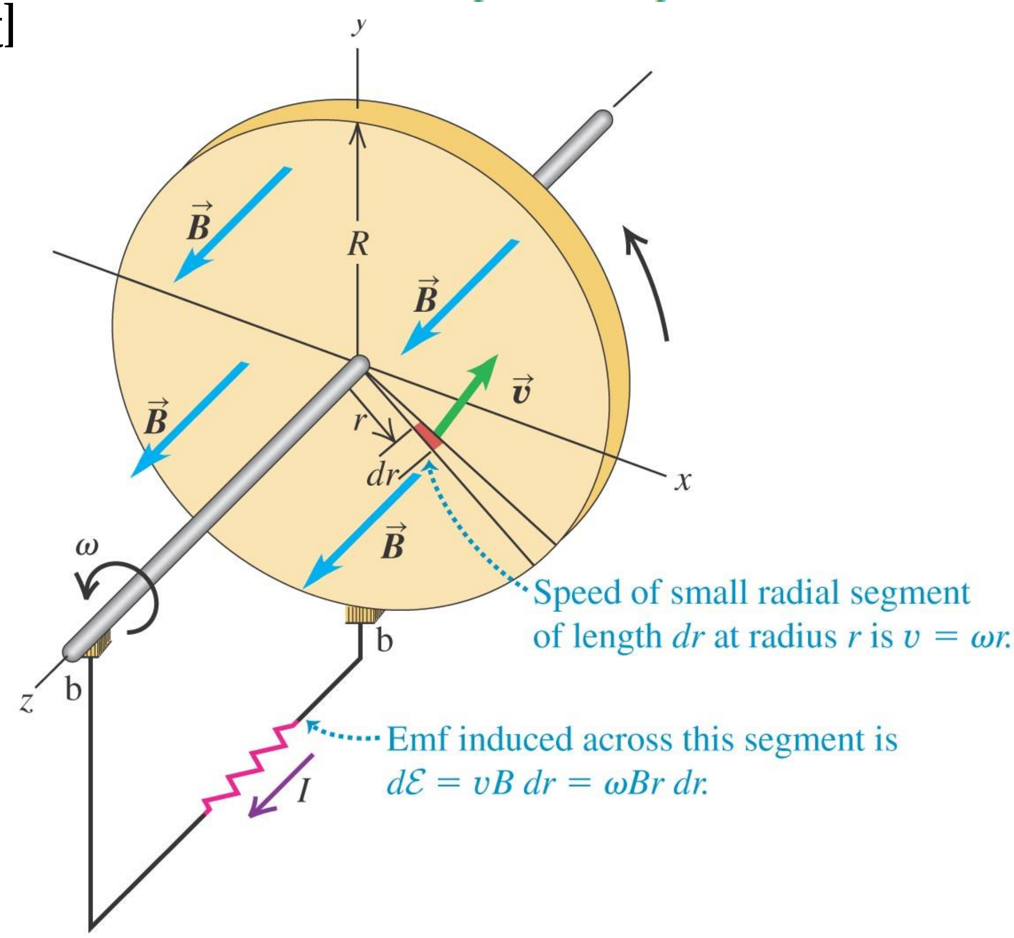




A slidewire generator and a dynamo

- Follow Example 29.9 for the slidewire generator.
- Follow Example 29.10 for tl
29.16 below.

