

PHYS 122-Lecture 12:

Electromagnetic Induction

Today: Chap 29:

- a) Faraday's Law

 - Maxwell's Laws [almost complete!]

- b) Lenz's Law

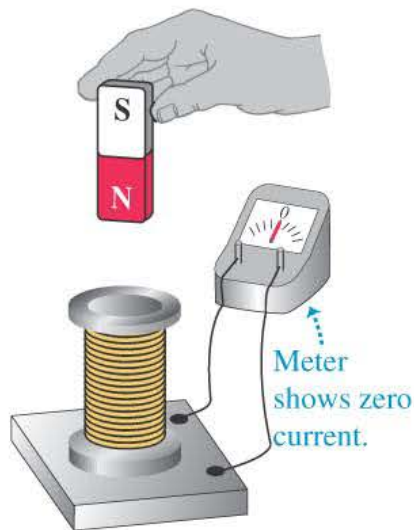
- c) Examples

- d) Correction to Ampere's Law

Induced current

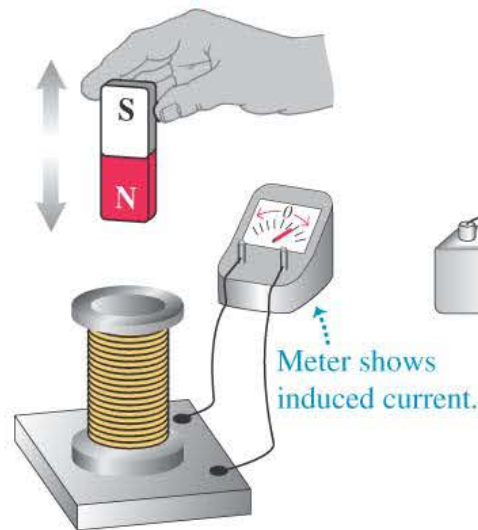
- A changing magnetic flux causes an *induced current*. See Figure 29.1 below.
- The *induced emf* is the corresponding emf causing the current.

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

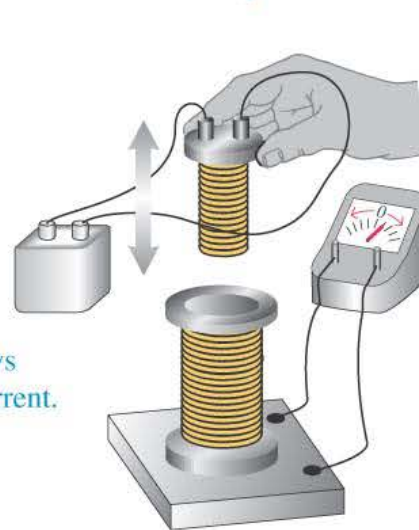


All these actions DO induce a current in the coil. What do they have in common?*

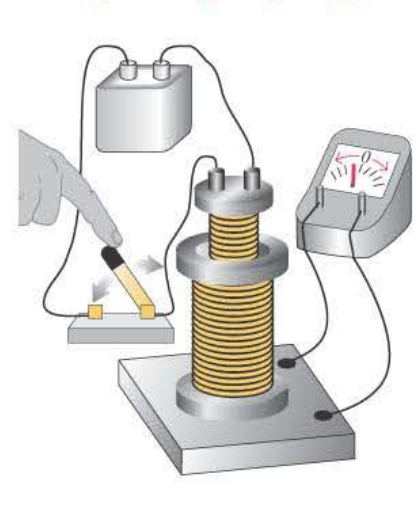
(b) Moving the magnet toward or away from the coil



