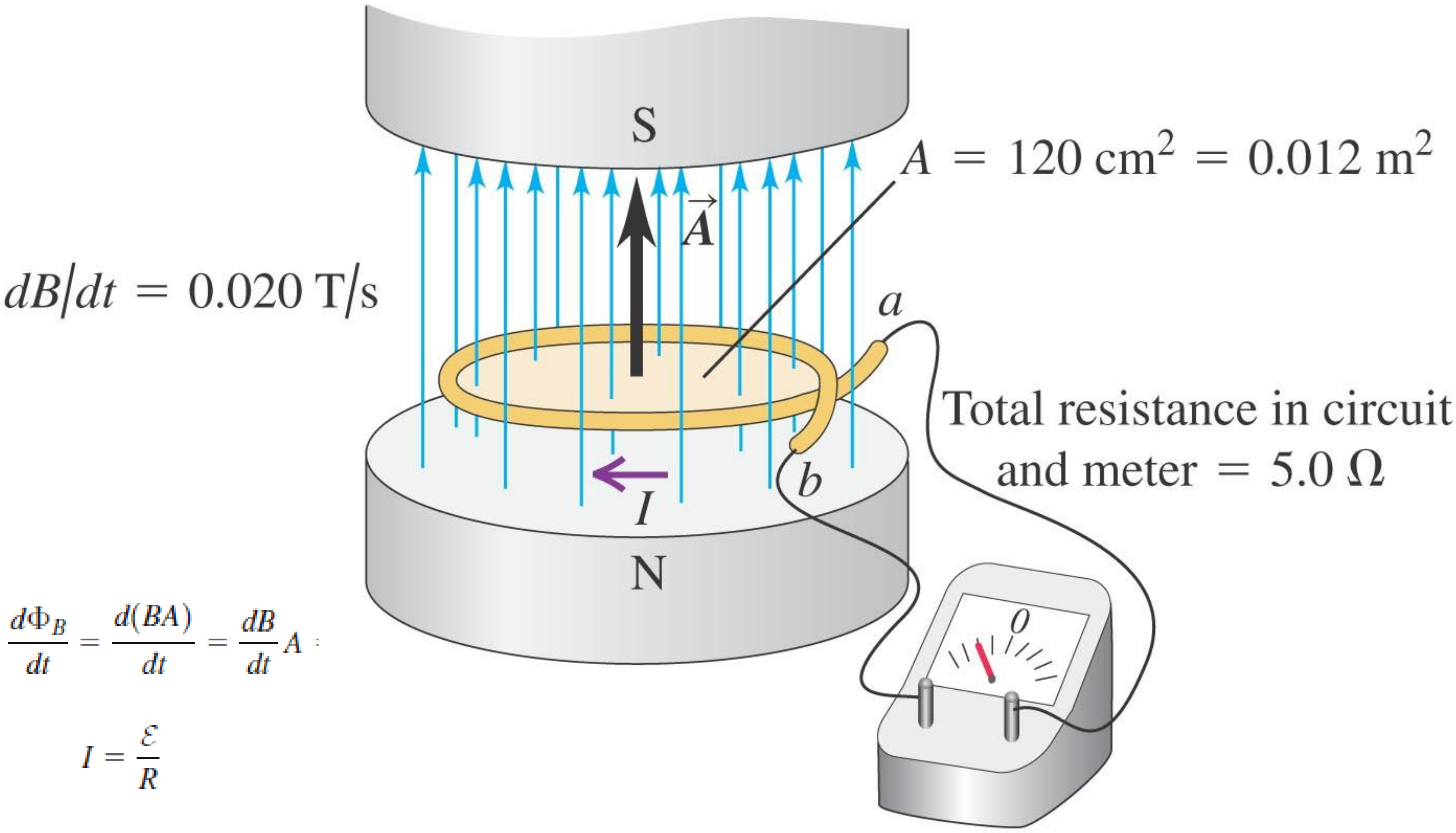
Chapter 29

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

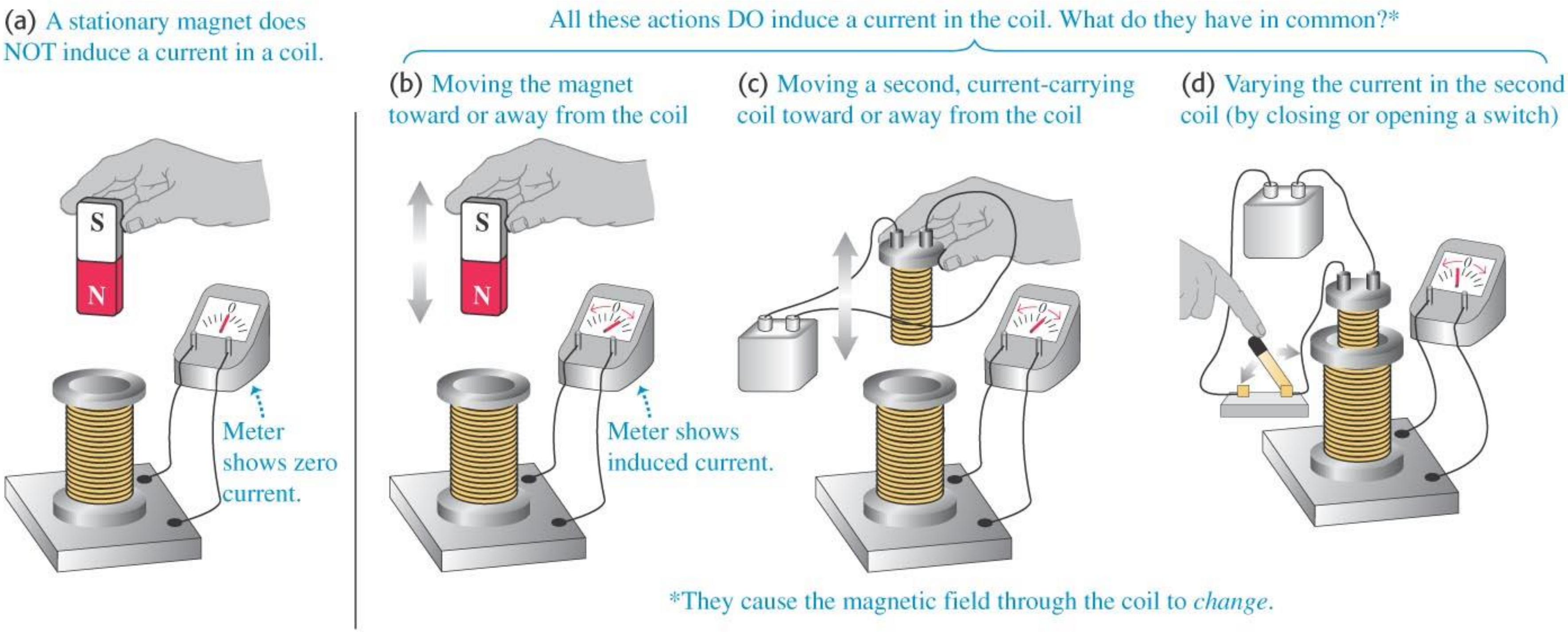
- To examine experimental evidence that a changing magnetic field induces an emf
- To learn how Faraday's law relates the induced emf to the change in flux
- To determine the direction of an induced emf
- To calculate the emf induced by a moving conductor
- To learn how a changing magnetic flux generates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

Introduction

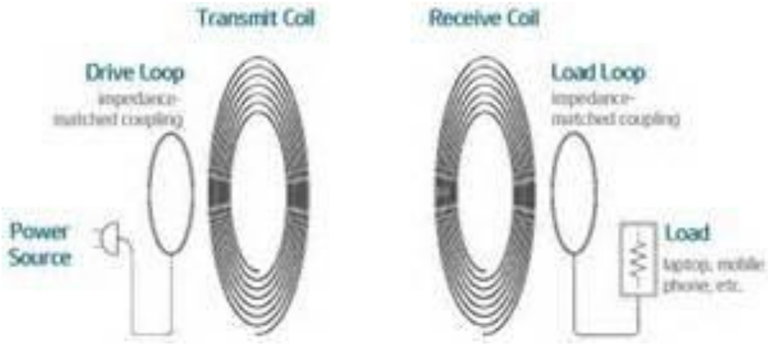
- How is a credit card reader related to magnetism?
- Energy conversion makes use of electromagnetic induction.
- Faraday's law and Lenz's law tell us about induced currents.
- Maxwell's equations describe the behavior of electric and magnetic fields in *any* situation.

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.



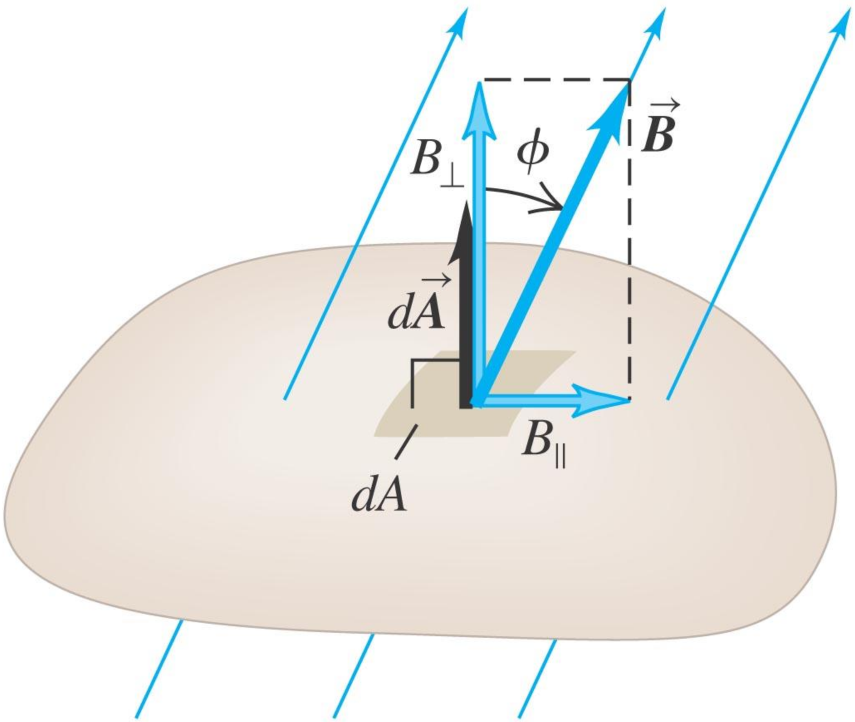
Induced current



Induced current

Magnetic flux through an area element

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

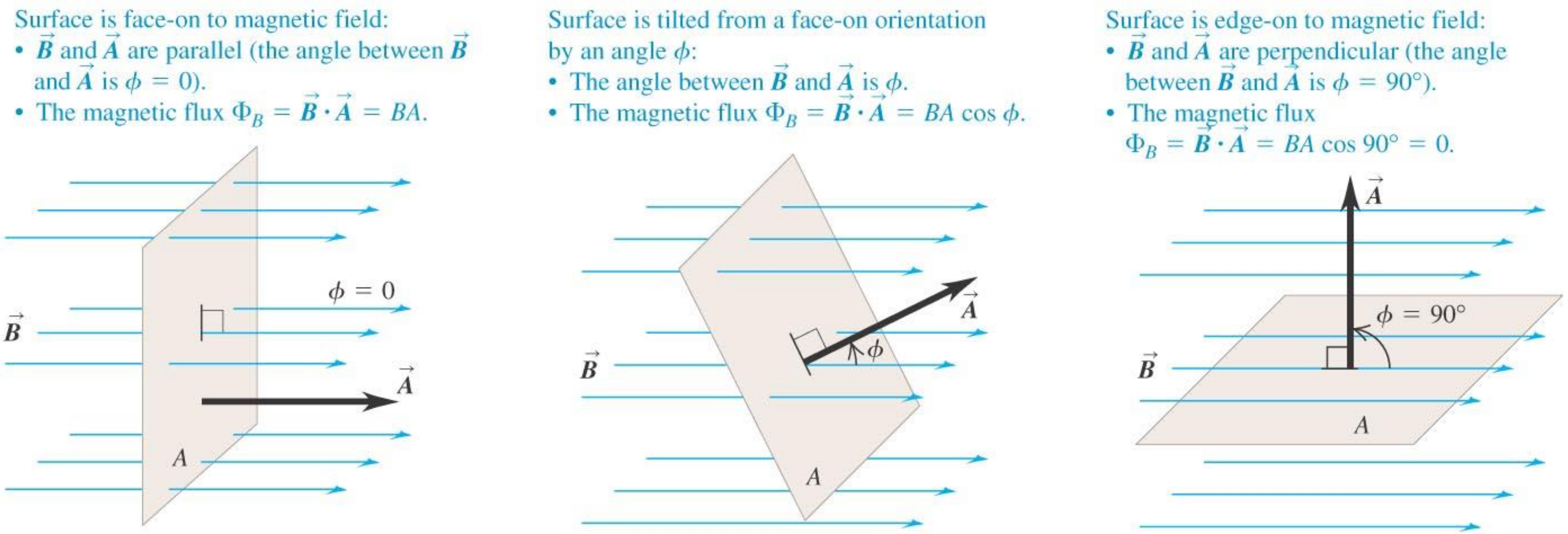


Magnetic flux through element of area $d\vec{A}$:

$$d\Phi_B = \vec{B} \cdot d\vec{A} = B_\perp dA = B\, dA \cos\phi$$

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:

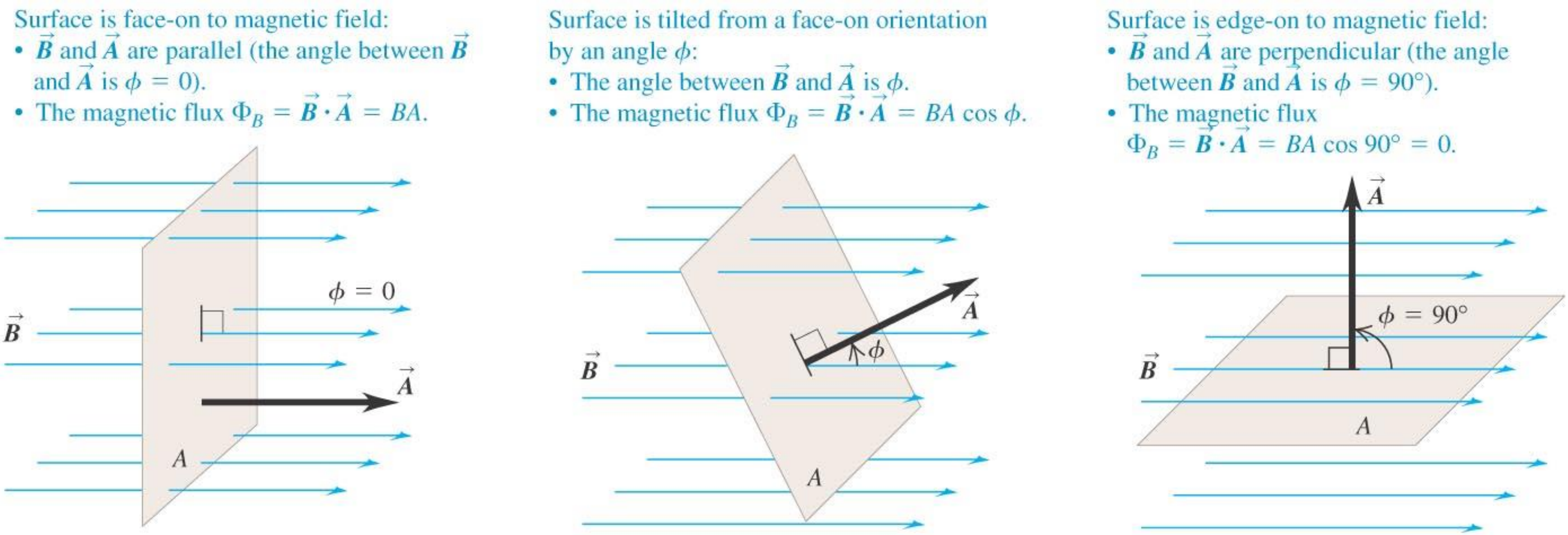
The induced emf in a closed loop equals the negative of the time rate of change of magnetic flux through the loop.

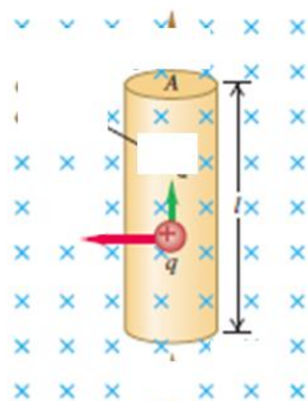
In symbols, Faraday's law is

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

Faraday's law

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

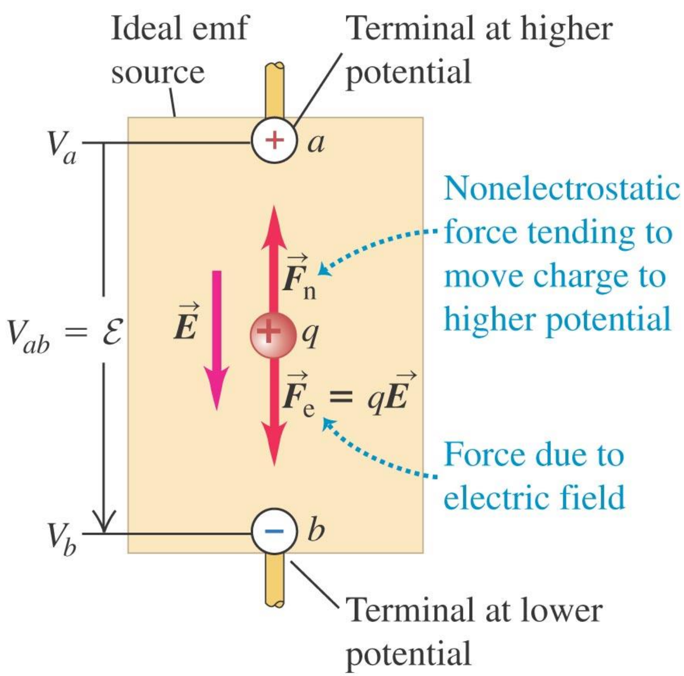




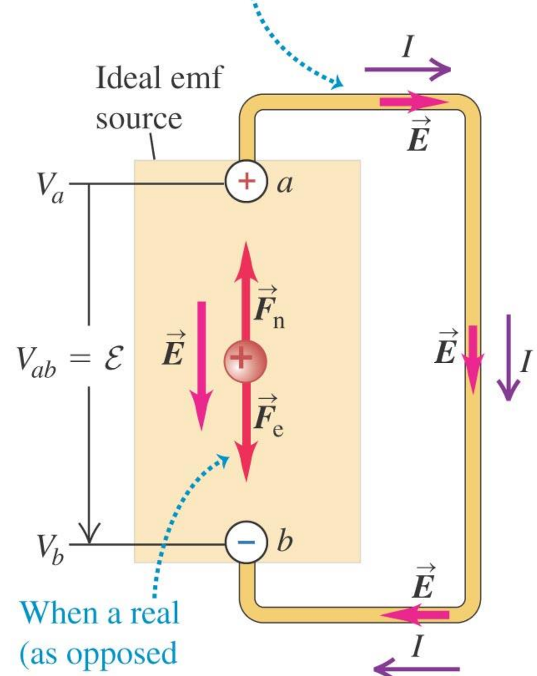
$$\vec{F} = q\vec{v} \times \vec{B}$$

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).