The Faraday disk dynamo



$$d\mathcal{E} = (\vec{v} \times \vec{B}) \cdot d\vec{l}$$

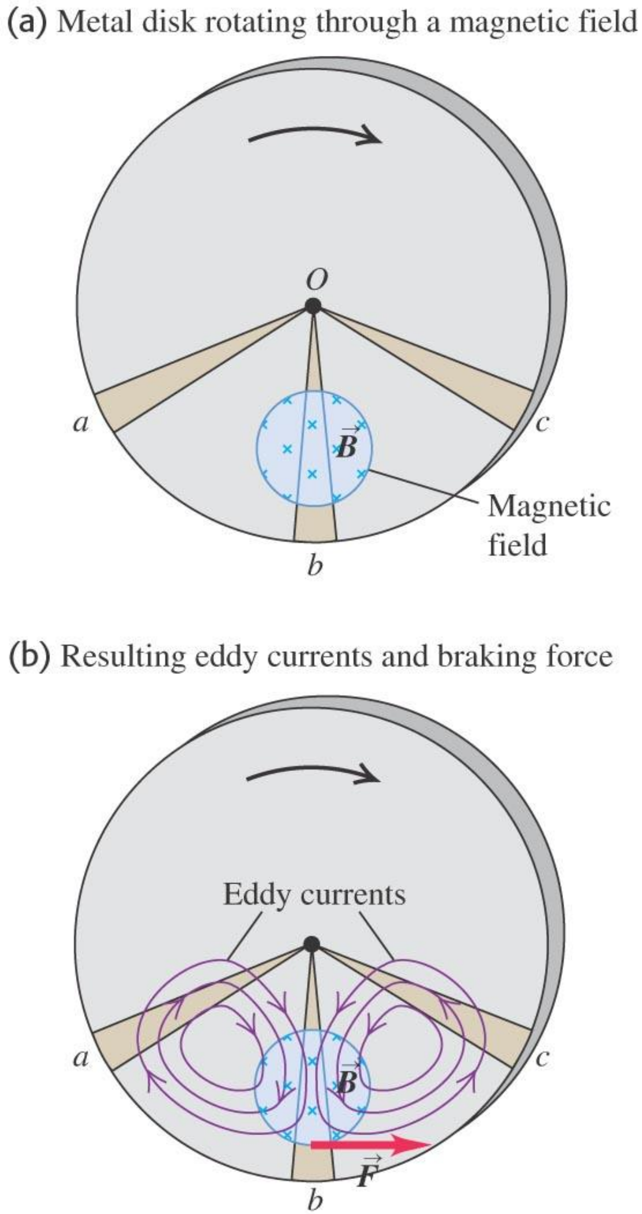
Motional emf: General Form

$$\mathcal{E} = \oint (\vec{v} \times \vec{B}) \cdot d\vec{l}$$

$$\mathcal{E} = \int_0^R \omega B r\,dr = \tfrac{1}{2}\omega B R^2$$

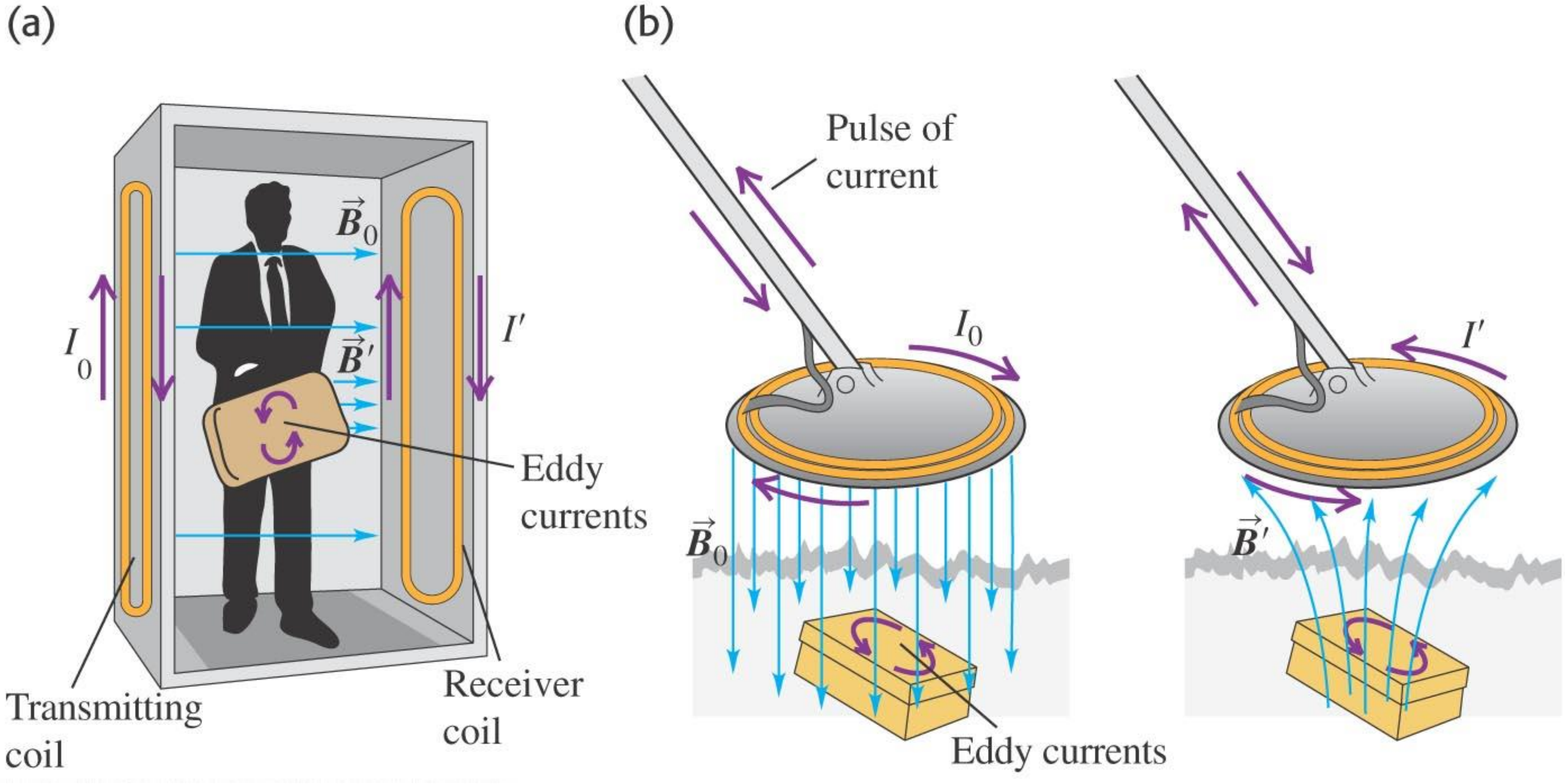
Eddy currents

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



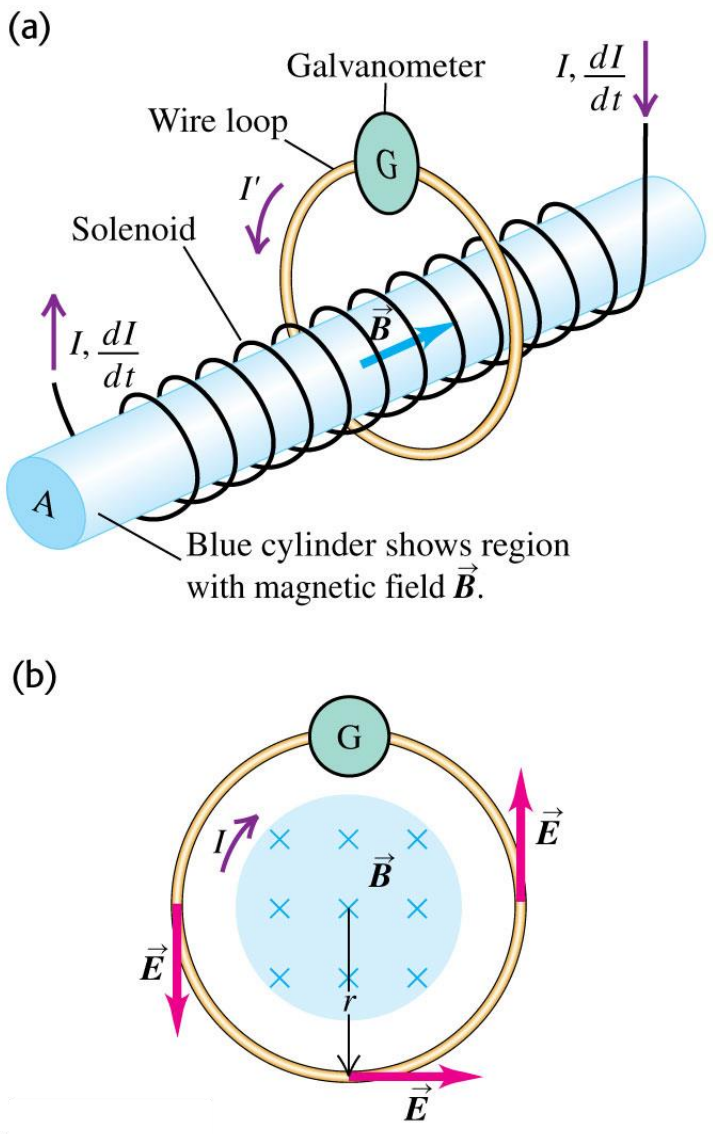
Using eddy currents