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



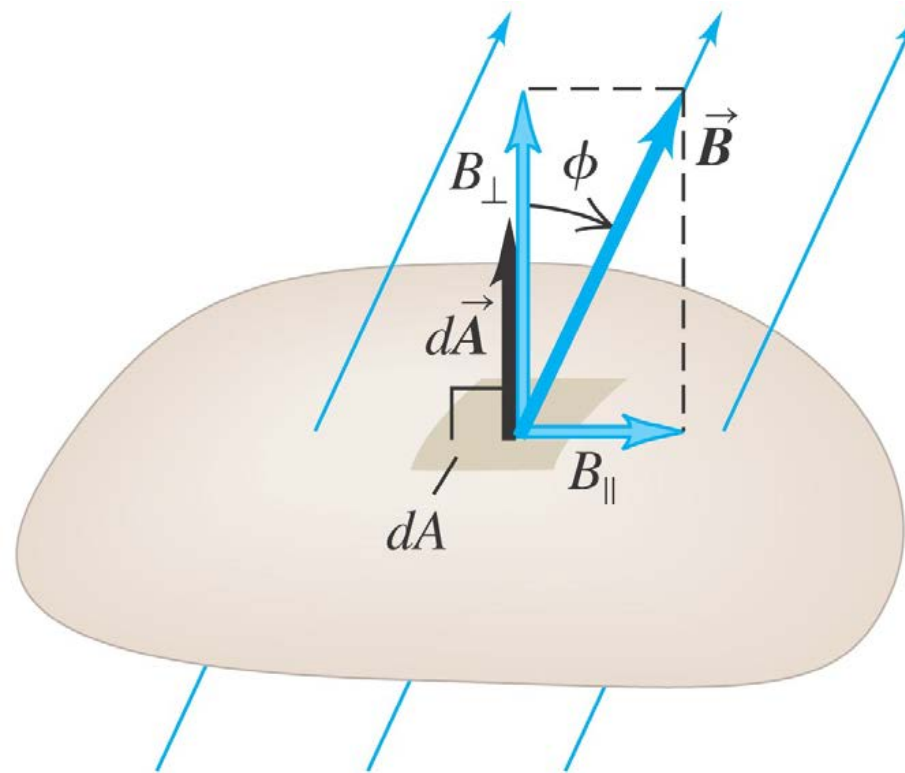
(d) Varying the current in the second coil (by closing or opening a switch)



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

Magnetic flux through an area element

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



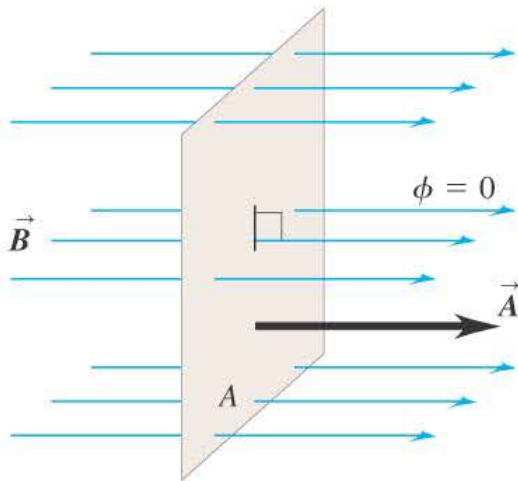
Magnetic flux through element of area $d\vec{A}$:
$$d\Phi_B = \vec{B} \cdot d\vec{A} = B_{\perp} dA = B dA \cos \phi$$

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 $\xi = -d\Phi_B/dt$.

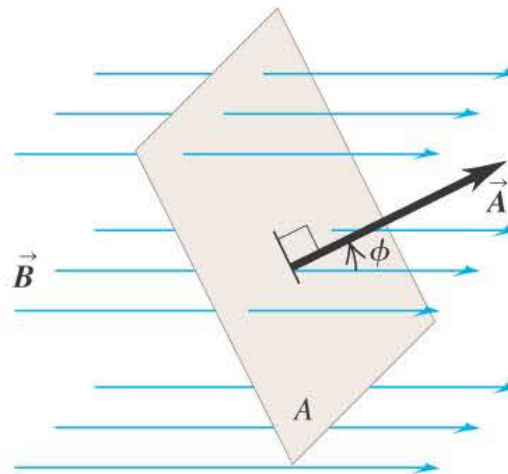
Surface is face-on to magnetic field:

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



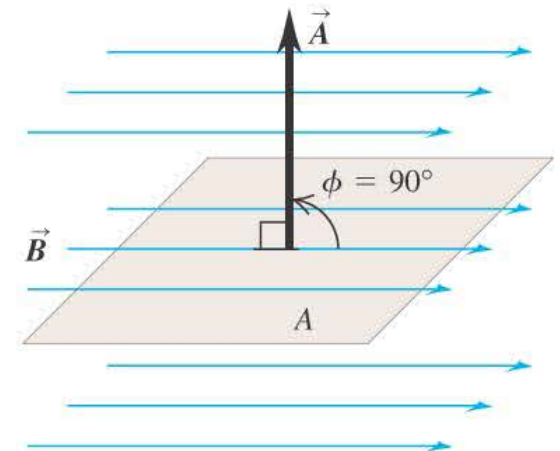
Surface is tilted from a face-on orientation by an angle ϕ :