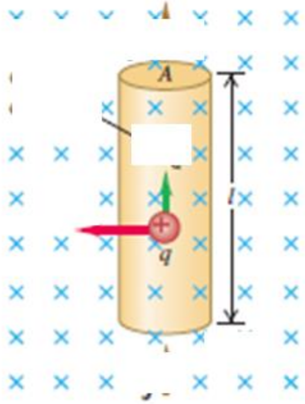
When the emf source is not part of a closed circuit, $F_n = F_e$ and there is no net motion of charge between the terminals.

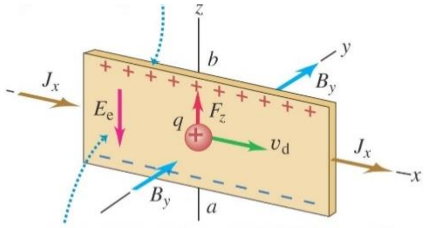


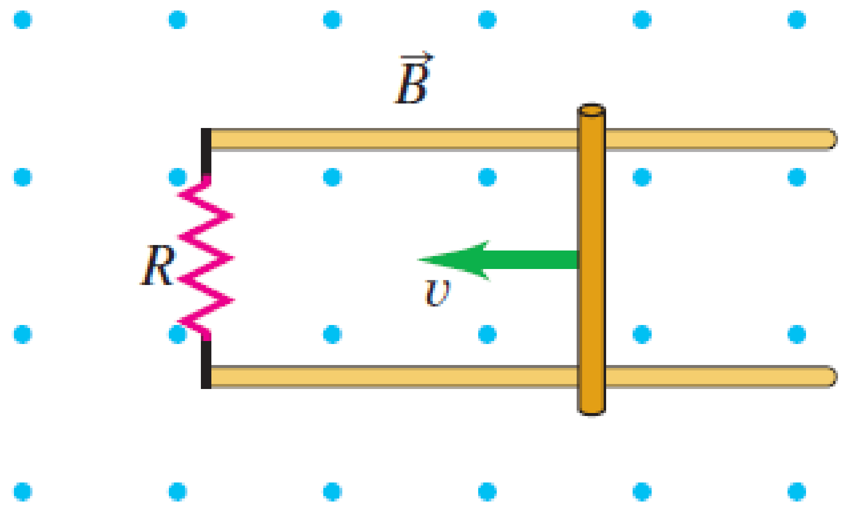
When a real (as opposed to ideal) emf source is connected to a circuit, V_{ab} and thus F_e fall, so that $F_n > F_e$ and $\vec{F}_n$ does work on the charges.

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).

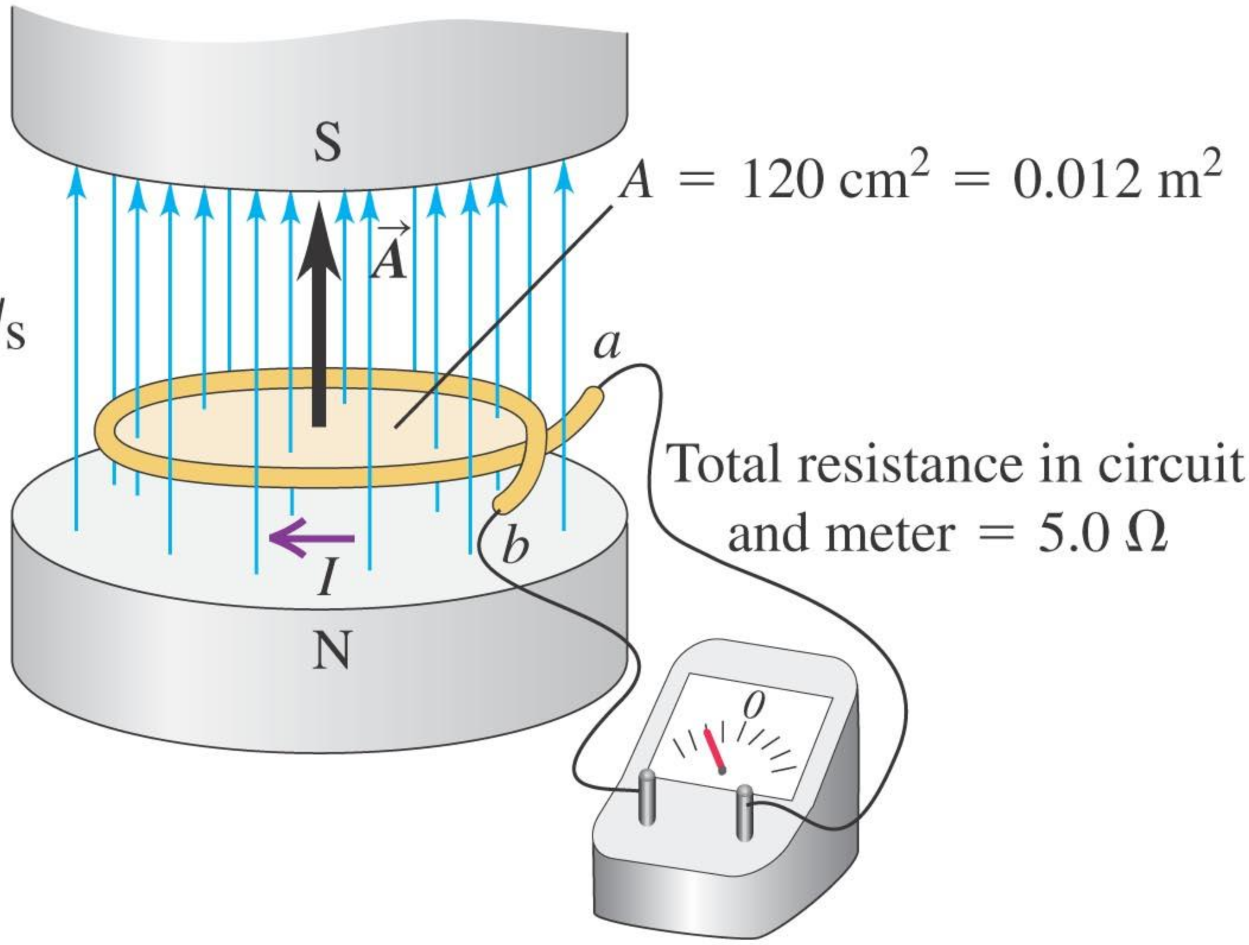






Emf and the current induced in a loop

- Follow Example 29.1 using Figure 29.5 below.

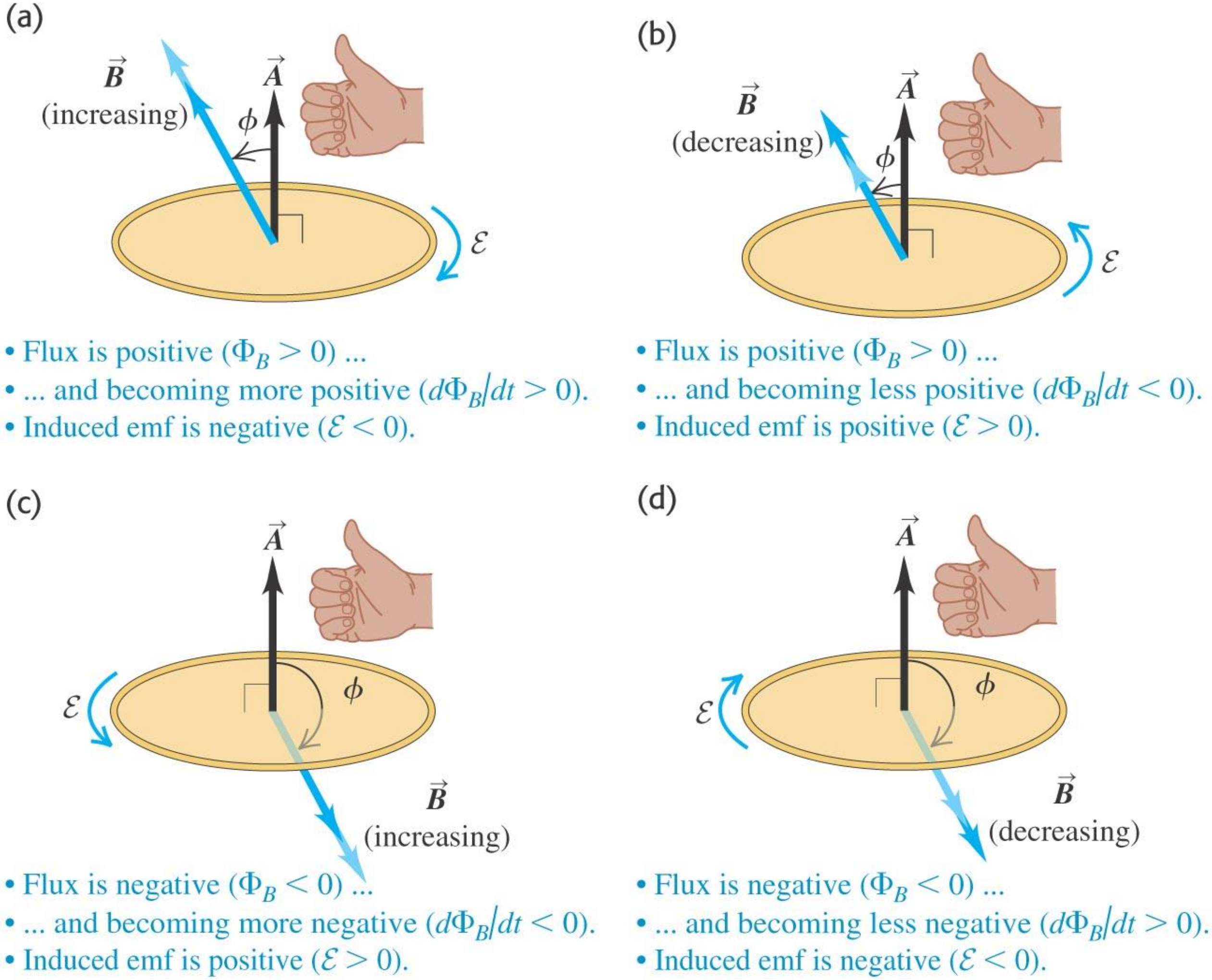


$$\frac{d\Phi_B}{dt} = \frac{d(BA)}{dt} = \frac{dB}{dt}A$$

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

Direction of the induced emf

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

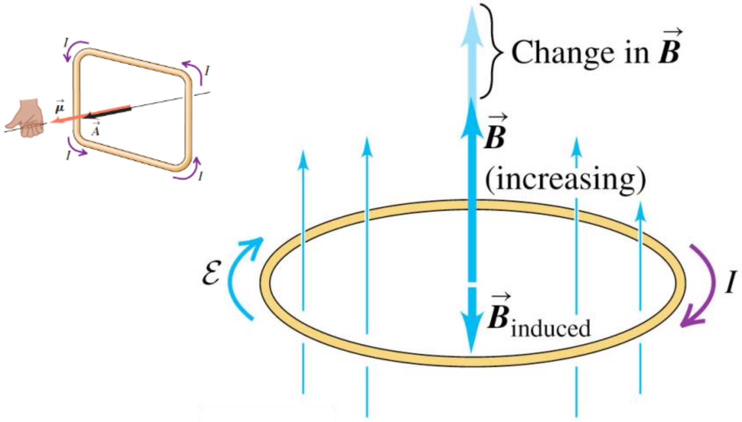


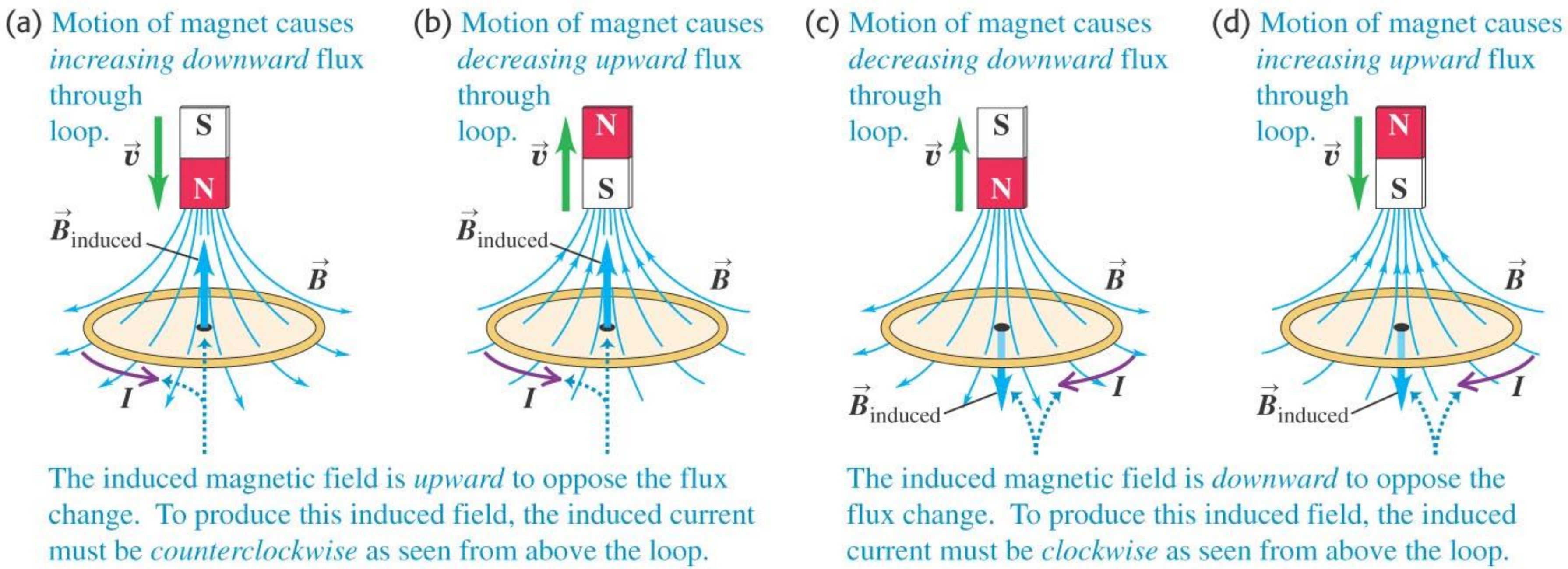
Lenz's law

- *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).

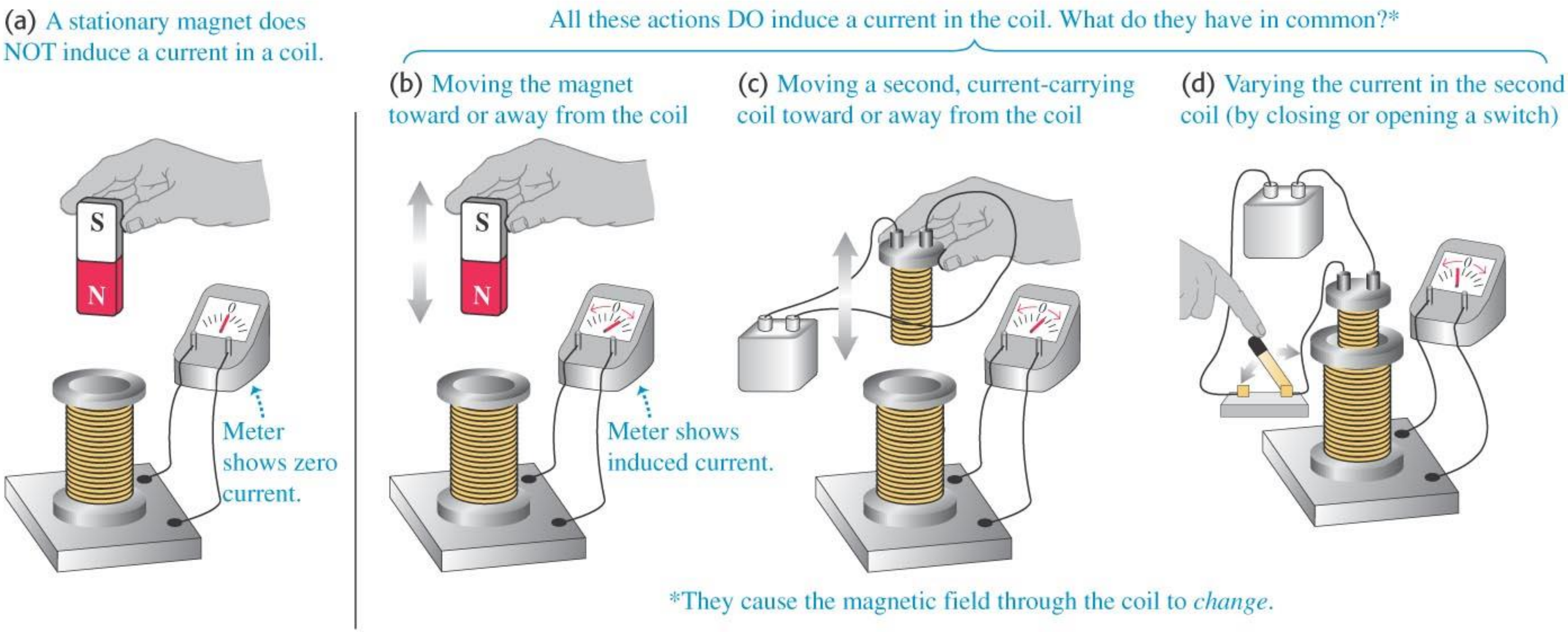




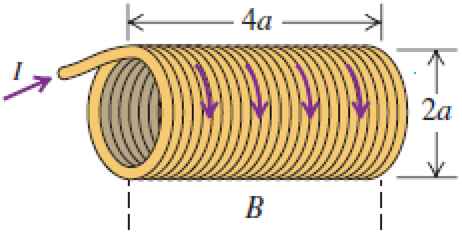
What about F?

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.