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



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.



Induced electric fields

$$\Phi_B = BA = \mu_0 n I A$$

$$\mathcal{E} = -\frac{d\Phi_B}{dt} = -\mu_0 n A \frac{dI}{dt}$$

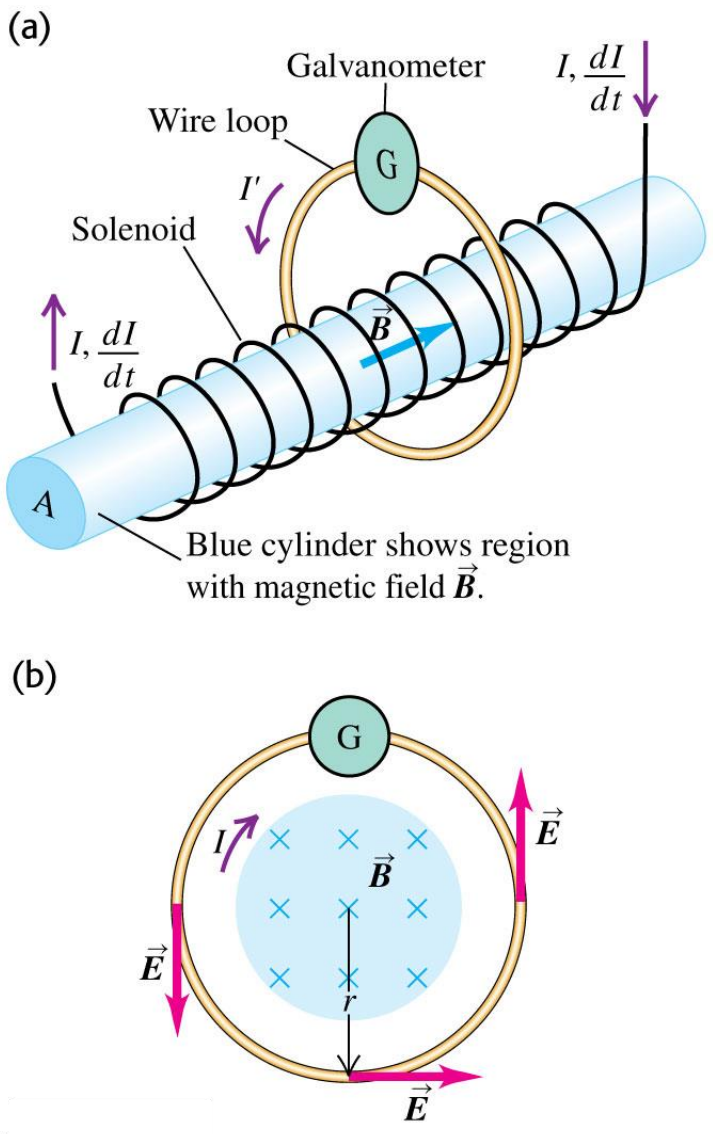
$V_{ab} = \mathcal{E}$ (ideal source of emf) ; $I' = \mathcal{E}/R$.

induced electric field $\oint \vec{E} \cdot d\vec{l} = \mathcal{E}$

$$\oint \vec{E} \cdot d\vec{l} = -\frac{d\Phi_B}{dt} \qquad \text{(stationary integration path)}$$