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



Surface is edge-on to magnetic field:

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



Faraday's Law

$$V = - \frac{\delta}{\delta t} \Phi$$

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

Faraday's Law

$$V = -\frac{\delta}{\delta t} \Phi$$

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

$$\oint \vec{E} \cdot d\vec{\ell} = V = -\frac{\delta}{\delta t} \int \vec{B} \cdot d\vec{A}$$

Faraday's Law

$$V = -\frac{\delta}{\delta t} \Phi$$

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

$$\oint \vec{E} \cdot d\vec{\ell} = V = -\frac{\delta}{\delta t} \int \vec{B} \cdot d\vec{A}$$

$$\oint \vec{E} \cdot d\vec{\ell} = -\frac{\delta}{\delta t} \int \vec{B} \cdot d\vec{A}$$

Faraday's Law

$$V = -\frac{\delta}{\delta t} \Phi$$

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

$$\oint \vec{E} \cdot d\vec{\ell} = V = -\frac{\delta}{\delta t} \int \vec{B} \cdot d\vec{A}$$

$$\oint \vec{E} \cdot d\vec{\ell} = -\frac{\delta}{\delta t} \int \vec{B} \cdot d\vec{A}$$

$$\oint (\nabla \times \vec{E}) \cdot d\vec{A} = -\frac{\delta}{\delta t} \int \vec{B} \cdot d\vec{A}$$

Faraday's Law

$$V = -\frac{\delta}{\delta t} \Phi$$

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

$$\oint \vec{E} \cdot d\vec{\ell} = V = -\frac{\delta}{\delta t} \int \vec{B} \cdot d\vec{A}$$

$$\oint \vec{E} \cdot d\vec{\ell} = -\frac{\delta}{\delta t} \int \vec{B} \cdot d\vec{A}$$

$$\oint (\nabla \times \vec{E}) \cdot d\vec{A} = -\frac{\delta}{\delta t} \int \vec{B} \cdot d\vec{A}$$

$$\nabla \times \vec{E} = -\frac{\delta \vec{B}}{\delta t}$$

Maxwell's Equations To Date

$$\oint \vec{E} \cdot d\vec{A} = \frac{Q_{enc}}{\epsilon_o}$$

Gauss' Law

$$\oint \vec{B} \cdot d\vec{A} = 0$$

"No Name Law"

$$\oint \vec{B} \cdot d\vec{\ell} = \mu_o I_{enc}$$

Ampere's Law

$$V = -\frac{\delta}{\delta t} \Phi$$

Faraday's Law

$$\oint \vec{E} \cdot d\vec{\ell} = -\frac{\delta}{\delta t} \int \vec{B} \cdot d\vec{A}$$

Maxwell's Equations To Date

$$\oint \vec{E} \cdot d\vec{A} = \frac{Q_{enc}}{\epsilon_o}$$

Gauss' Law

$$\oint \vec{B} \cdot d\vec{A} = 0$$

"No Name Law"