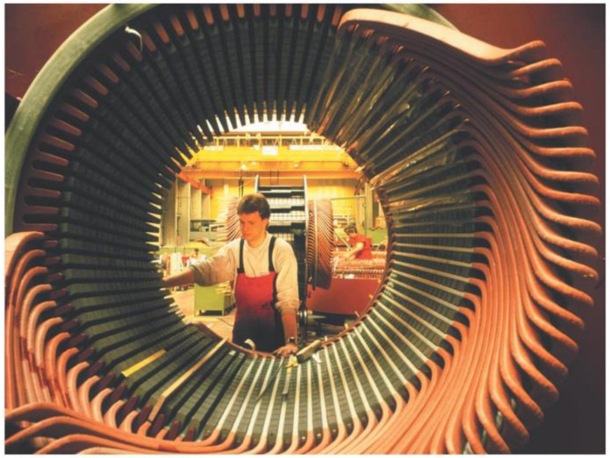
induced emf



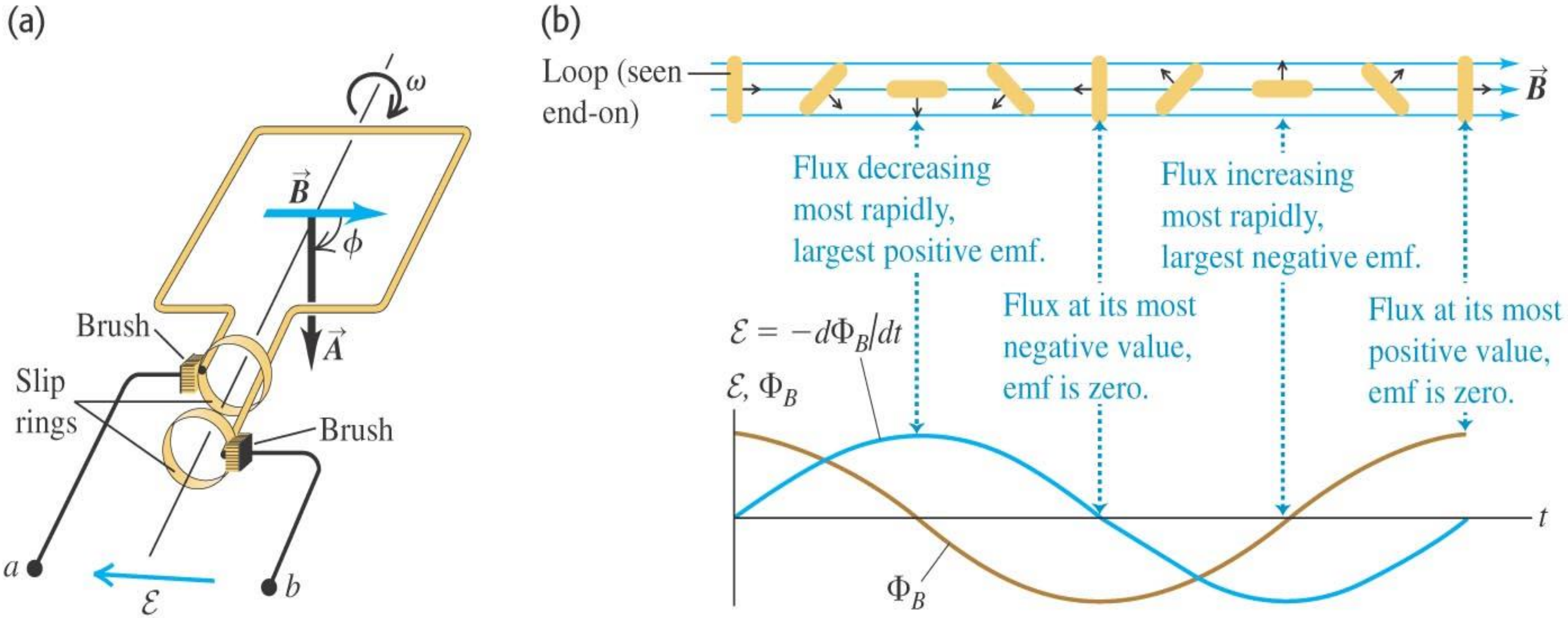
$$\mathcal{E} = -N\frac{d\Phi_B}{dt}$$

A simple alternator

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



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



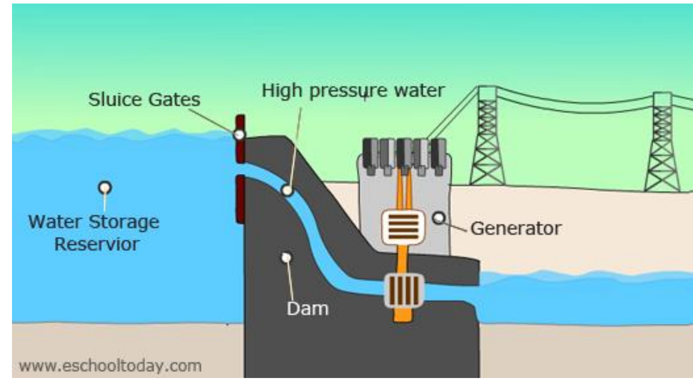
作者：彭科峰 来源：科学网 www.sciencenet.cn 发布时间：2017/8/8 16:02:58 选择字号：小 中 大

我国首台基于国产YBCO超导带材的高温超导发电机研发成功

日前，记者从中科院电工所获悉，上海电气集团上海电机厂有限公司组织专家对该所项目“采用第二代高温超导带材的高温超导电机研发”进行了现场验收。验收专家对该项目给予了高度评价。

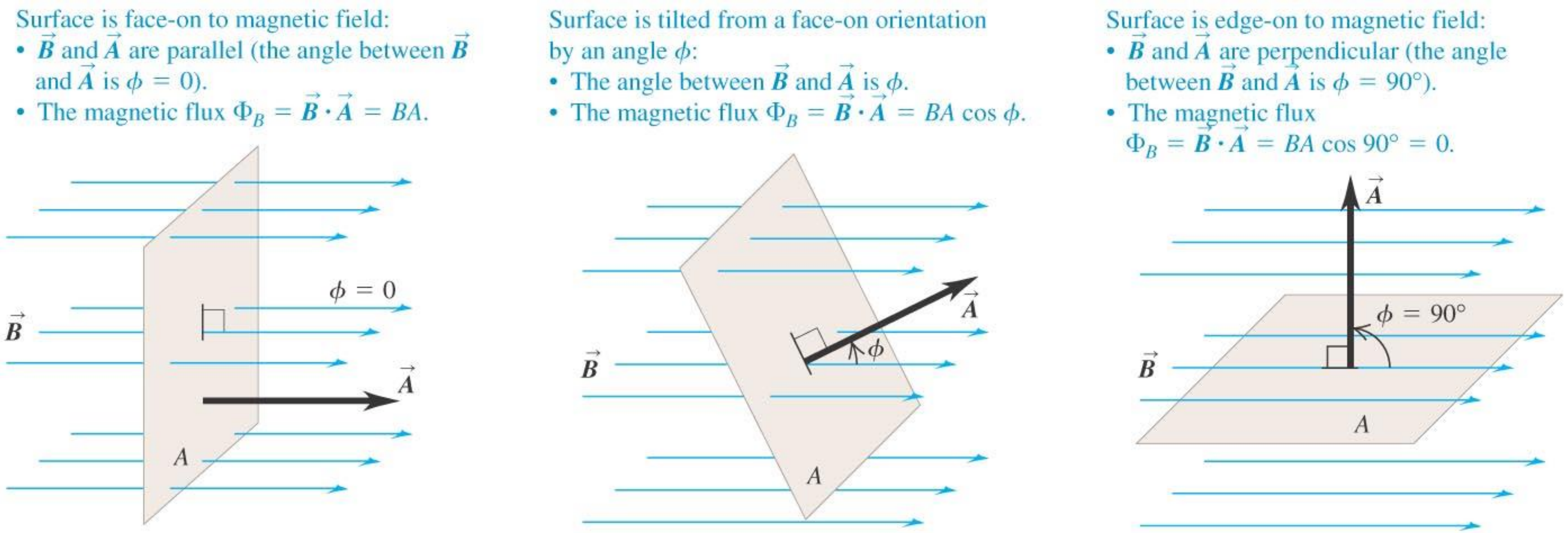
据介绍，在上海市科委的支持下，中科院电工所协同上海电气集团上海电机厂有限公司共同开展了高温超导发电机技术研究，并在此基础上研制了500kW高温超导发电机原理样机。该发电机为国内首台基于国产YBCO超导带材的高温超导发电机，电机设计为4极绕线式转子超导同步发电机，其中超导转子励磁绕组为YBCO高温超导带材绕制而成的跑道线圈结构，冷却方式为液氮浸泡开放式冷却，运行温区为77K，低温杜瓦为双层旋转薄壁杜瓦，液氦传输耦合器采用磁流体旋转动密封，转子多段组合结构，定子为常规铜绕组，冷却方式为强迫风冷。

经过4年攻坚克难，研发团队与上海电机厂密切合作，先后解决了各种技术和工艺的难题，掌握了超导线圈绕制、薄壁杜瓦、冷却系统和转子结构设计、低温旋转密封和无线参数检测等多方面的关键技术和工艺。2017年3月和5月通过对超导电机的运行测试，电机运行良好，各项指标依据国标测试达到了预期值。



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:

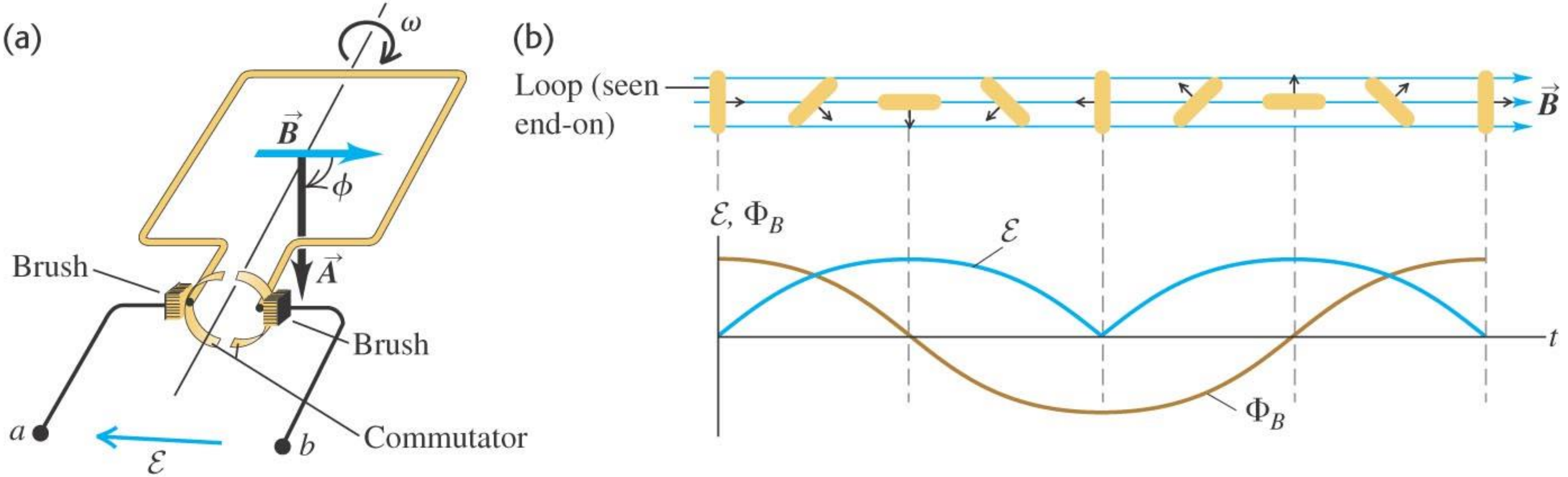
The induced emf in a closed loop equals the negative of the time rate of change of magnetic flux through the loop.

In symbols, Faraday's law is

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

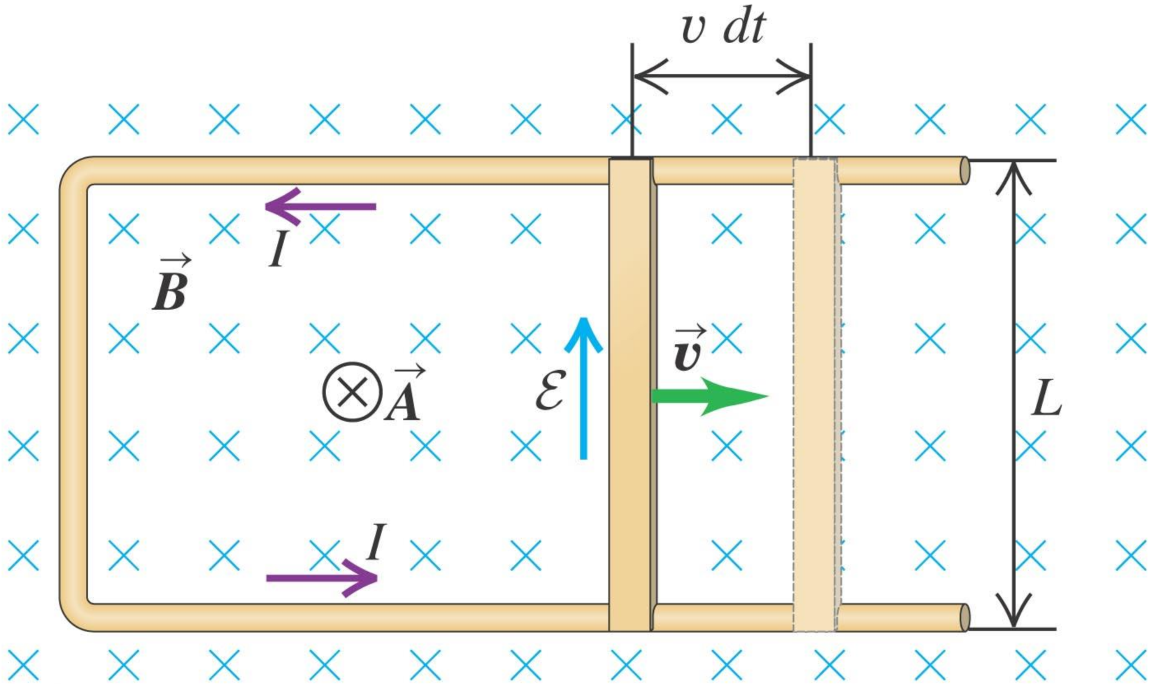
DC generator and back emf in a motor

- Follow Example 29.4 using Figure 29.10 below.



Slidewire generator

- Follow Example 29.5 using Figure 29.11 below.



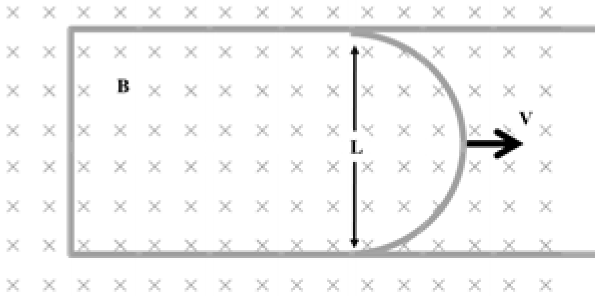
$$\mathcal{E} = -\frac{d\Phi_B}{dt} = -B\frac{dA}{dt}$$

$$w = w_0 + vt$$

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

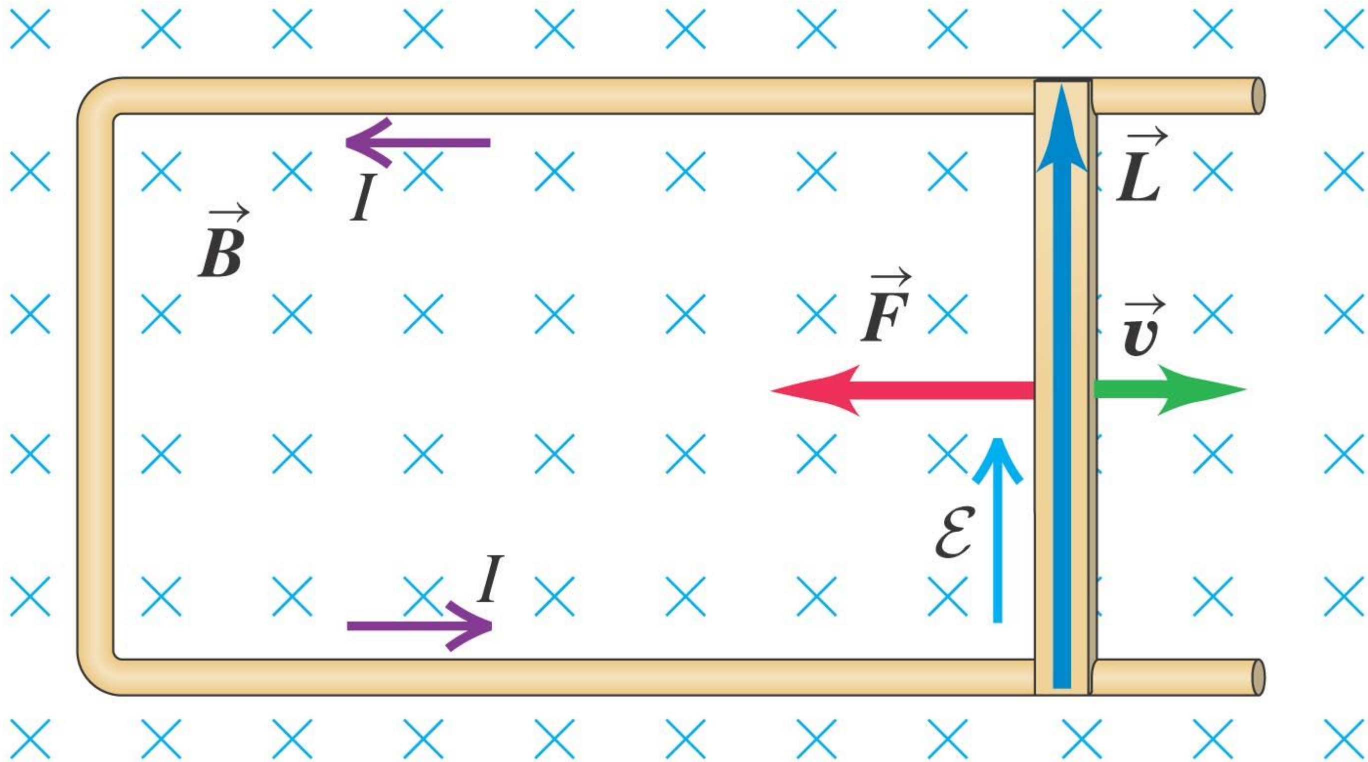
Work and power in the slidewire generator

5. (20%) In a slide-wire generator in a uniform B field shown below, at the time t_0, the half-ring wire with radius L/2 is moving with a constant speed v to the right, the loop's resistance is R (a) find the current I (b) Find the magnetic force F on the half-ring section.

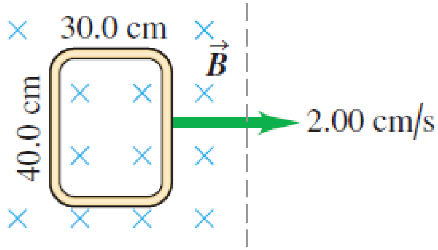


Work and power in the slidewire generator

- 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

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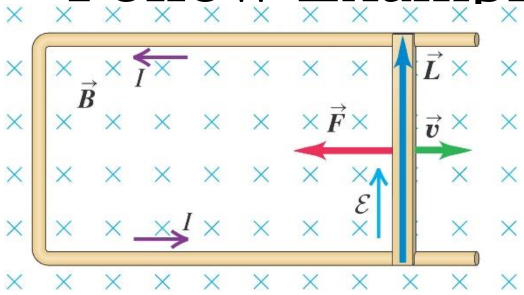


$\mathcal{E} = -BLv$, so the current in the rod is $I = |\mathcal{E}|/R = Blv/R$. Hence

$$P_{\text{dissipated}} = I^2R = \left(\frac{BLv}{R}\right)^2 R = \frac{B^2L^2v^2}{R}$$

To calculate P_{applied}, we first calculate the magnitude of $\vec{F} = I\vec{L} \times \vec{B}$. Since $\vec{L}$ and $\vec{B}$ are perpendicular, this magnitude is

$$F = ILB = \frac{BLv}{R}LB = \frac{B^2L^2v}{R}$$

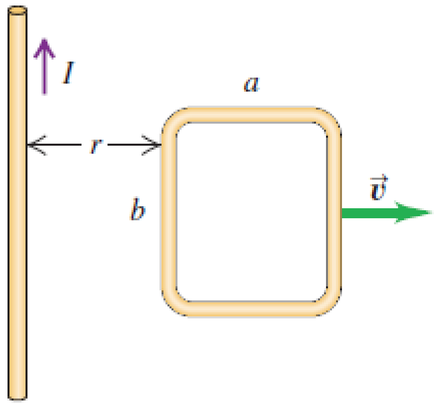
The applied force has the same magnitude and does work at the rate

$$P_{\text{applied}} = Fv = \frac{B^2L^2v^2}{R}$$

Work and power in the slidewire generator

- Follow Example 29.6 using Figure 29.12 below.