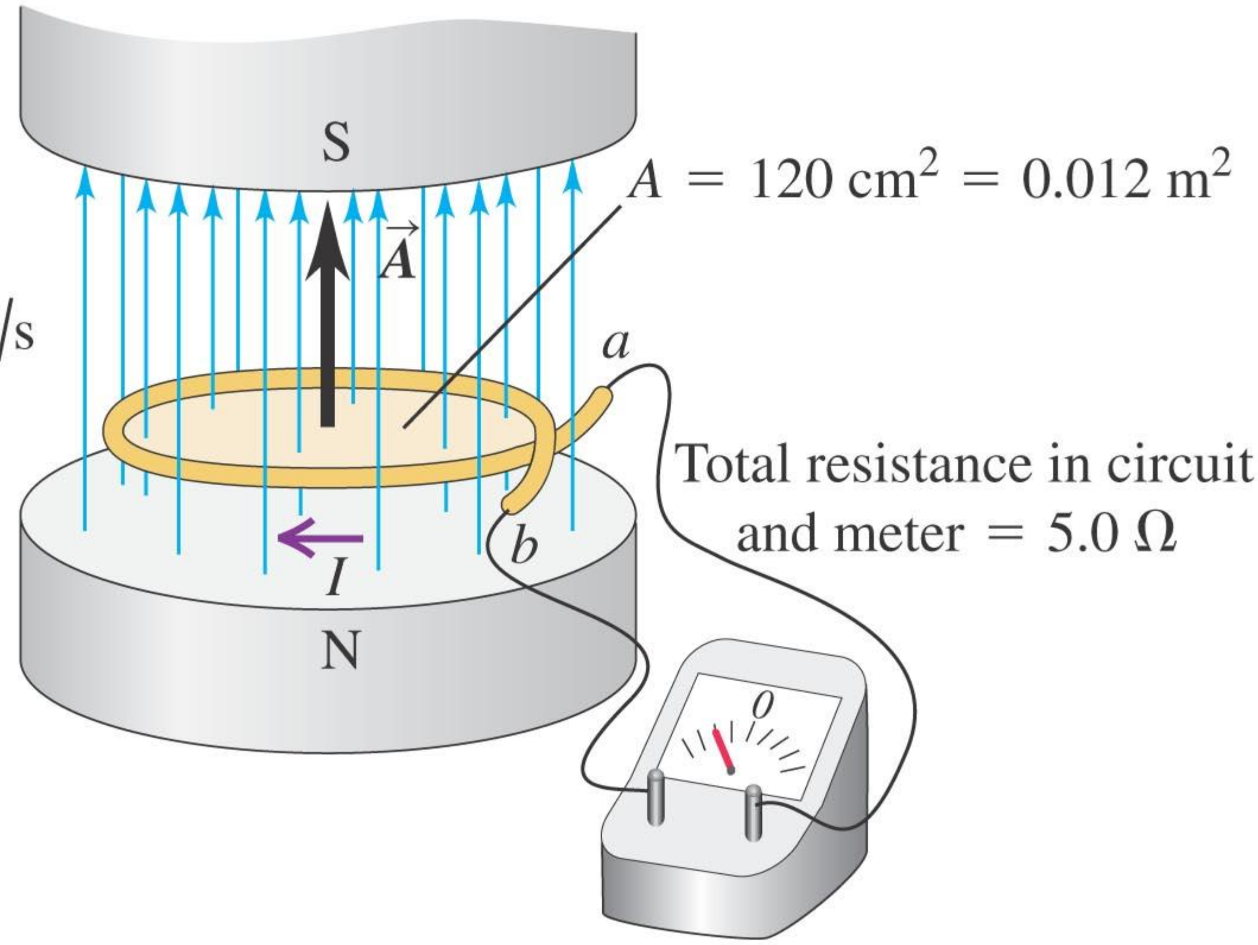
$\oint \vec{E} \cdot d\vec{l} = 2\pi r E$, and Eq. (29.10) gives

$$E = \frac{1}{2\pi r}\left|\frac{d\Phi_B}{dt}\right|$$



Emf and the current induced in a loop

- Follow Example 29.1 using Figure 29.5 below.