$$\oint \vec{B} \cdot d\vec{\ell} = \mu_o I_{enc}$$

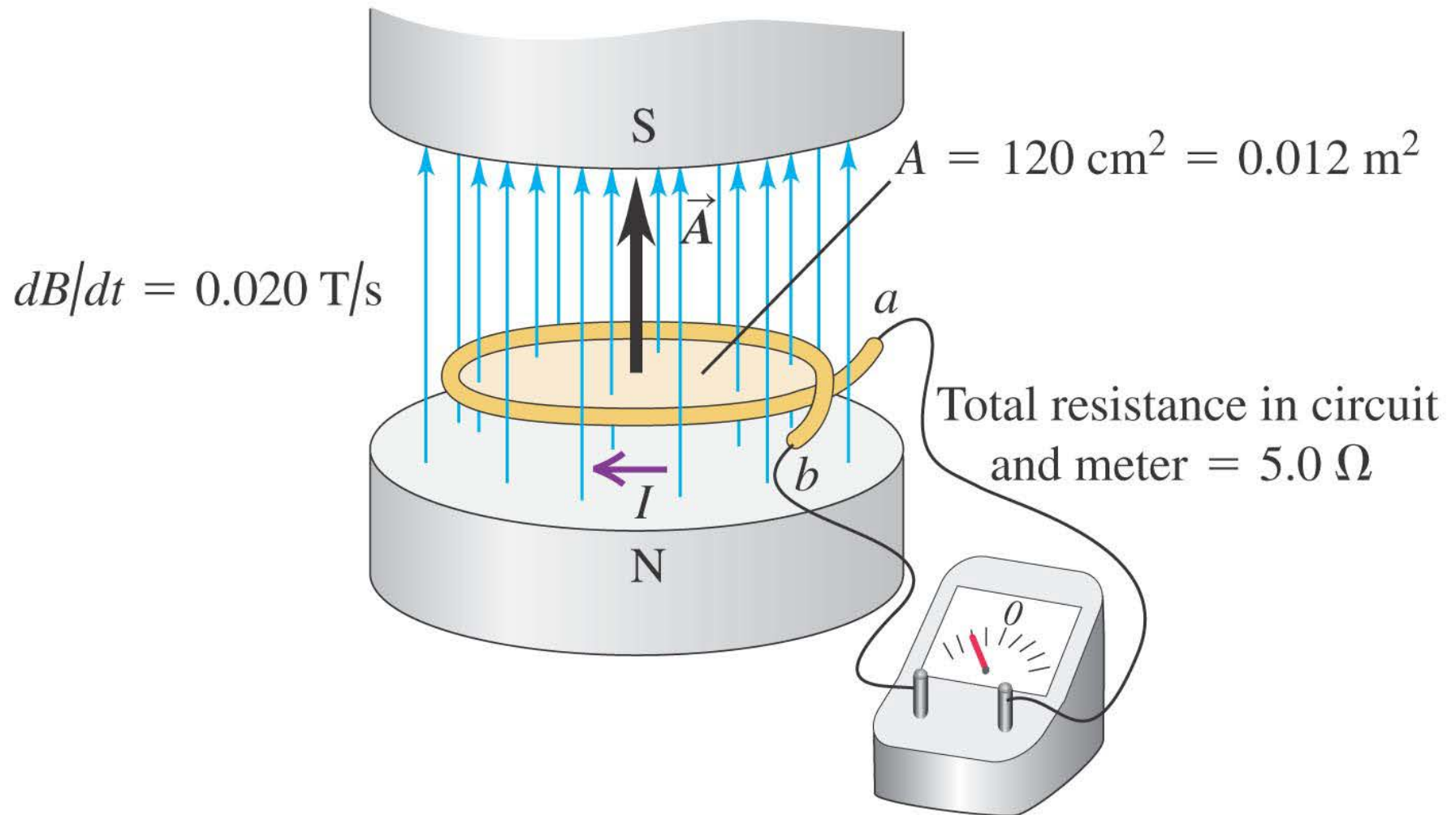
Ampere's Law

$$\oint \vec{E} \cdot d\vec{\ell} = -\frac{\delta}{\delta t} \int \vec{B} \cdot d\vec{A}$$

Faraday's Law

Emf and the current induced in a loop

- Follow Example 29.1 using Figure 29.5 below.

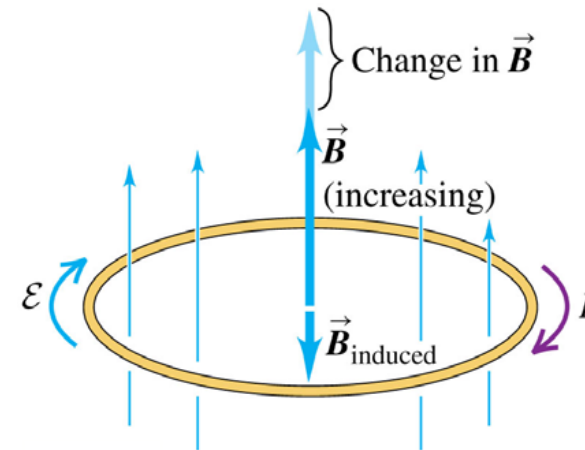


Lenz's law

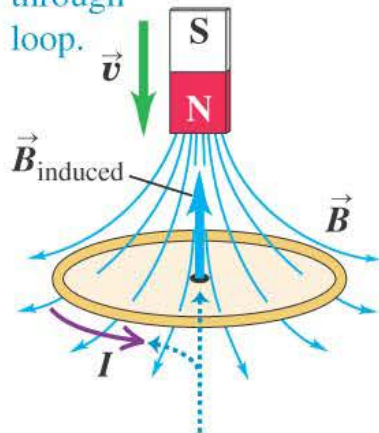
- *Lenz's law*: The direction of any magnetic induction effect is such as to oppose the cause of the effect.
- Follow Conceptual Example 29.7.