Figure **P29.53**

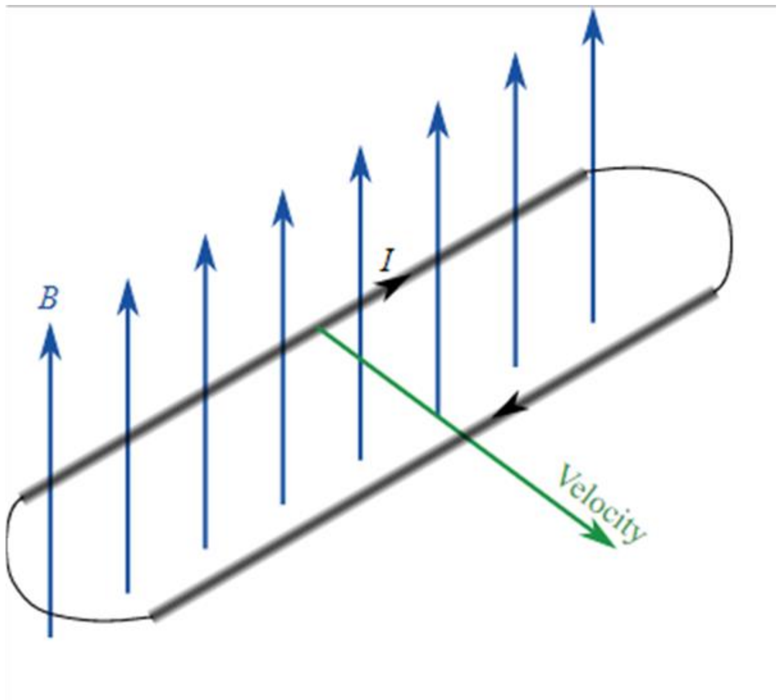


$$B = \frac{\mu_0 I}{2\pi r}$$

$$r = r_0 + vt$$

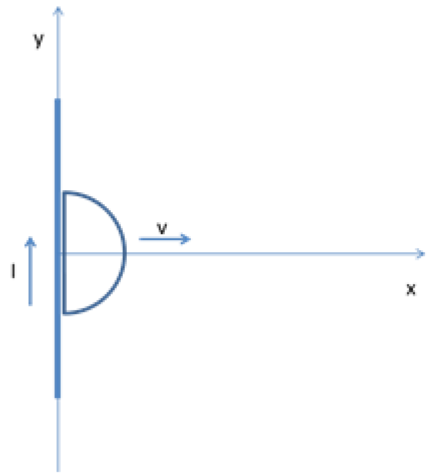
$$\Phi_B = \int \vec{B} \cdot d\vec{A}$$

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


B
I
Velocity

Work and power in the slidewire generator

(5) (20%) A metal hemisphere with radius of R is moving away from a vertical INFINITE long current wire carrying current I at the speed of v. at time t=0, the hemisphere is just on the y-axis. Find the force at that time.

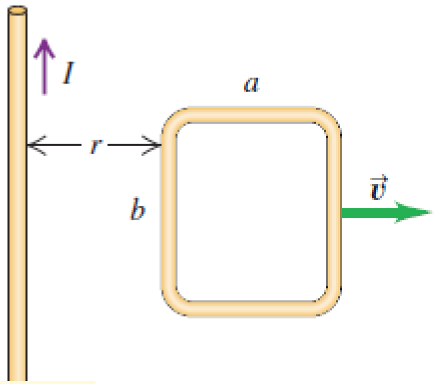


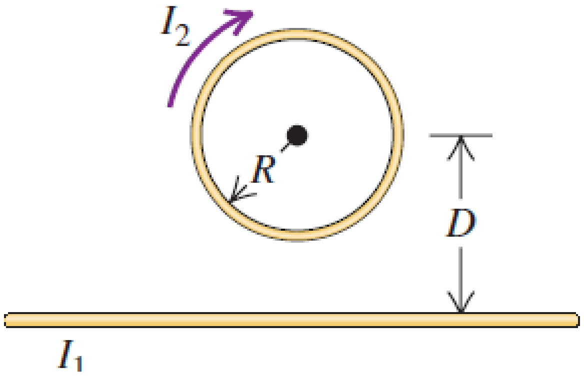
$$r=r_0+vt$$

Work and power in the slidewire generator

- Follow Example 29.6 using Figure 29.12 below.

Figure **P29.53**





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

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

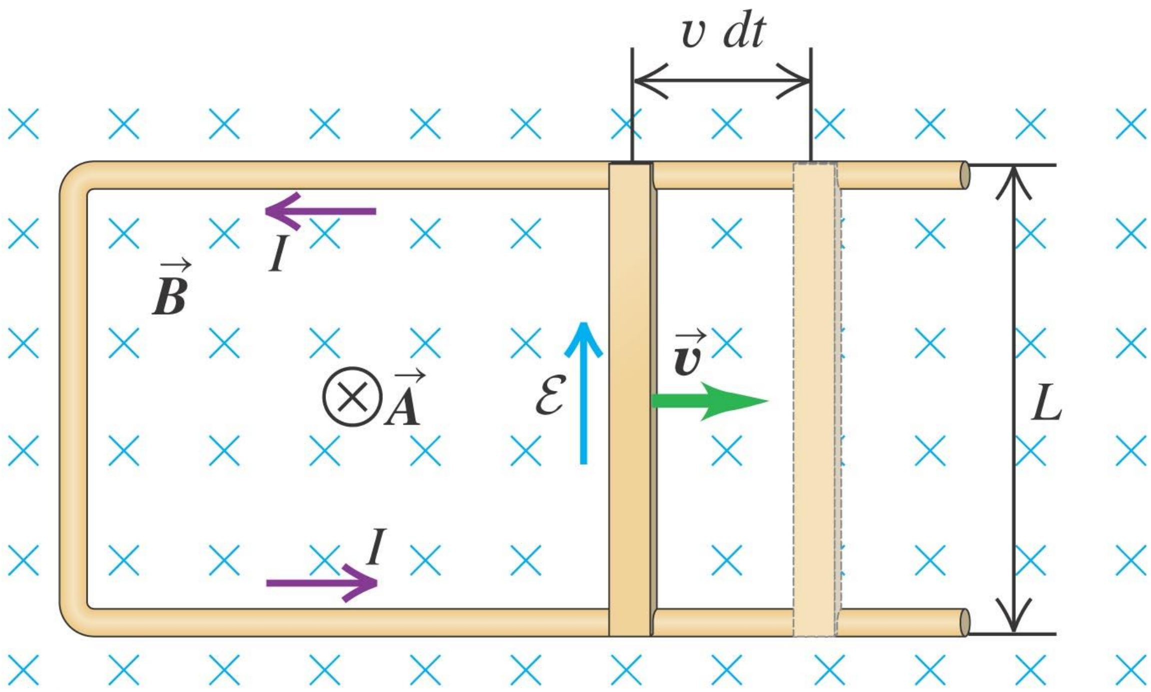
$$d\vec{F} = I\, d\vec{l} \times \vec{B}$$

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

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

Slidewire generator

- Follow Example 29.5 using Figure 29.11 below.



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

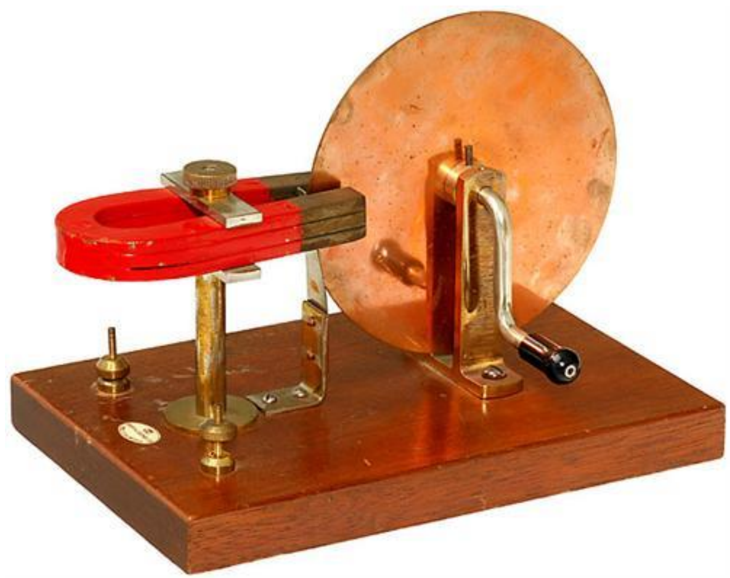
$w = w_0 + vt$

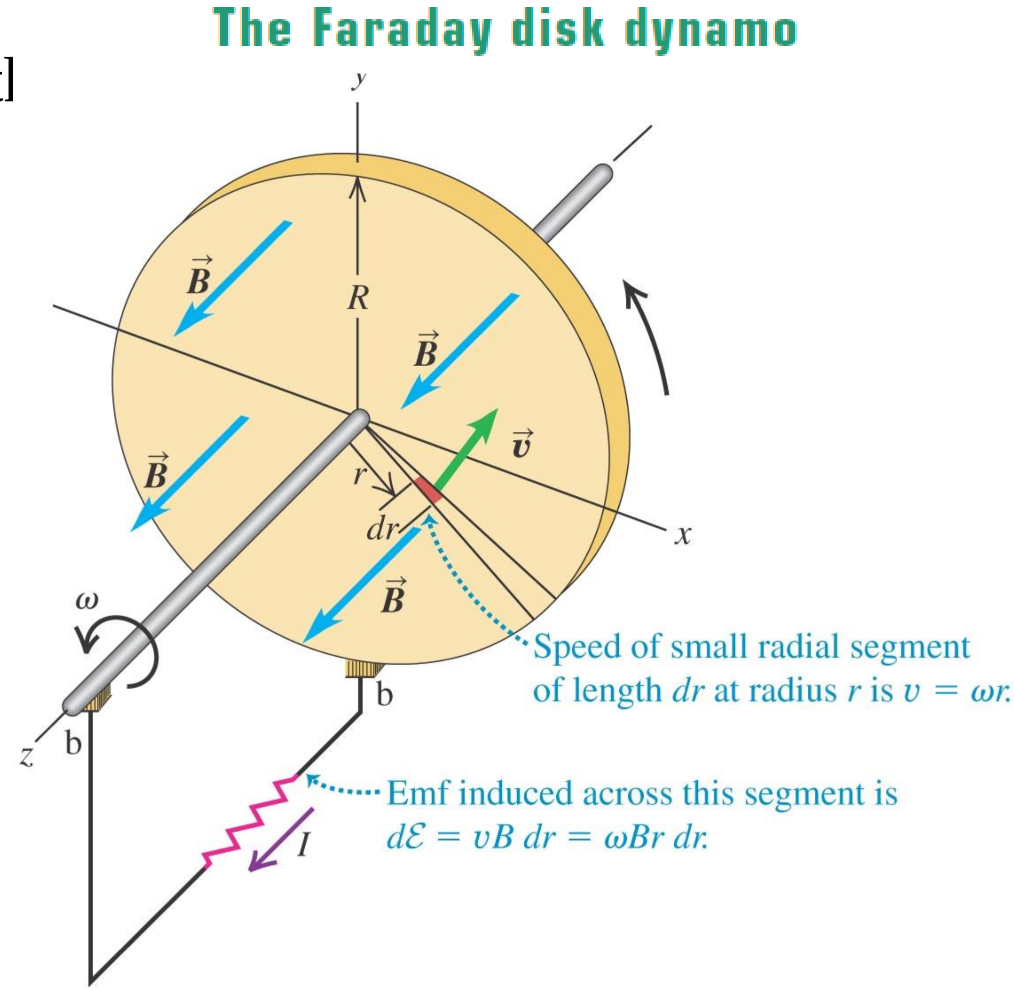
$$\mathcal{E} = -B\frac{Lv\,dt}{dt} = -BLv$$

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

A slidewire generator and a dynamo

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



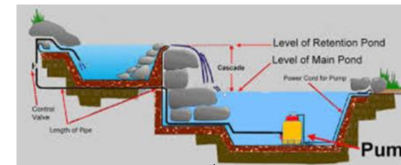


$$\mathcal{E} = \int_0^R \omega Br\,dr = \frac{1}{2}\omega BR^2$$

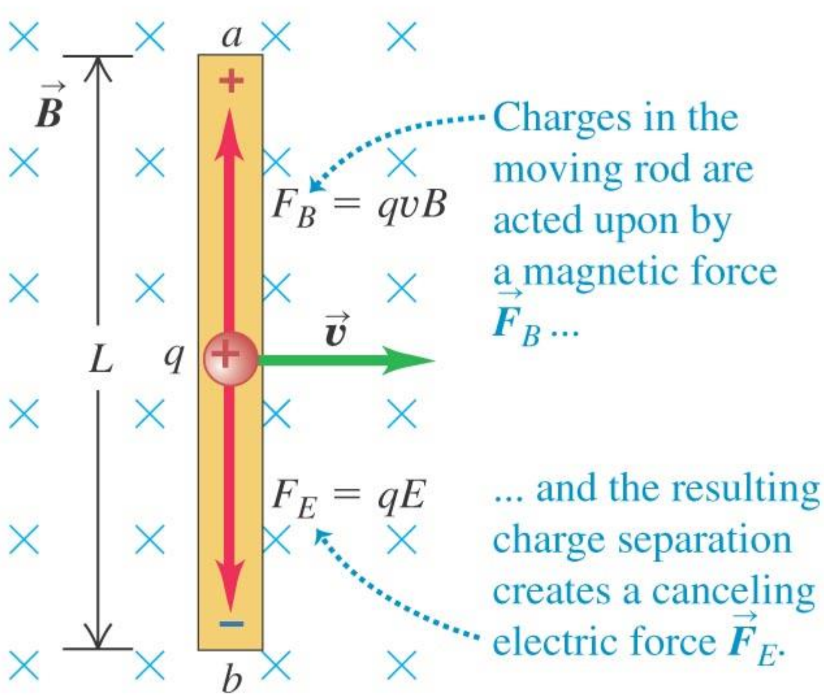
Motional electromotive force

- 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.

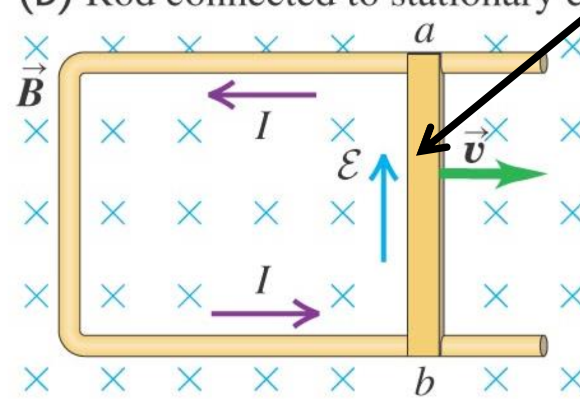
- Follow the general form of motional emf in the text.



(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.

$$qE = qvB$$

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

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

A slidewire generator and a dynamo

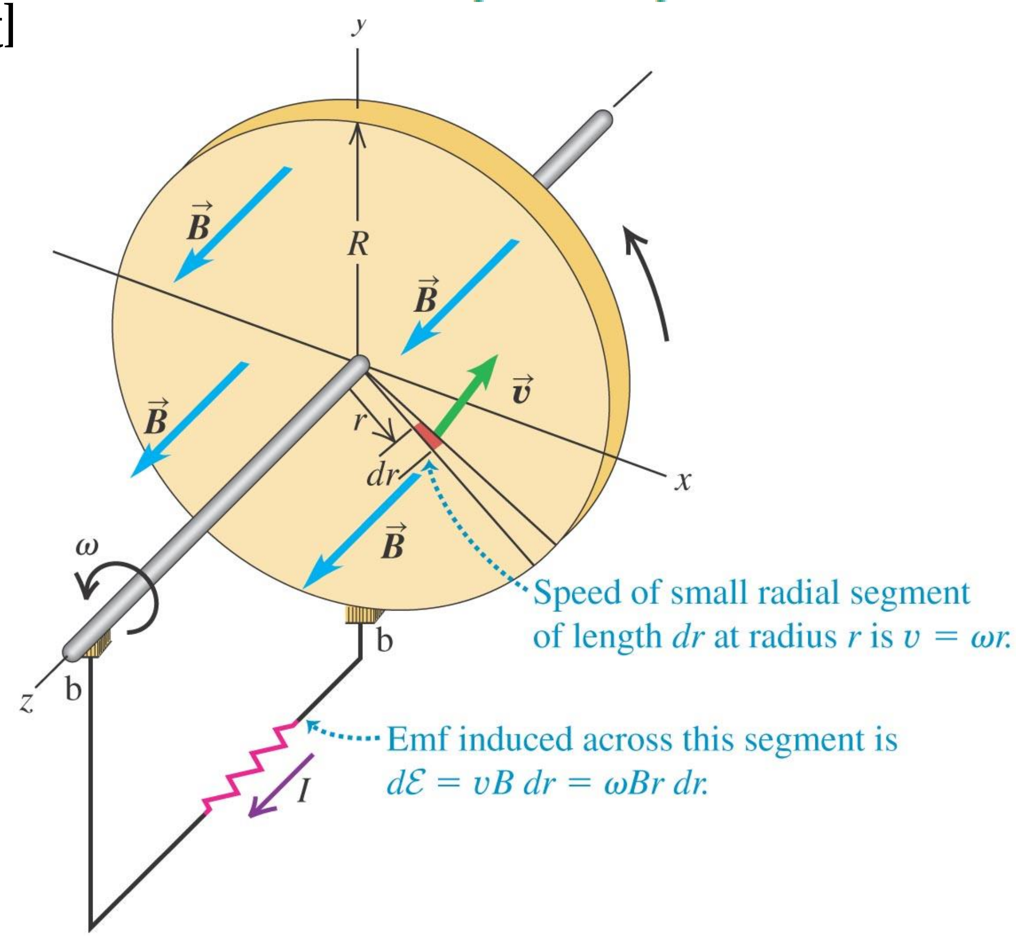
- Follow Example 29.9 for the slidewire generator.
- Follow Example 29.10 for tl
  29.16 below.