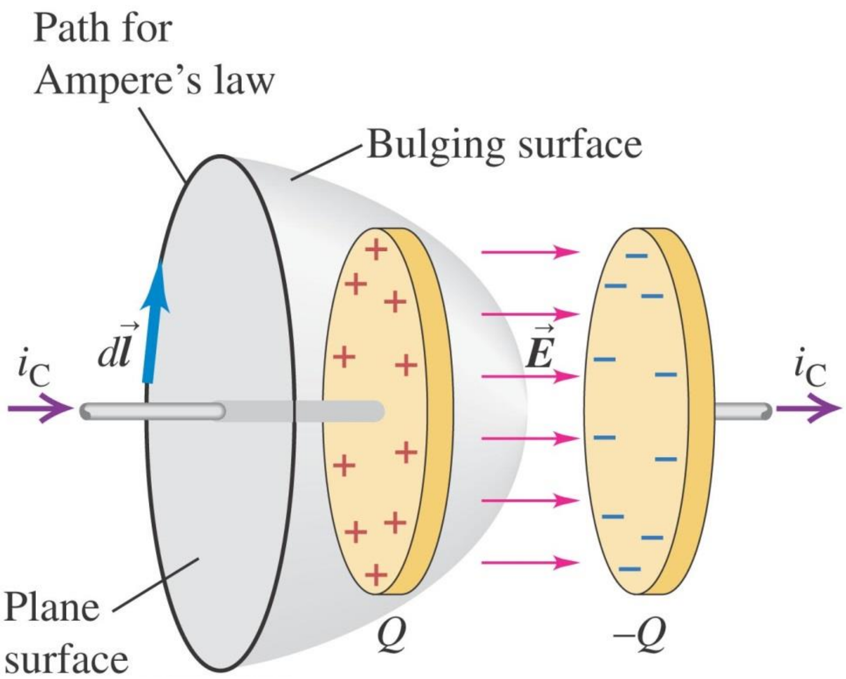


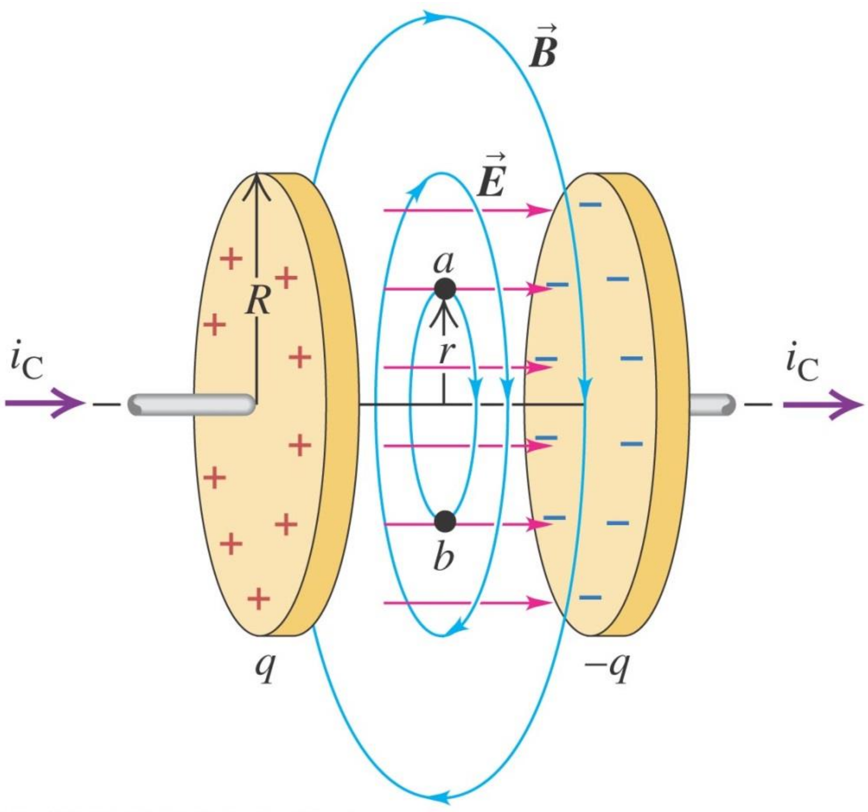
$$\frac{d\Phi_B}{dt} = \frac{d(BA)}{dt} = \frac{dB}{dt}A$$

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

Displacement current

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





Displacement current

Substituting these expressions for C and v into $q = Cv$, we can express the capacitor charge q as

$$q = Cv = \frac{\epsilon A}{d}(Ed) = \epsilon EA = \epsilon \Phi_E \qquad (29.12)$$

where $\Phi_E = EA$ is the electric flux through the surface.

As the capacitor charges, the rate of change of q is the conduction current, $i_C = dq/dt$. Taking the derivative of Eq. (29.12) with respect to time, we get

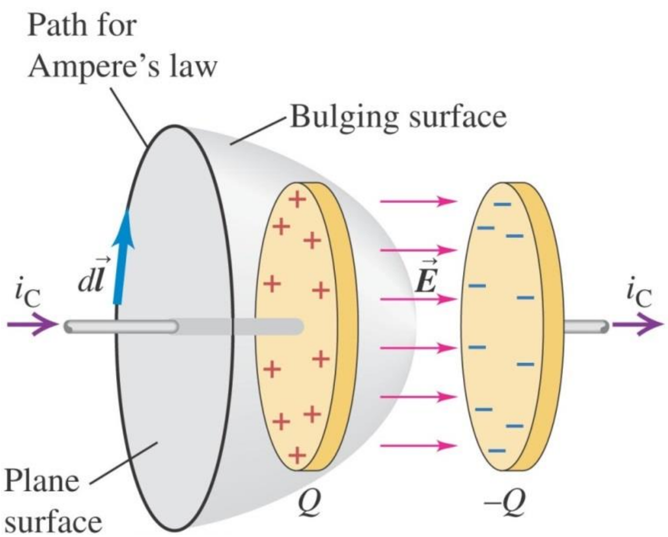
$$i_C = \frac{dq}{dt} = \epsilon \frac{d\Phi_E}{dt} \qquad (29.13)$$

Now, stretching our imagination a little, we invent a fictitious **displacement current** i_D in the region between the plates, defined as

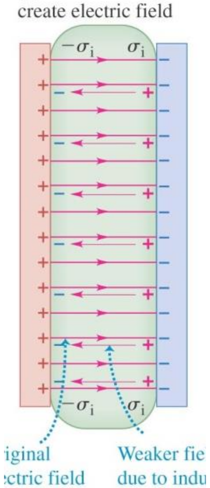
$$i_D = \epsilon \frac{d\Phi_E}{dt} \qquad \text{(displacement current)} \qquad (29.14)$$

rent i_C, in Ampere's law:

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 (i_C + i_D)_{\text{encl}} \qquad \text{(generalized Ampere's law)} \qquad (2$$