Lenz's law and the direction of induced current

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

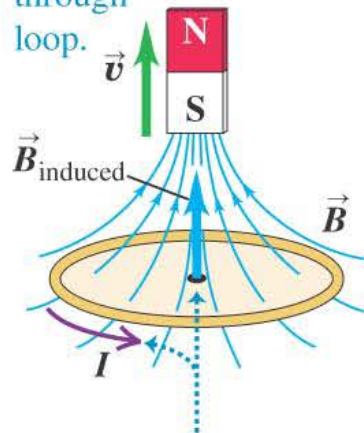


- (a) Motion of magnet causes *increasing downward flux* through loop.

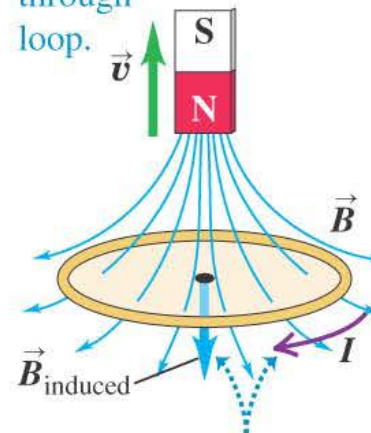


The induced magnetic field is *upward* to oppose the flux change. To produce this induced field, the induced current must be *counterclockwise* as seen from above the loop.

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

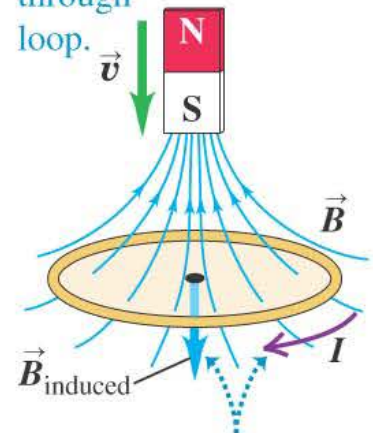


- (c) Motion of magnet causes *decreasing downward flux* through loop.



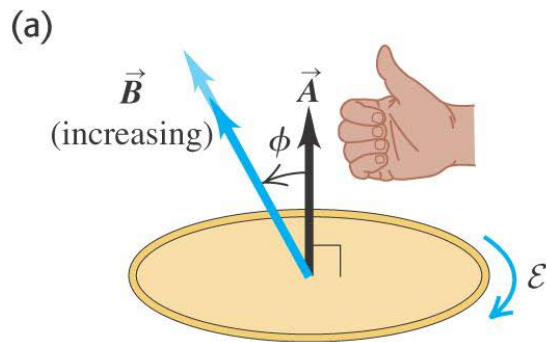
The induced magnetic field is *downward* to oppose the flux change. To produce this induced field, the induced current must be *clockwise* as seen from above the loop.

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

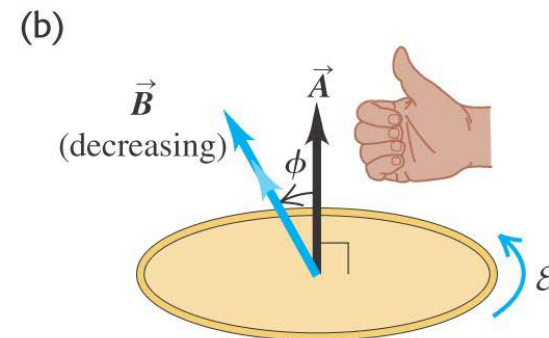


Direction of the induced emf

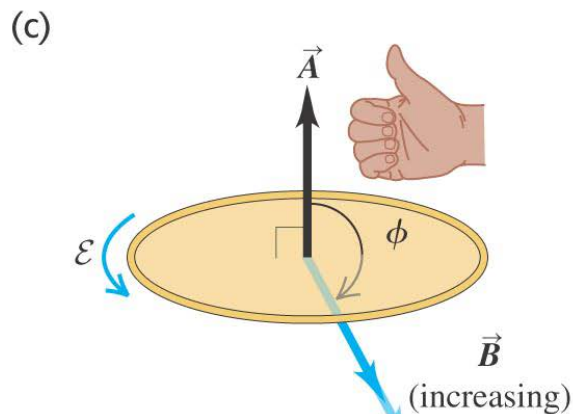
- Follow the text discussion on the direction of the induced emf, using Figure 29.6 below.