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

Motional emf: General Form

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

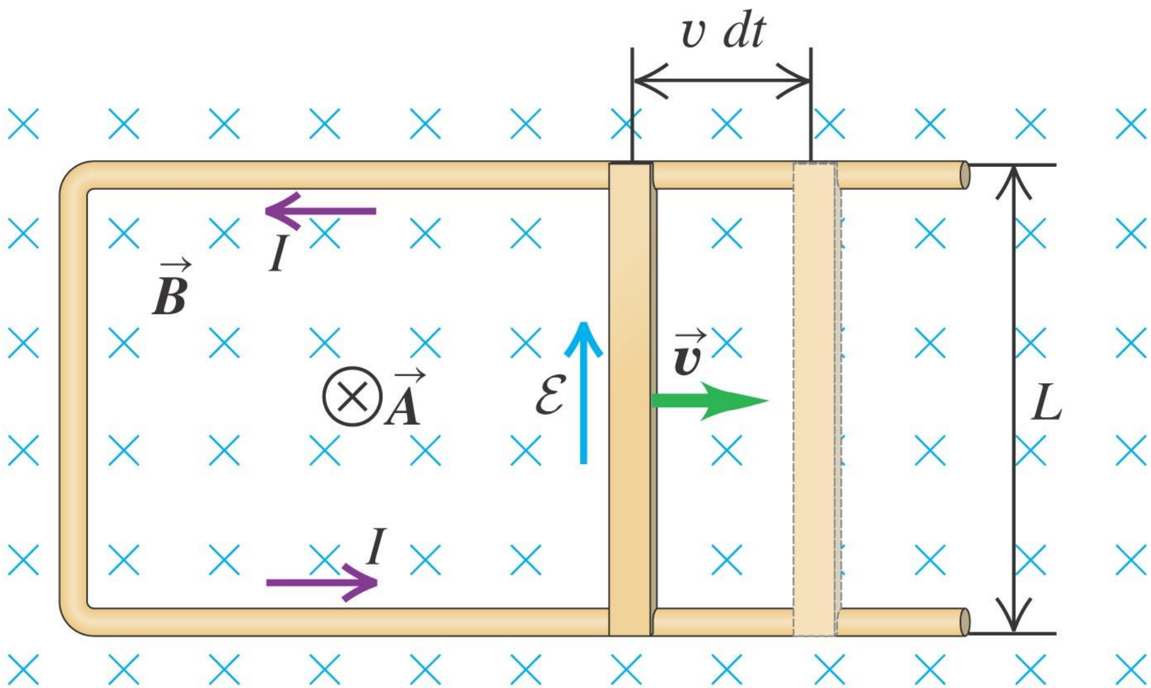
The Faraday disk dynamo



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

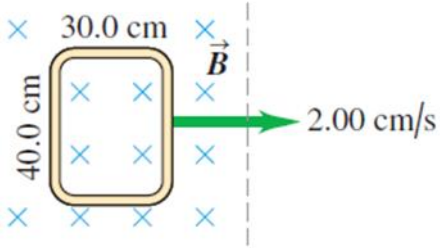
Slidewire generator

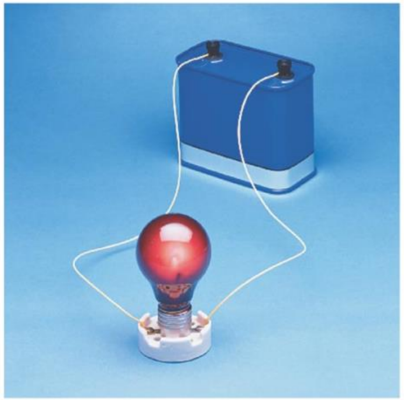
- Follow Example 29.5 using Figure 29.11 below.



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

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

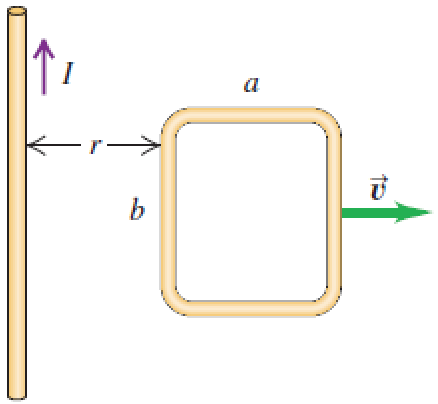




Work and power in the slidewire generator

- Follow Example 29.6 using Figure 29.12 below.

Figure **P29.53**

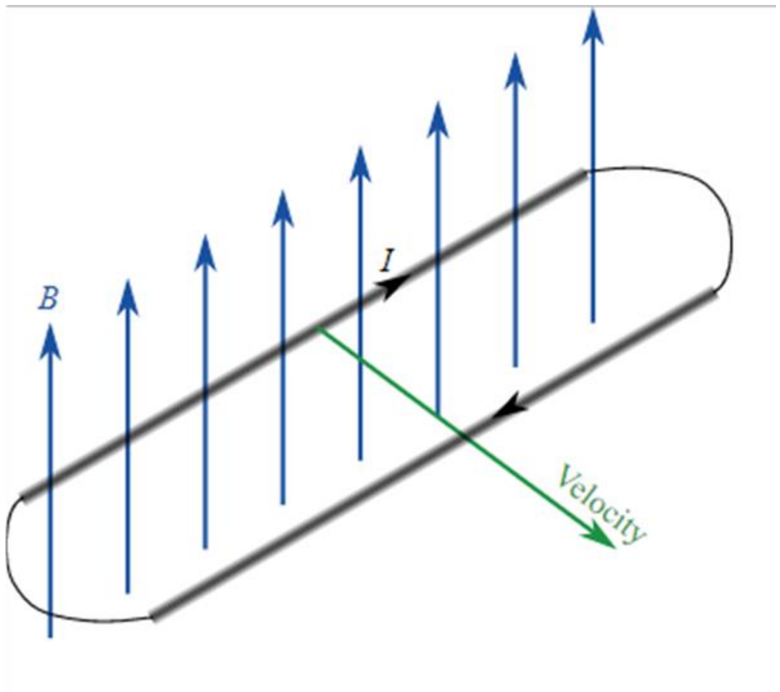


$$B = \frac{\mu_0 I}{2\pi r}$$

$$r = r_0 + vt$$

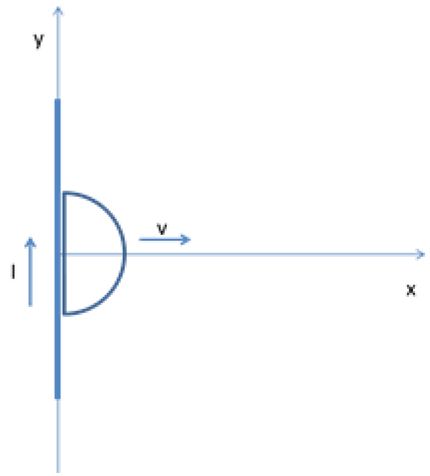
$$\Phi_B = \int \vec{B} \cdot d\vec{A}$$

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


B
I
Velocity

Work and power in the slidewire generator

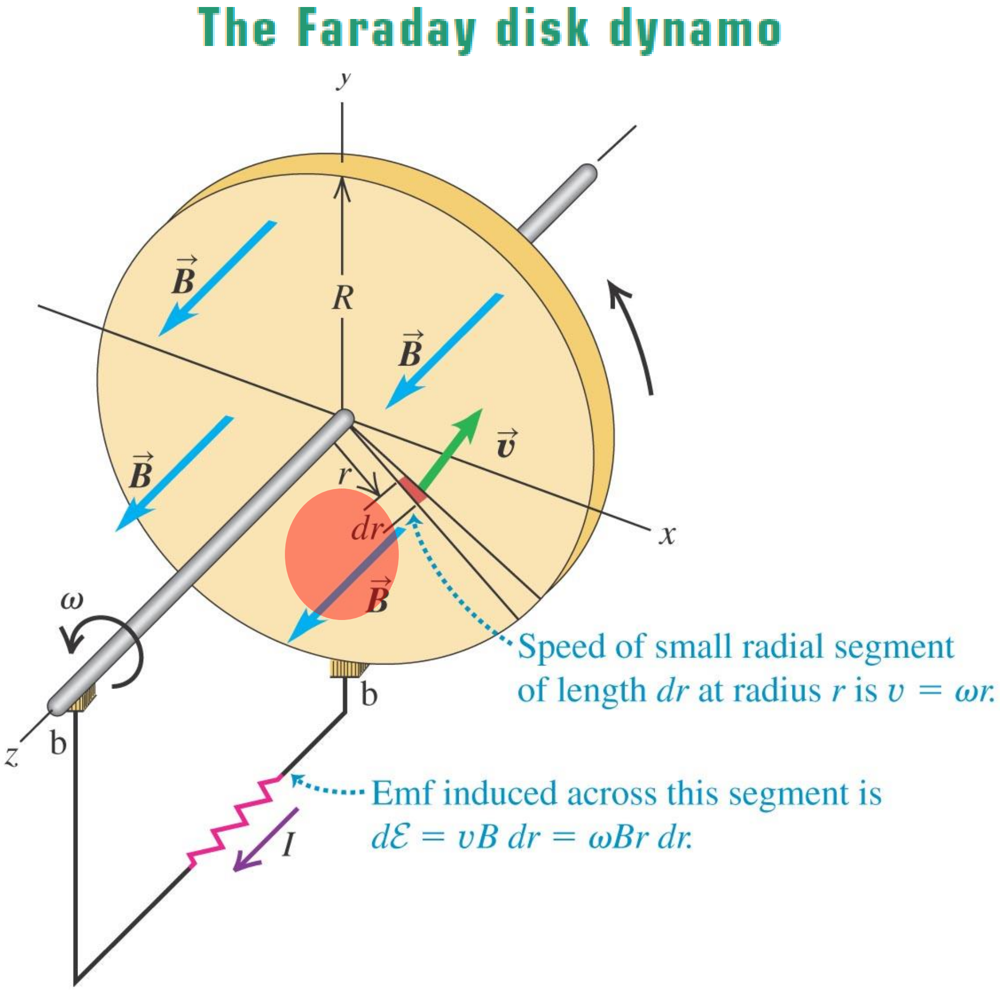
(5) (20%) A metal hemisphere with radius of R is moving away from a vertical INFINITE long current wire carrying current I at the speed of v. at time t=0, the hemisphere is just on the y-axis. Find the force at that time.



$$r = r_0 + vt$$

A slidewire generator and a dynamo

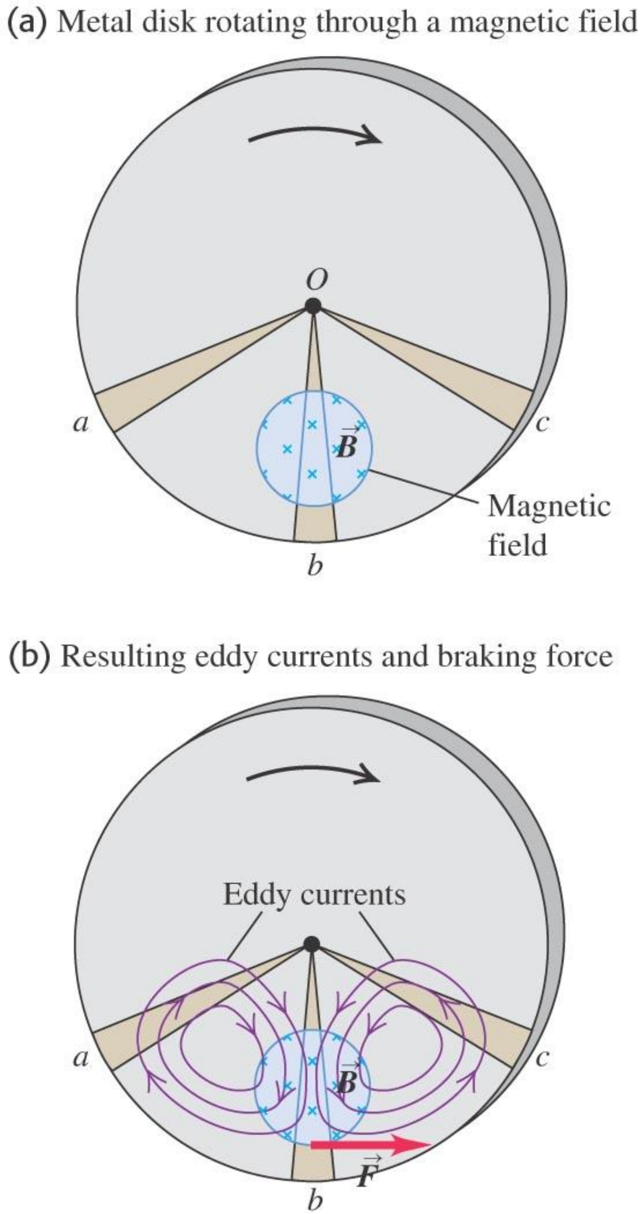
$$d\mathcal{E} = (\vec{v} \times \vec{B}) \cdot d\vec{l}$$



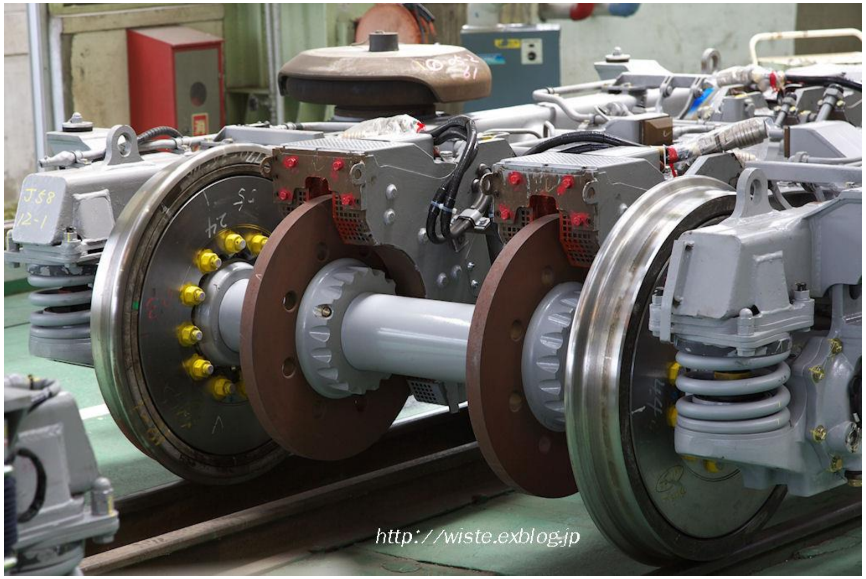
$$\mathcal{E} = \int_0^R \omega Br\,dr = \frac{1}{2}\omega BR^2$$

Eddy currents

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

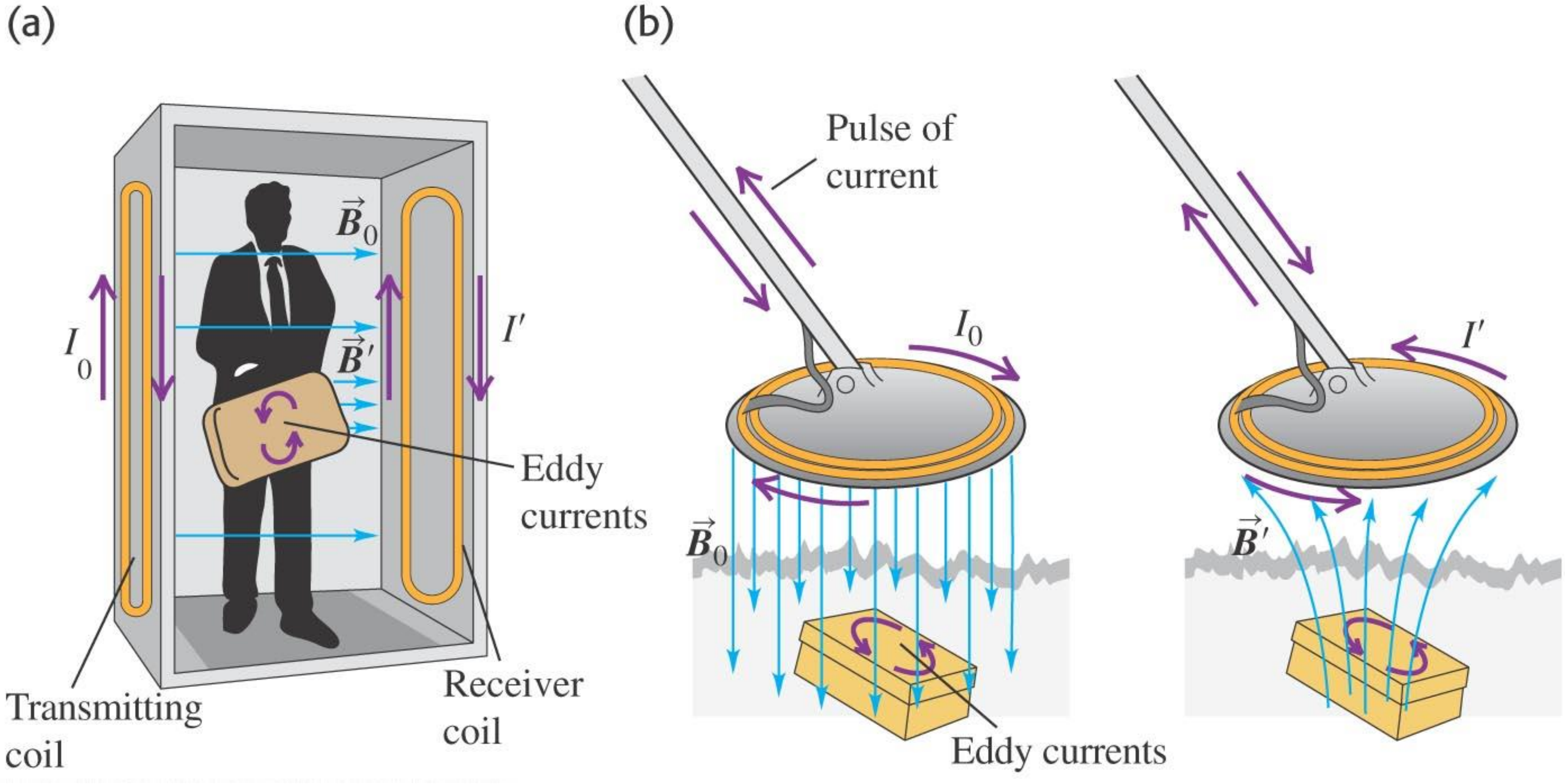


Eddy currents



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.

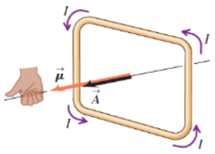


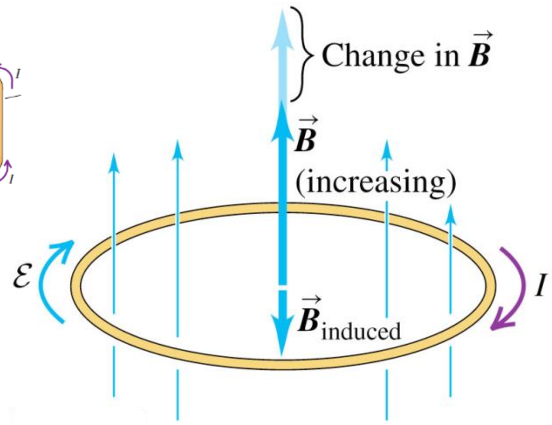
Lenz's law

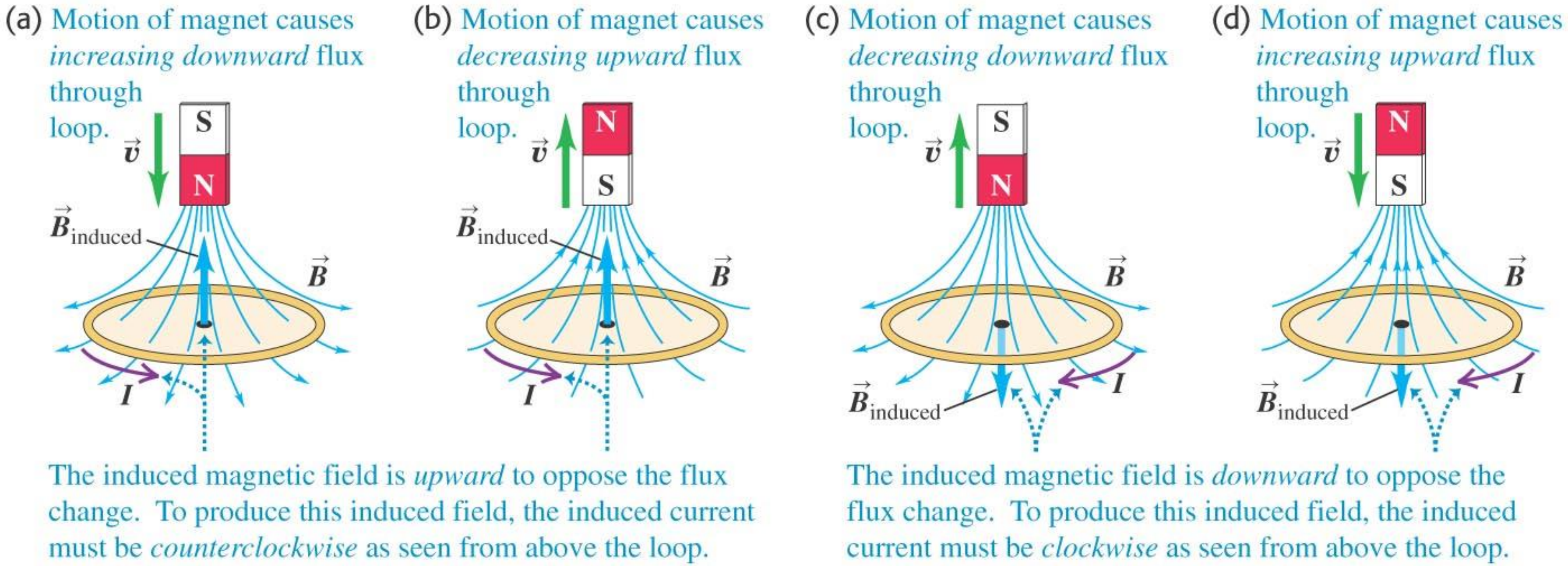
- *Lenz's law*: The direction of any magnetic induction effect is such as to ***oppose*** the cause of the effect.