(c) Induced charges create electric field

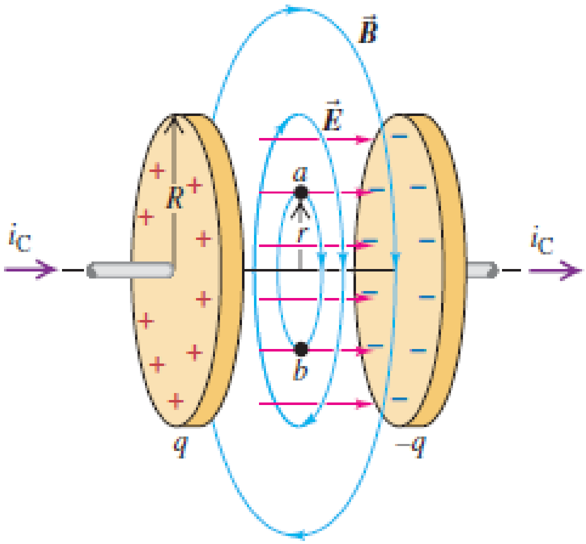


Displacement current

$$\oint \vec{B} \cdot d\vec{l} = 2\pi r B = \mu_0 \frac{r^2}{R^2} i_C$$

$$B = \frac{\mu_0}{2\pi} \frac{r}{R^2} i_C$$

$$i_D = i_C$$

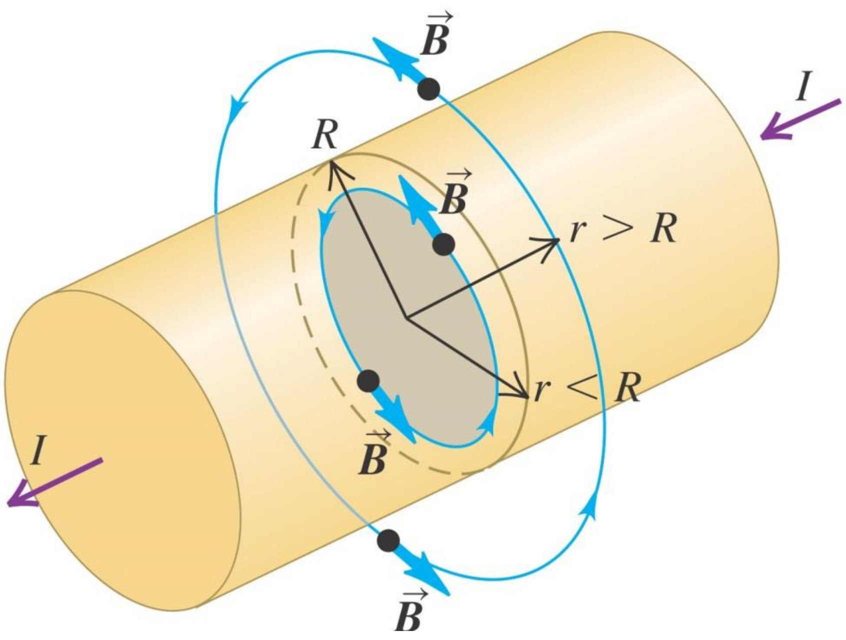


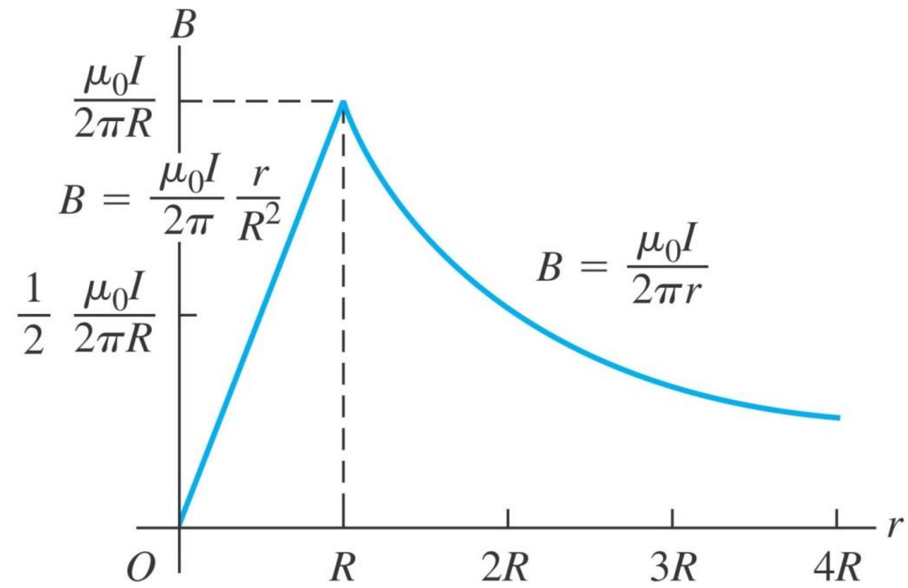
$$\boxed{i_D = \epsilon \frac{d\Phi_E}{dt}}$$

$\Phi_E = EA$ i $(i_D/\pi R^2)(\pi r^2)$.

Magnetic fields of long conductors

- Read Problem-Solving Strategy 28.2.
- Follow Example 28.7 for a long straight conductor.
- Follow Example 28.8 for a long cylinder, using Figures 28.20 and 28.21 below.





Maxwell's equations

- ✓ Gauss's law for the electric field

$$\oint \vec{E} \cdot d\vec{A} = \frac{Q_{\text{encl}}}{\epsilon_0} \qquad \text{(Gauss's law for } \vec{E}\text{)}$$

- ✓ Gauss's law for the magnetic field

$$\oint \vec{B} \cdot d\vec{A} = 0 \qquad \text{(Gauss's law for } \vec{B}\text{)}$$

- ✓ Ampere's law

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 \left(i_C + \epsilon_0 \frac{d\Phi_E}{dt} \right)_{\text{encl}} \qquad \text{(Ampere's law)}$$

- ✓ Faraday's law.

$$\oint \vec{E} \cdot d\vec{l} = -\frac{d\Phi_B}{dt} \qquad \text{(Faraday's law)}$$

Maxwell's equations

- Gauss's law for the electric field
- Gauss's law for the magnetic fie
- Ampere's law
- Faraday's law.