Lenz's law and the direction of induced current

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

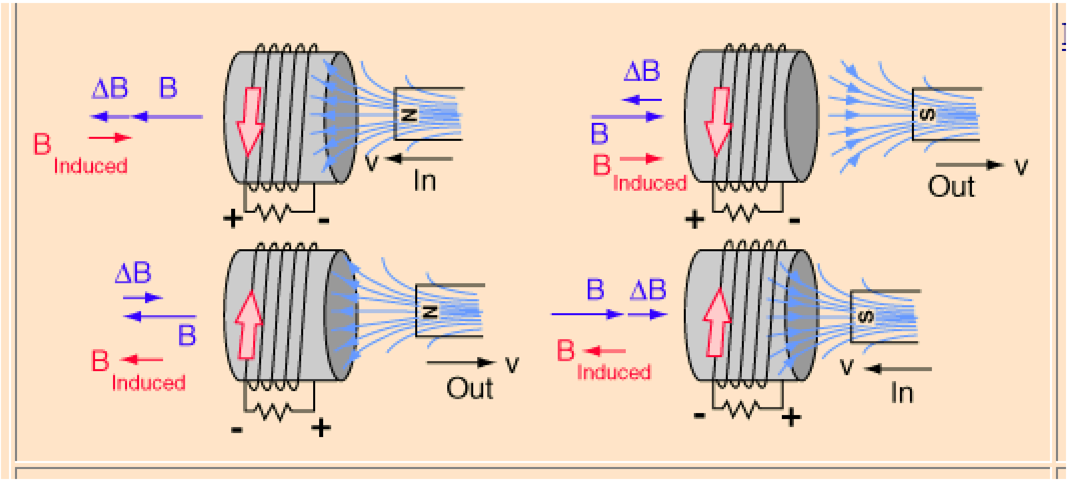


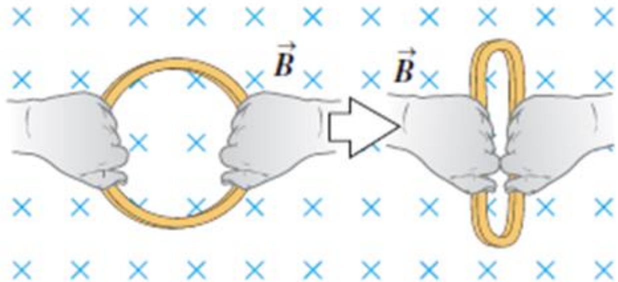




What about F?

Lenz’s law and the direction of induced current

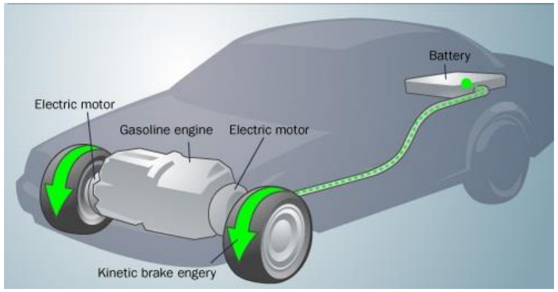


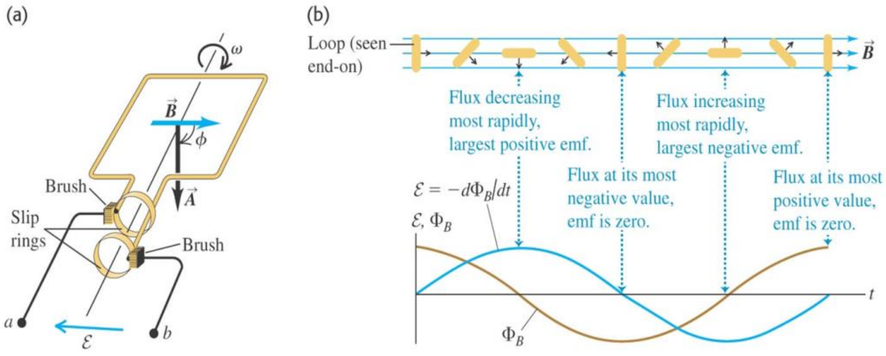


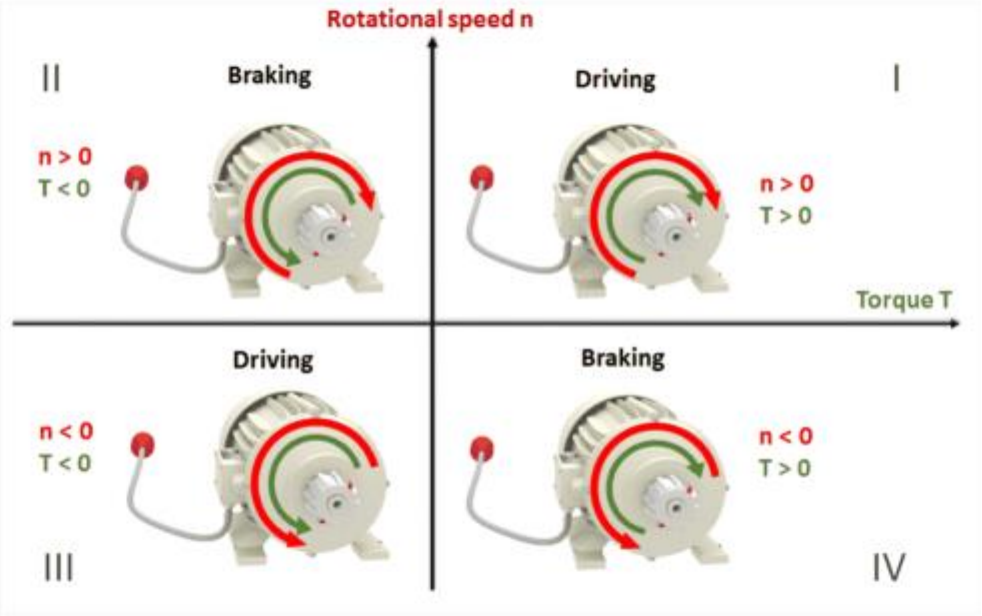
Circular wire coil

Coil squeezed into oval

Lenz's law and the direction of induced current

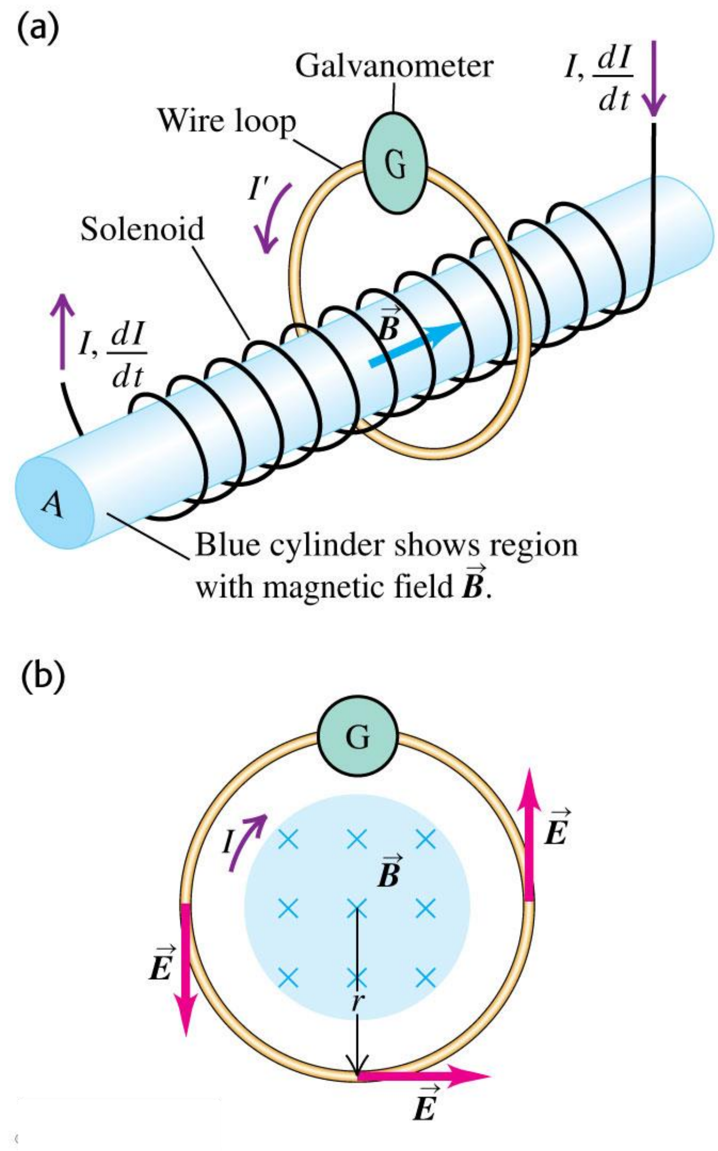






Induced electric fields

- 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

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

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

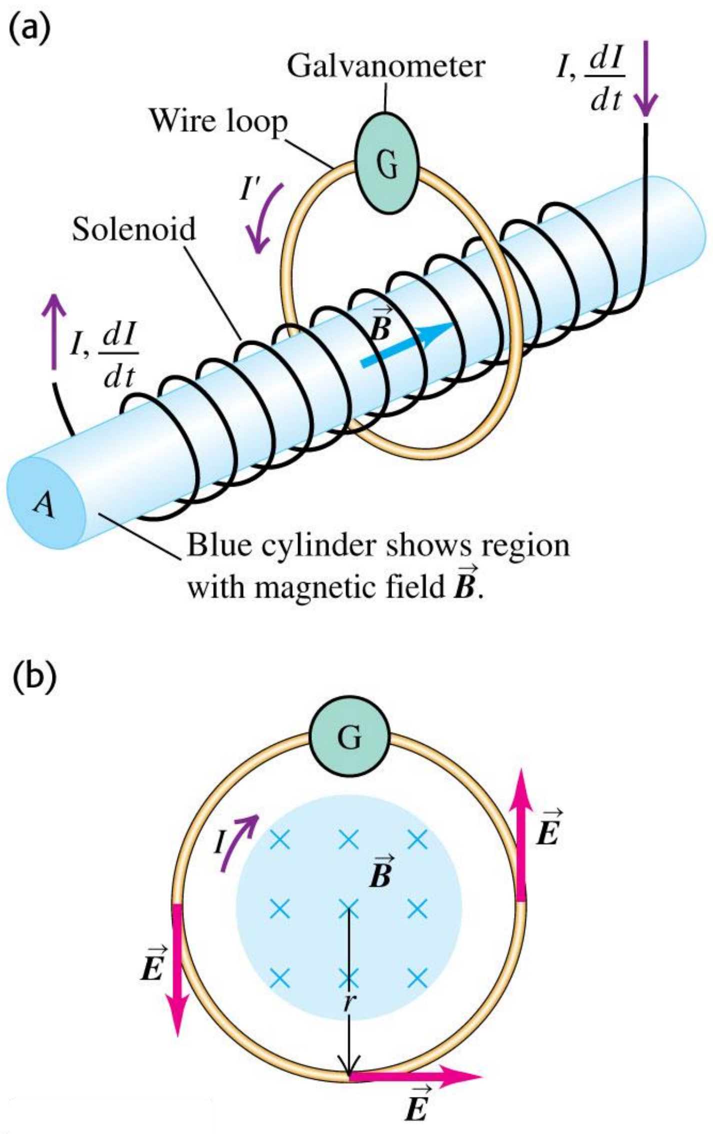
$V_{ab} = \mathcal{E}$ (ideal source of emf) ; $I' = \mathcal{E}/R$.

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

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

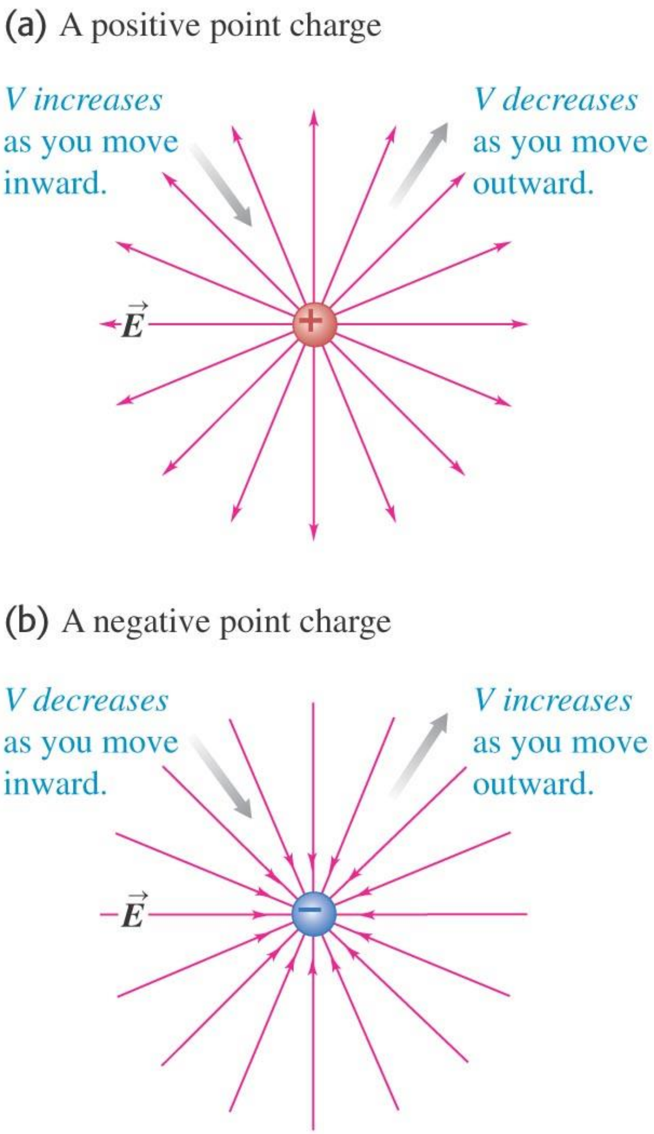
$\oint \vec{E} \cdot d\vec{l} = 2\pi r E$, and Eq. (29.10) gives

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



Finding electric potential from the electric field

- If you move in the direction of the electric field, the electric potential *decreases*, but if you move opposite the field, the potential *increases*. (See Figure 23.12 at the right.)

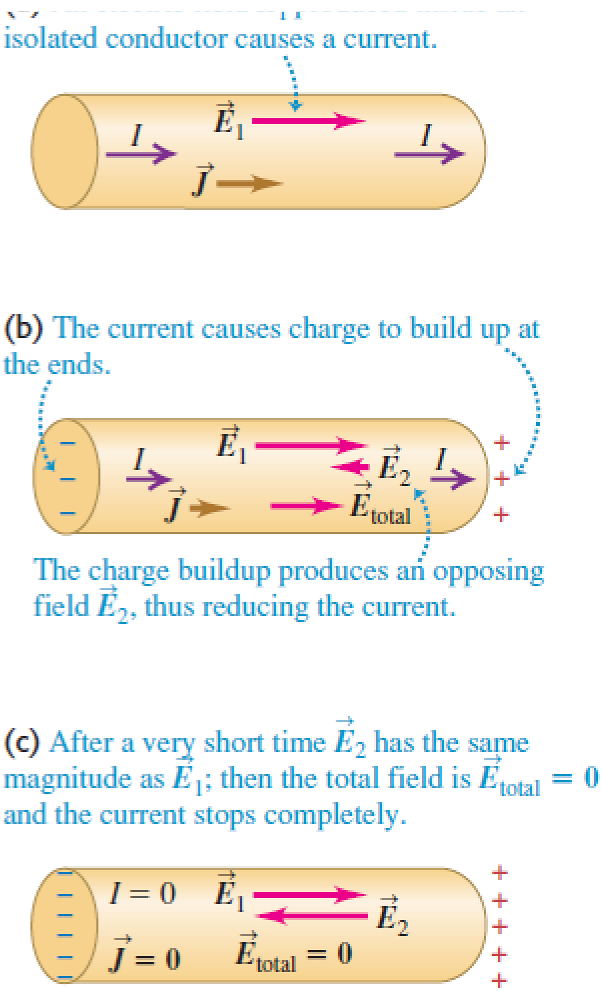


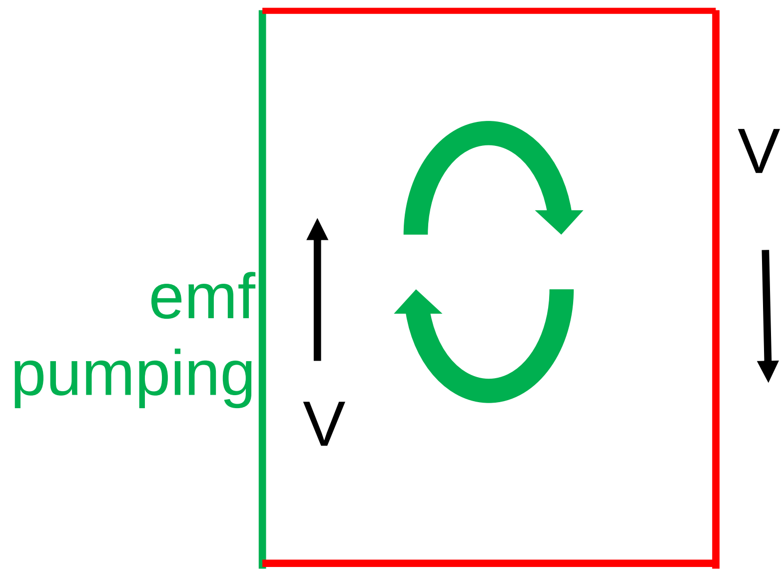
$$V_a - V_b = \int_a^b \vec{E} \cdot d\vec{l} = \int_a^b E \cos\phi \, dl \quad \text{(potential difference as an integral of } \vec{E}\text{)}$$

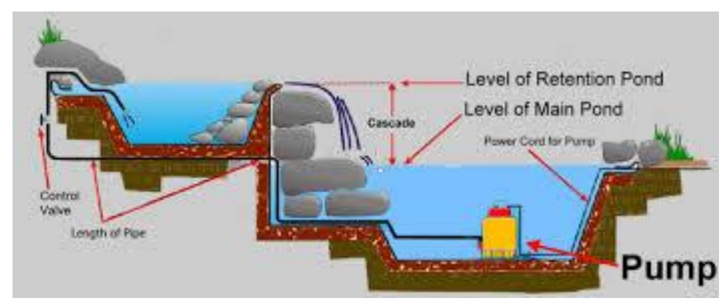
$$\cos\phi \, dl = dr.$$

Electromotive force and circuits

For a conductor to have a steady current, it must be part of a path that forms a closed loop or **complete circuit.** Here's why. If you establish an electric field $\vec{E}_1$

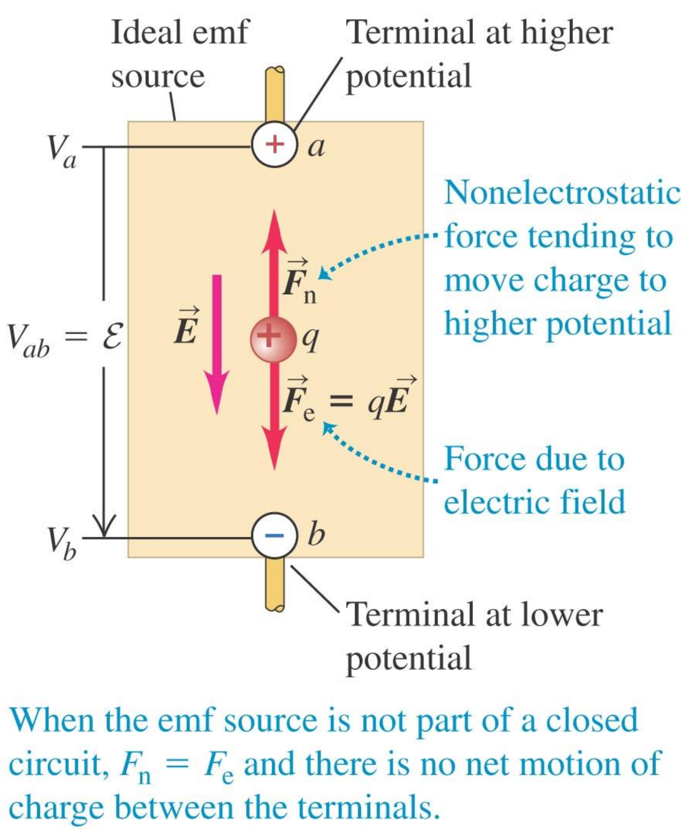


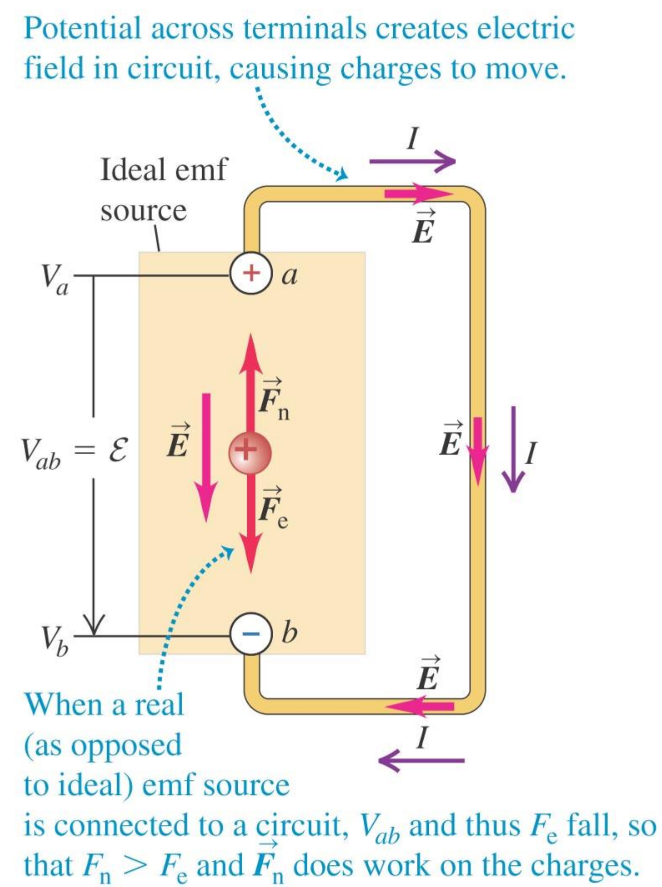




Electromotive force and circuits

- 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).



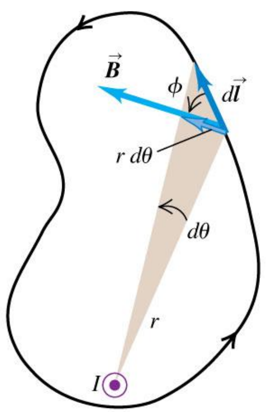


$$\boxed{\mathcal{E} = V_{ab} = IR \qquad \text{(ideal source of emf)}}$$

Ampere's law (general statement)

- Follow the text discussion of the general statement of Ampere's law, using Figures 28.17 and 28.18 below.

(a)

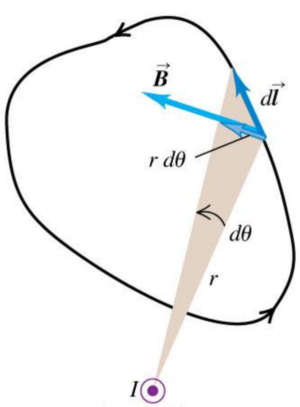


$$\vec{B} \cdot d\vec{l} = B\,dl\cos\phi$$

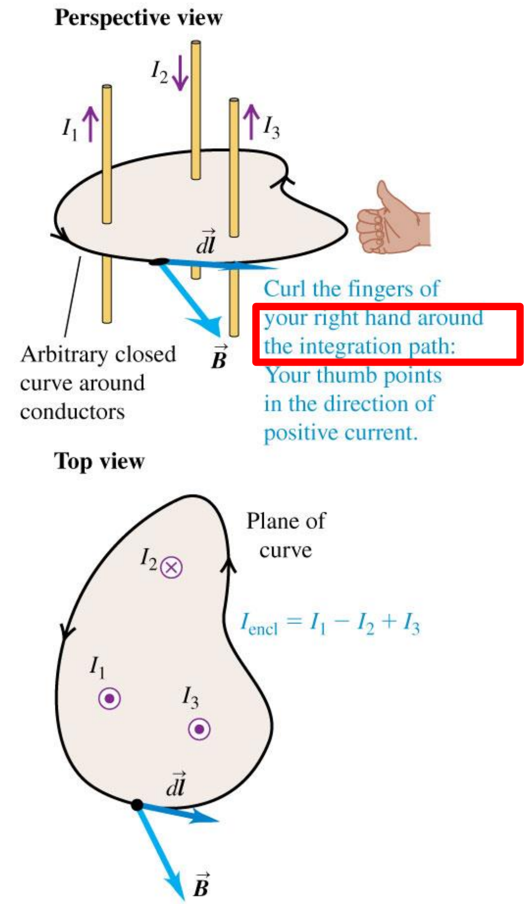
$$dl\cos\phi = r\,d\theta,$$

$$\oint \vec{B} \cdot d\vec{l} = \oint \frac{\mu_0 I}{2\pi r}(r\,d\theta) = \frac{\mu_0 I}{2\pi}\oint d\theta$$

(b)



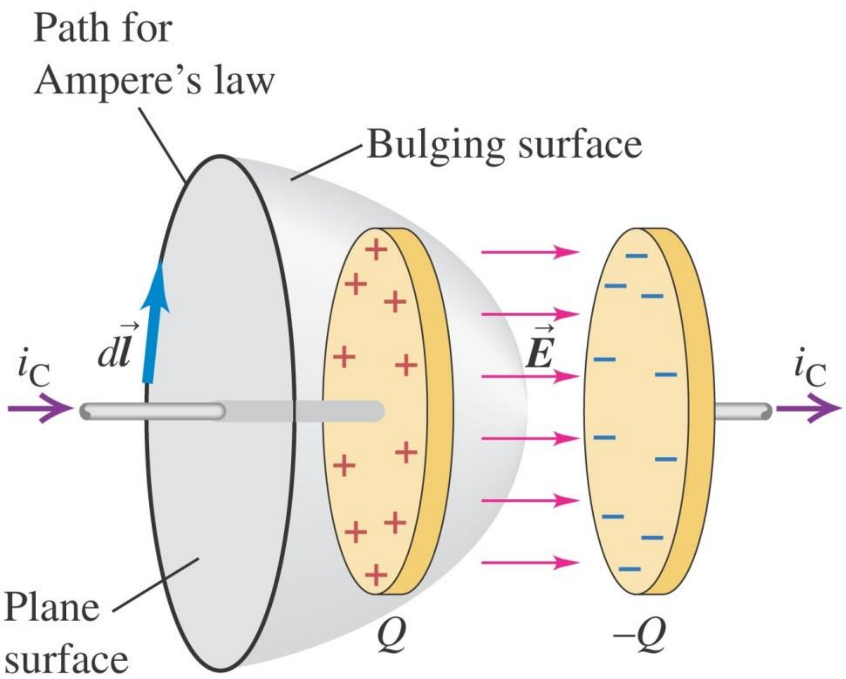
$$\oint \vec{B} \cdot d\vec{l} = \mu_0 I_{\text{encl}} \qquad \text{(Ampere's law)}$$

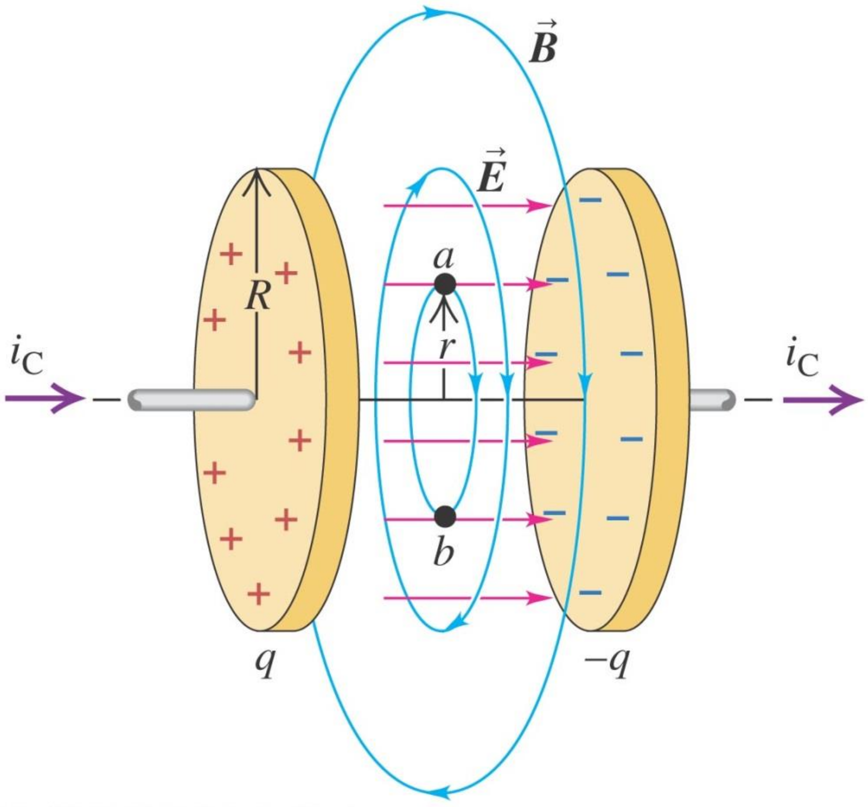


Ampere's law: If we calculate the line integral of the magnetic field around a closed curve, the result equals μ_0 times the total enclosed current: $\oint \vec{B} \cdot d\vec{l} = \mu_0 I_{\text{encl}}$.

Displacement current

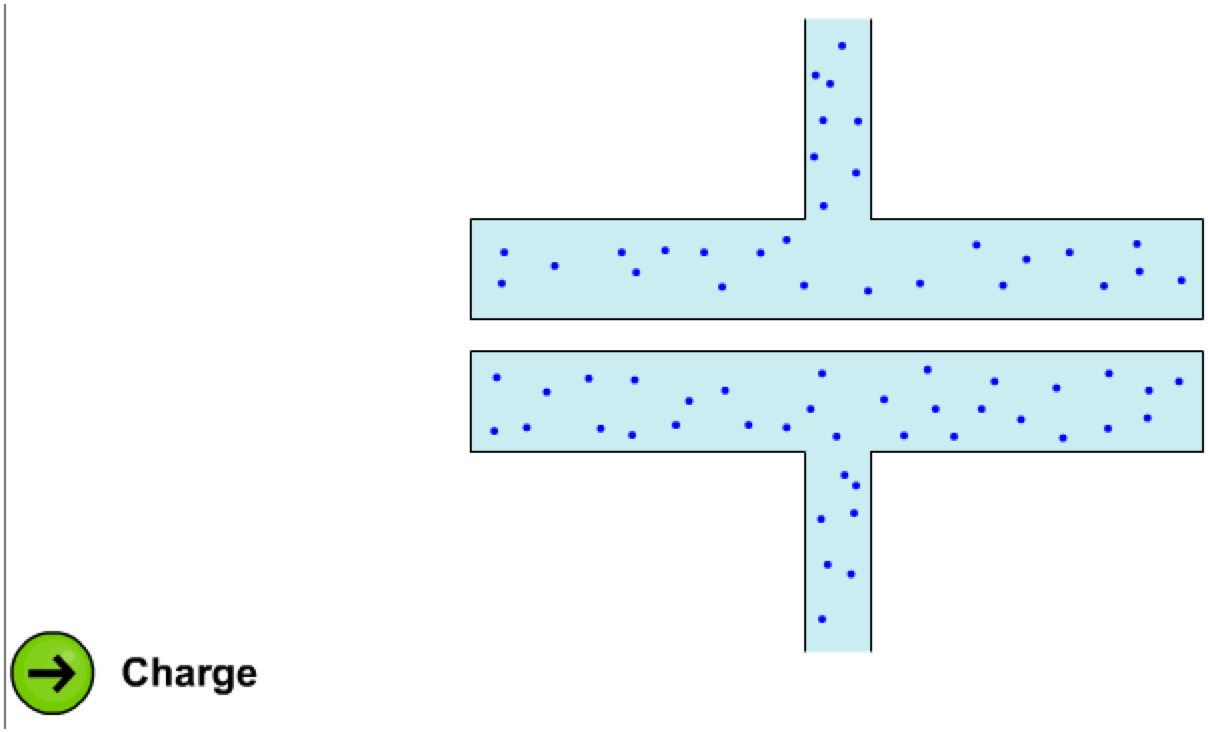
- Follow the text discussion displacement current using Figures 29.21 and 29.22 below.





Displacement current

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

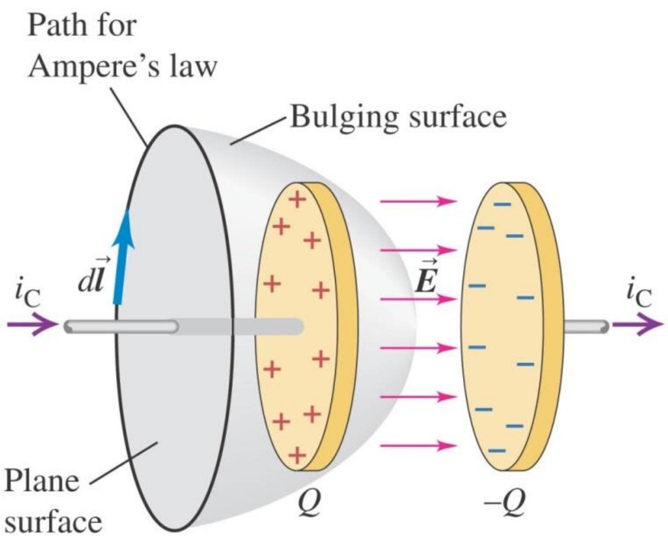


Displacement current James Clerk Maxwell

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

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

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

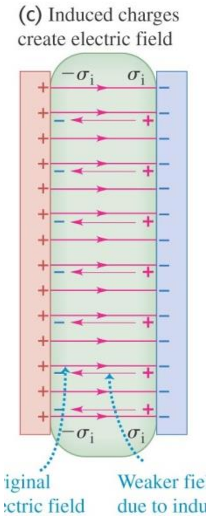
$$i_C = \frac{dq}{dt} = \epsilon \frac{d\Phi_E}{dt} \quad (29.13)$$

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

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

rent i_C, in Ampere's law:

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



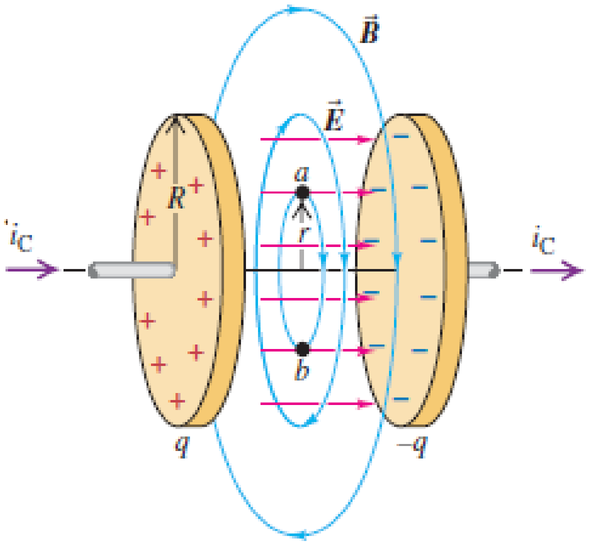
Displacement current

$$i_D = i_C$$

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

$\Phi_E = EA$ i

$(i_D/\pi R^2)(\pi r^2)$

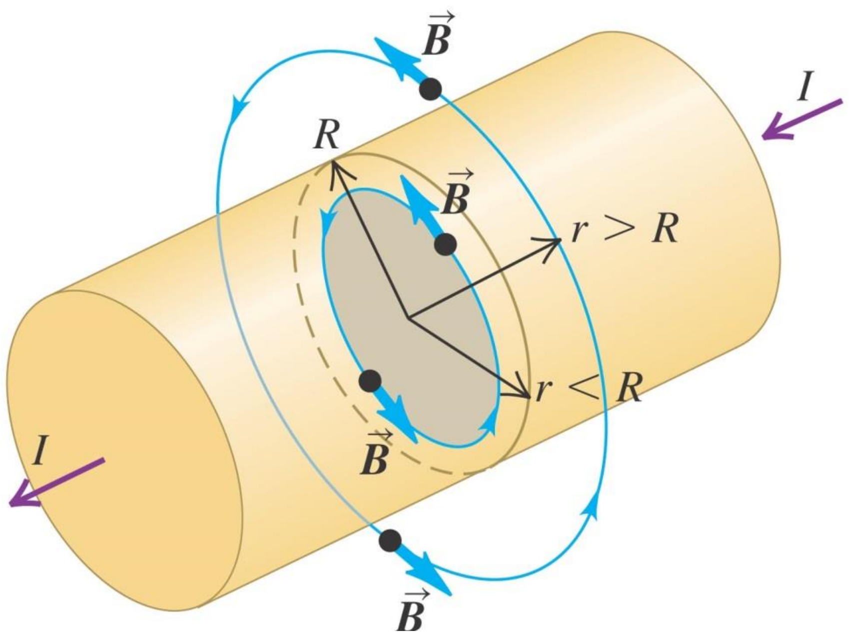


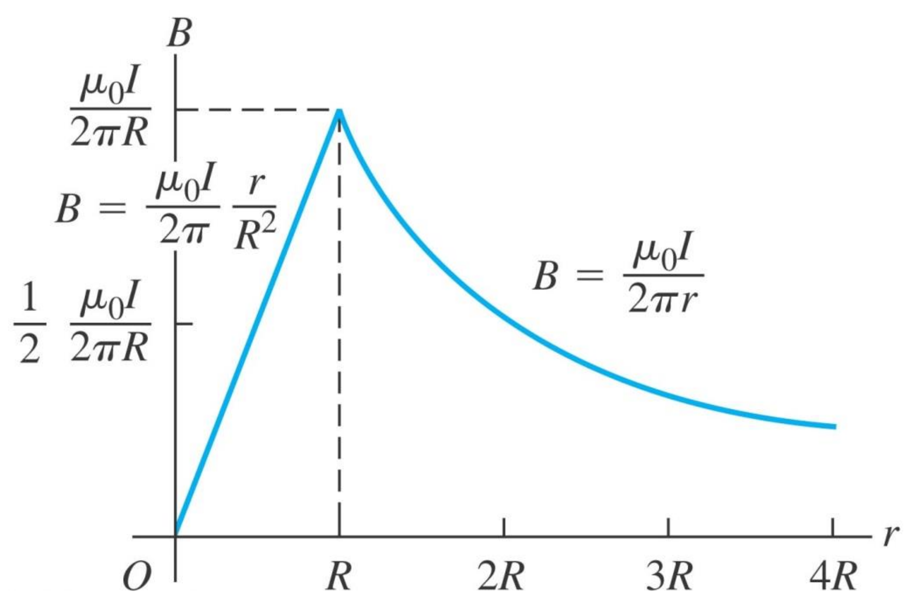
$$\oint \vec{B} \cdot d\vec{l} = 2\pi r B = \mu_0 \frac{r^2}{R^2} i_C$$

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

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.