(i) $\nabla \cdot \mathbf{E} = \frac{1}{\epsilon_0}\rho$ (Gauss's law),

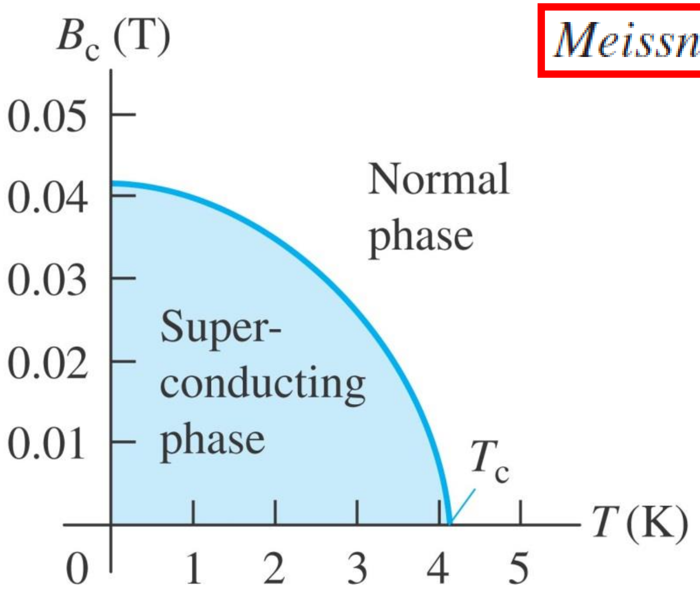
(ii) $\nabla \cdot \mathbf{B} = 0$ (no name),

(iii) $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$ (Faraday's law),

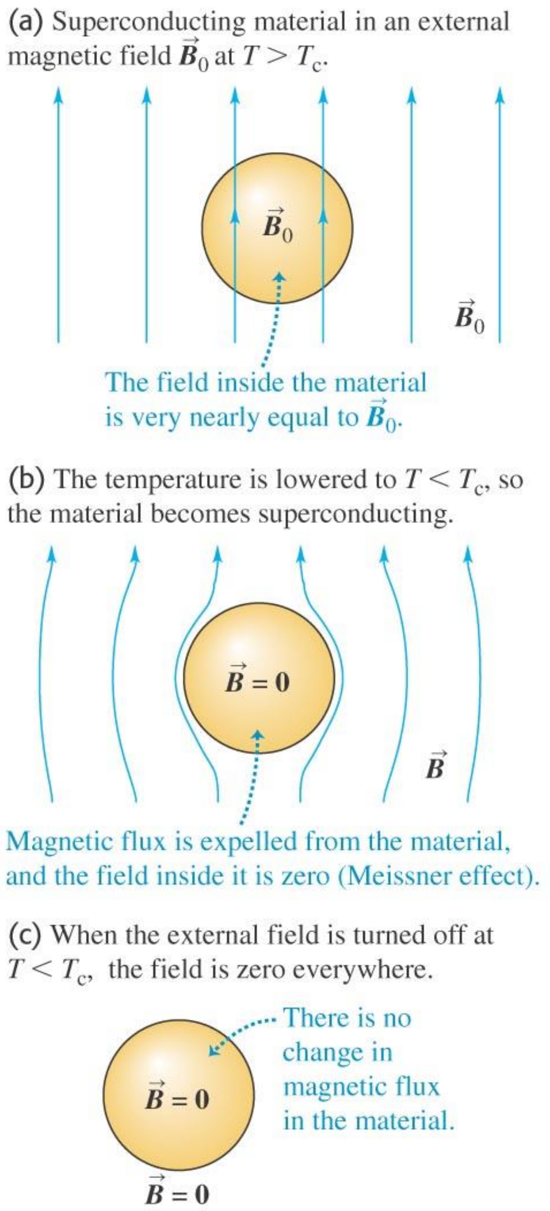
(iv) $\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$ (Ampère's law).

Superconductivity

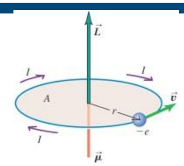
- When a superconductor is cooled below its *critical temperature*, it loses all electrical resistance.
- Follow the text discussion using Figures 29.23 (below) and 29.24 (right).



Meissner effect.

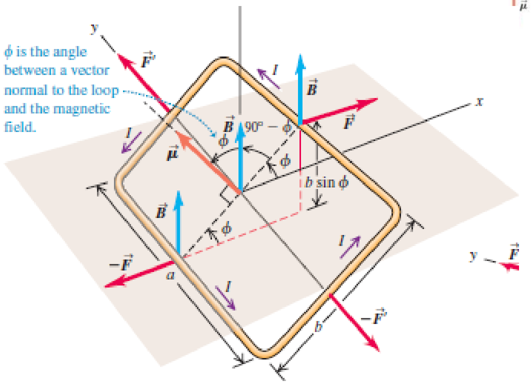


The Bohr magneton and paramagnetism



$$\mu = \frac{e}{2m}\left(\frac{h}{2\pi}\right) = \frac{eh}{4\pi m}$$

e **Bohr magneton,** denoted b



$$\vec{\tau} = \vec{\mu} \times \vec{B}.$$

magnetization of the material, denoted by $\vec{M}$:

$$\vec{M} = \frac{\vec{\mu}_{\text{total}}}{V}$$

, the total magnetic field $\vec{B}$ in the material is

$$\vec{B} = \vec{B}_0 + \mu_0\vec{M}$$

as μ and is called the **permeability**

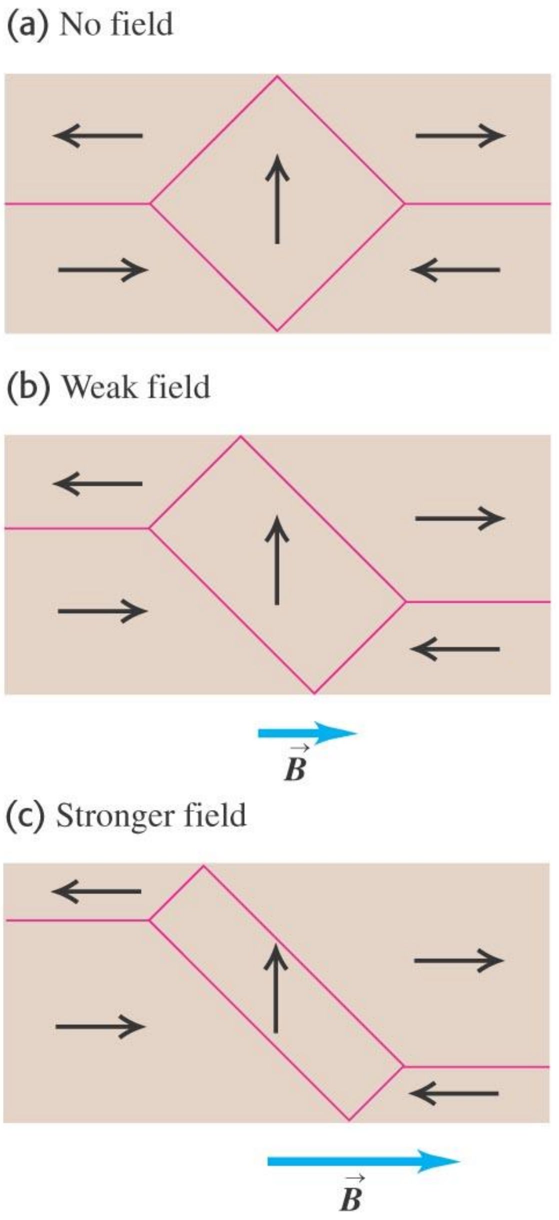
$$\mu = K_m\mu_0$$ (2

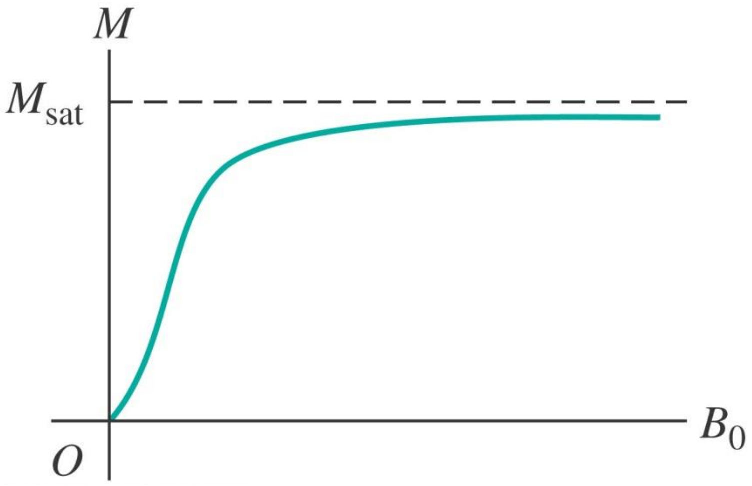
Table 28.1 Magnetic Susceptibilities of Paramagnetic and Diamagnetic Materials at $T = 20°C$

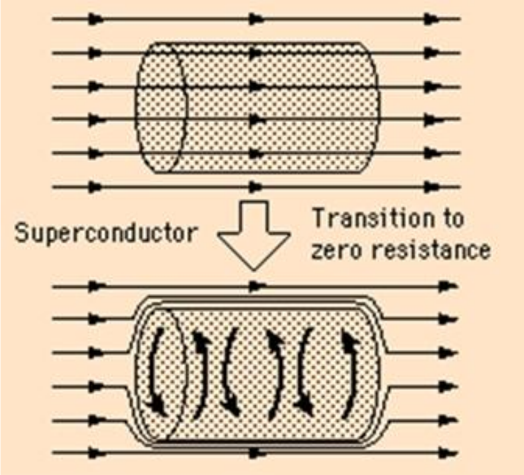
Material	$\chi_m = K_m - 1\ (\times 10^{-5})$
Paramagnetic	
Iron ammonium alum	66
Uranium	40
Platinum	26
Aluminum	2.2
Sodium	0.72
Oxygen gas	0.19
Diamagnetic	
Bismuth	−16.6
Mercury	−2.9
Silver	−2.6
Carbon (diamond)	−2.1
Lead	−1.8
Sodium chloride	−1.4
Copper	−1.0

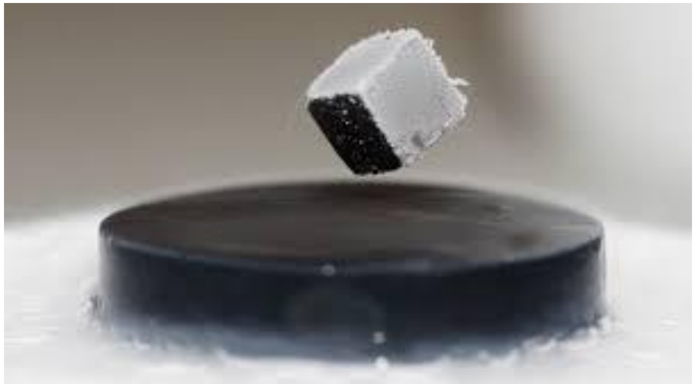
Diamagnetism and ferromagnetism

- Figure 28.27 at the right shows how *magnetic domains* react to an applied magnetic field.
- Figure 28.28 below shows a magnetization curve for a ferromagnetic material.






Superconductor
Transition to
zero resistance

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