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

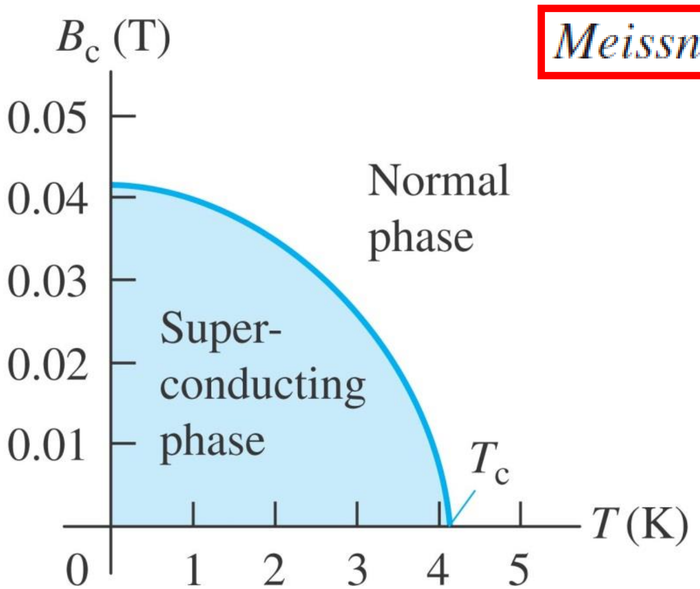
$$\text{(ii)} \quad \nabla \cdot \mathbf{B} = 0 \quad \text{(no name),}$$

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

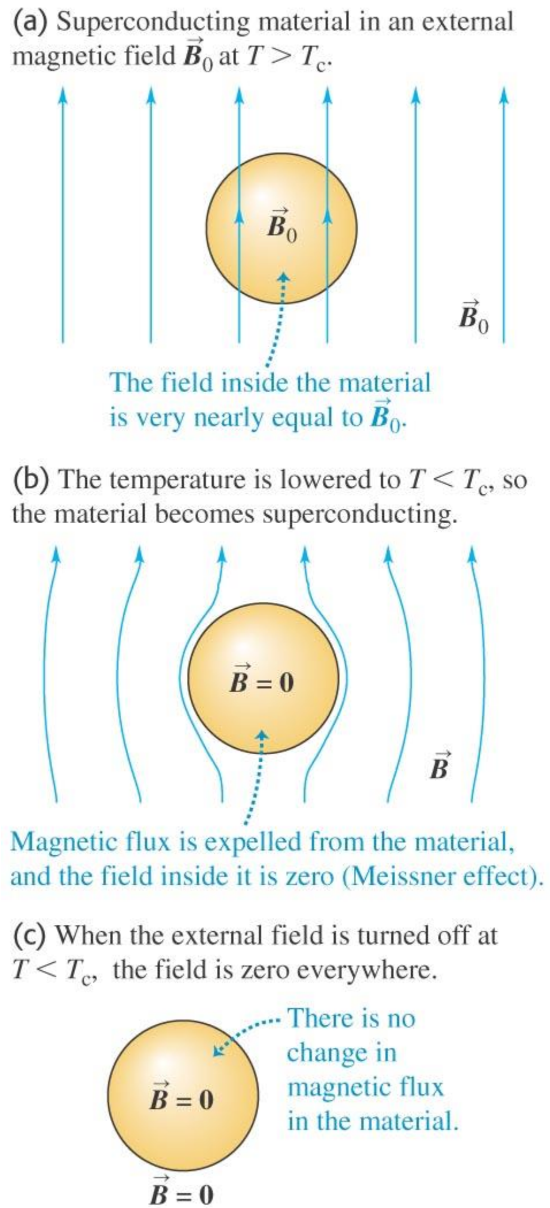
$$\text{(iv)} \quad \nabla \times \mathbf{B} = \mu_0 \mathbf{J} \quad \text{(Ampère's law).}$$

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).

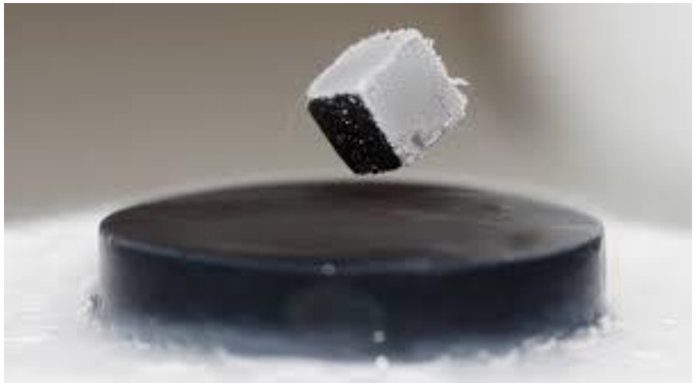


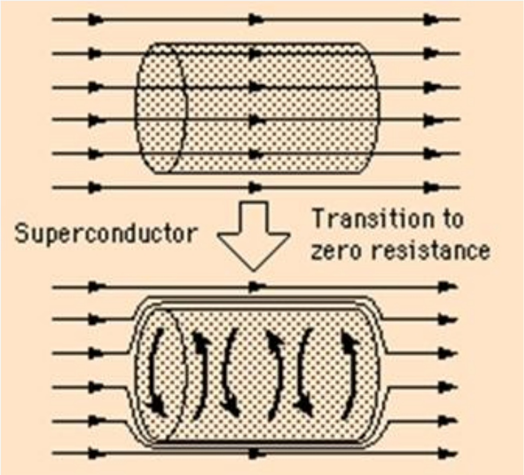
Meissner effect.



Perfect diamagnetism

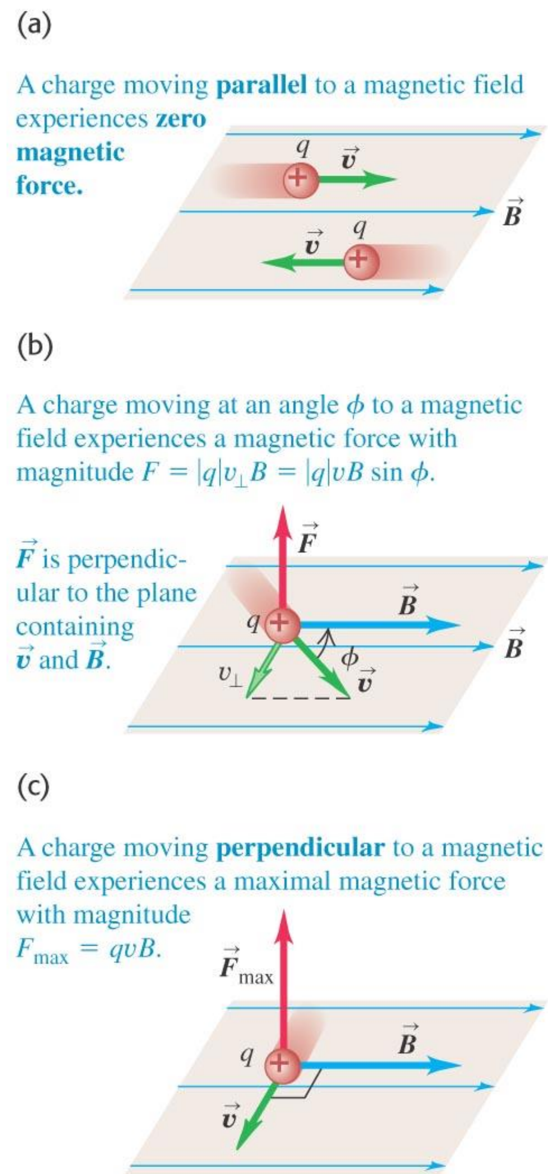
magnetic susceptibility $\chi_v = -1$

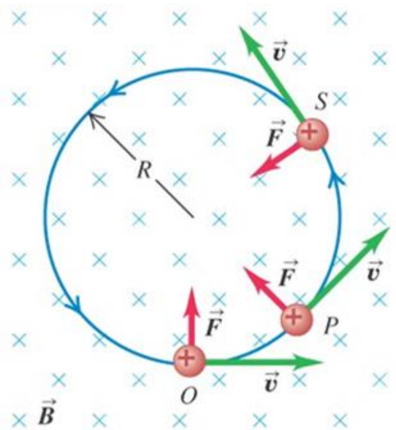




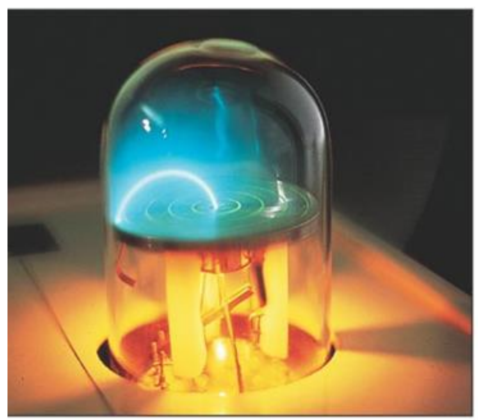
The magnetic force on a moving charge

- The magnetic force on q is perpendicular to *both* the velocity of q and the magnetic field. (See Figure 27.6 at the right.)
- The magnitude of the magnetic force is $F = |q|vB \sin\phi$.





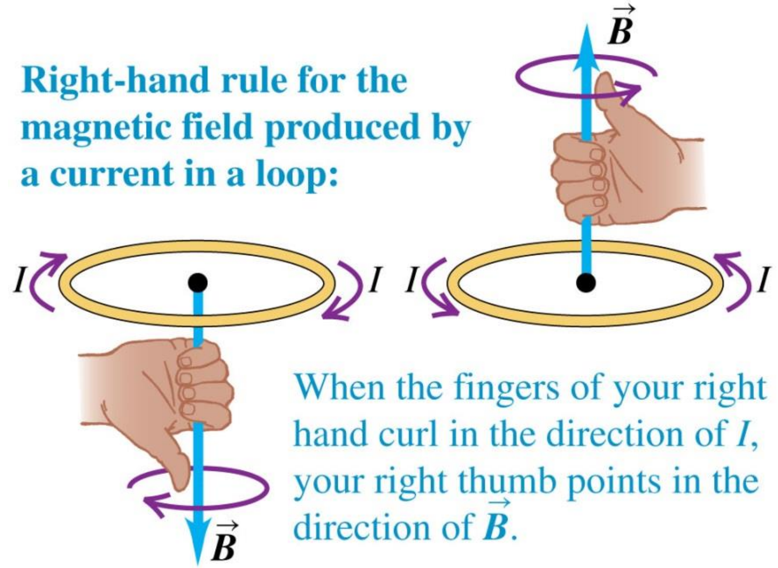
(b) An electron beam (seen as a blue arc) curving in a magnetic field

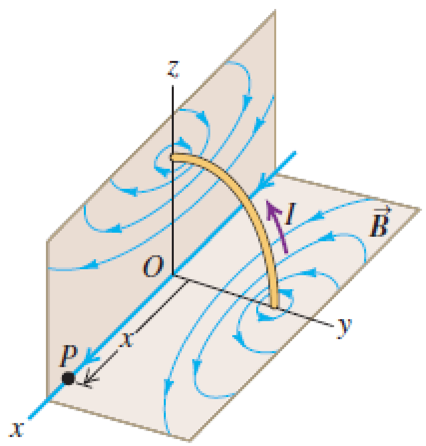


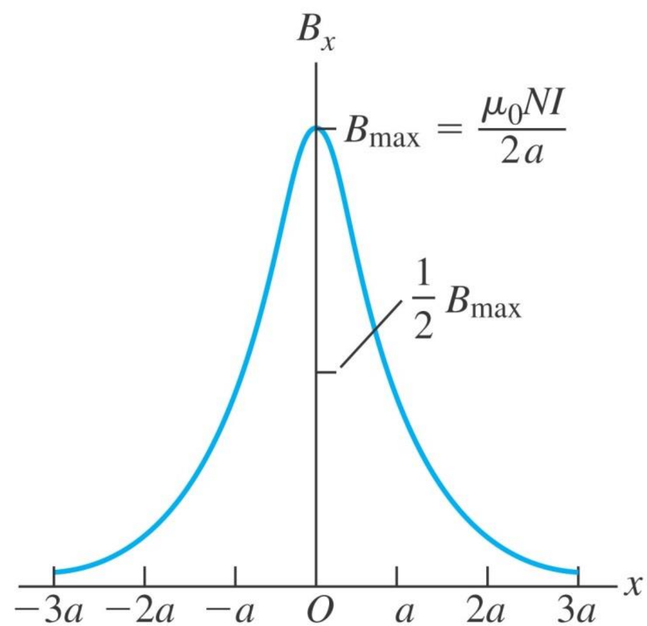
$$\vec{F} = q\vec{v} \times \vec{B} \quad \text{(magnetic force on a moving charged particle)} \quad (27.2)$$

Magnetic field of a coil

- Figure 28.13 (top) shows the direction of the field using the right-hand rule.
- Figure 28.14 (below) shows a graph of the field along the *x*-*a*xis.
-

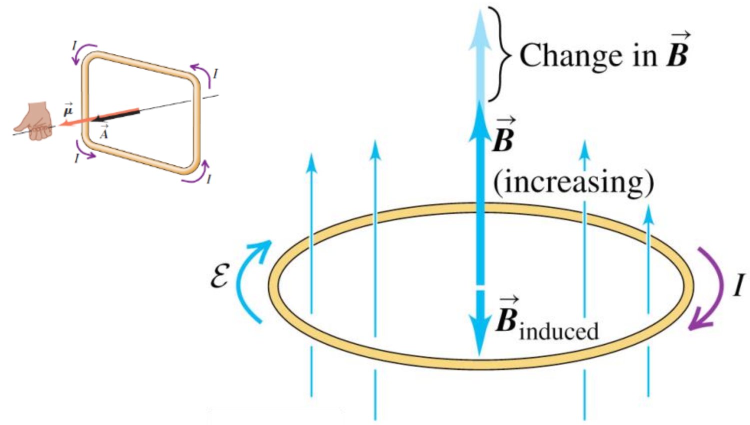


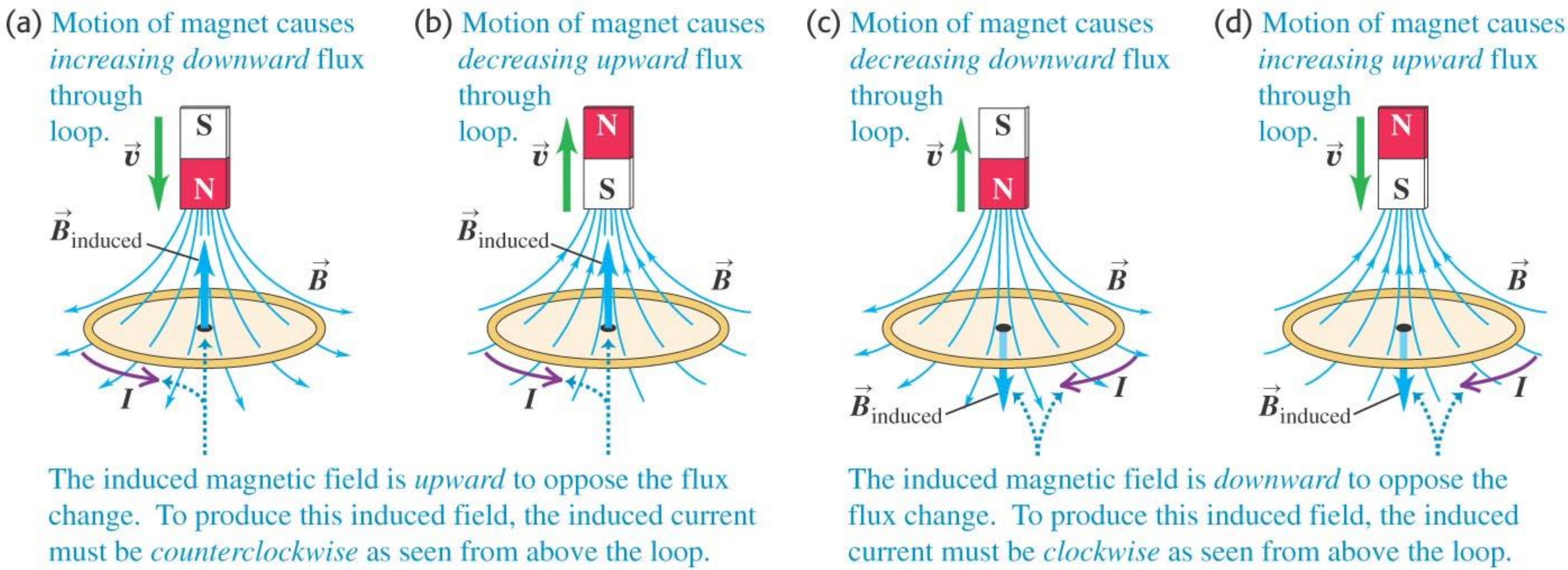




Lenz's law and the direction of induced current

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





What about F?