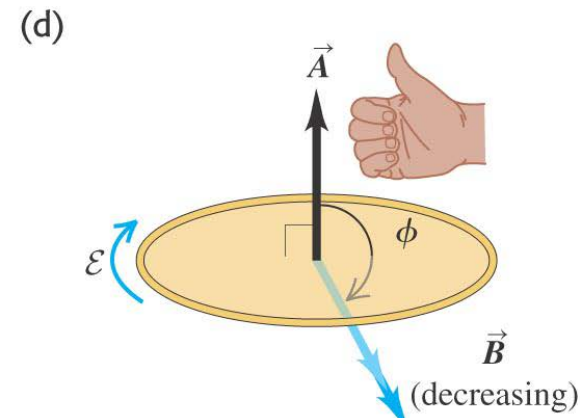
- Flux is positive ($\Phi_B > 0$) ...
- ... and becoming more positive ($d\Phi_B/dt > 0$).
- Induced emf is negative ($\mathcal{E} < 0$).



- 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 ($\mathcal{E} > 0$).

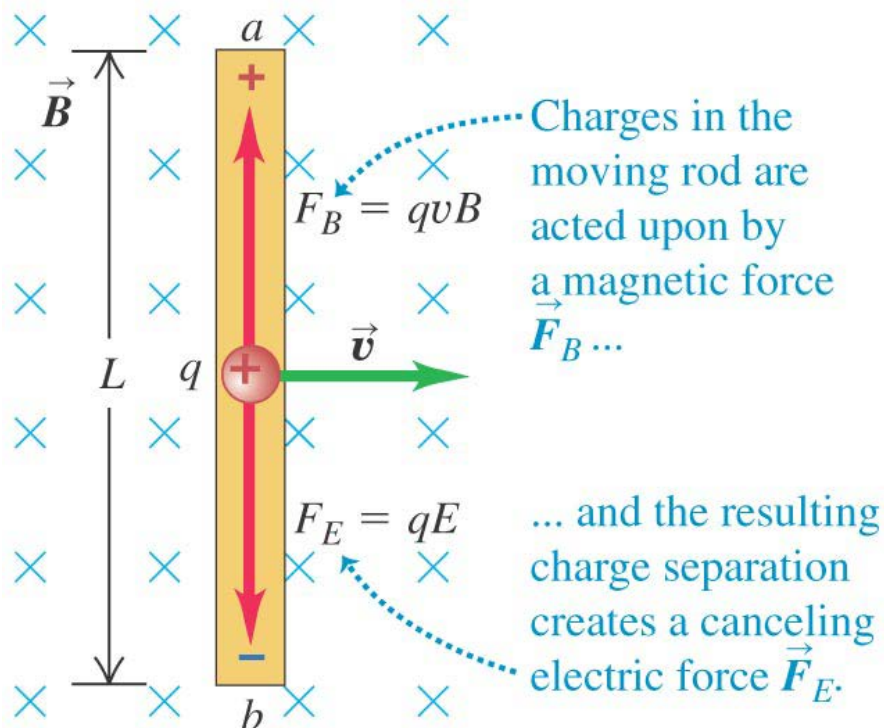


- Flux is negative ($\Phi_B < 0$) ...
- ... and becoming less negative ($d\Phi_B/dt > 0$).
- Induced emf is negative ($\mathcal{E} < 0$).

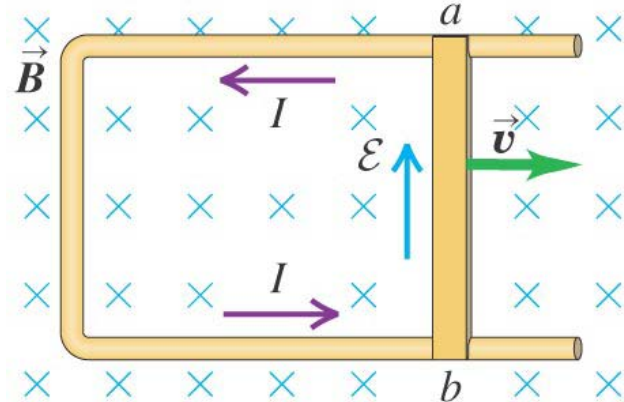
Motional electromotive force

- 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



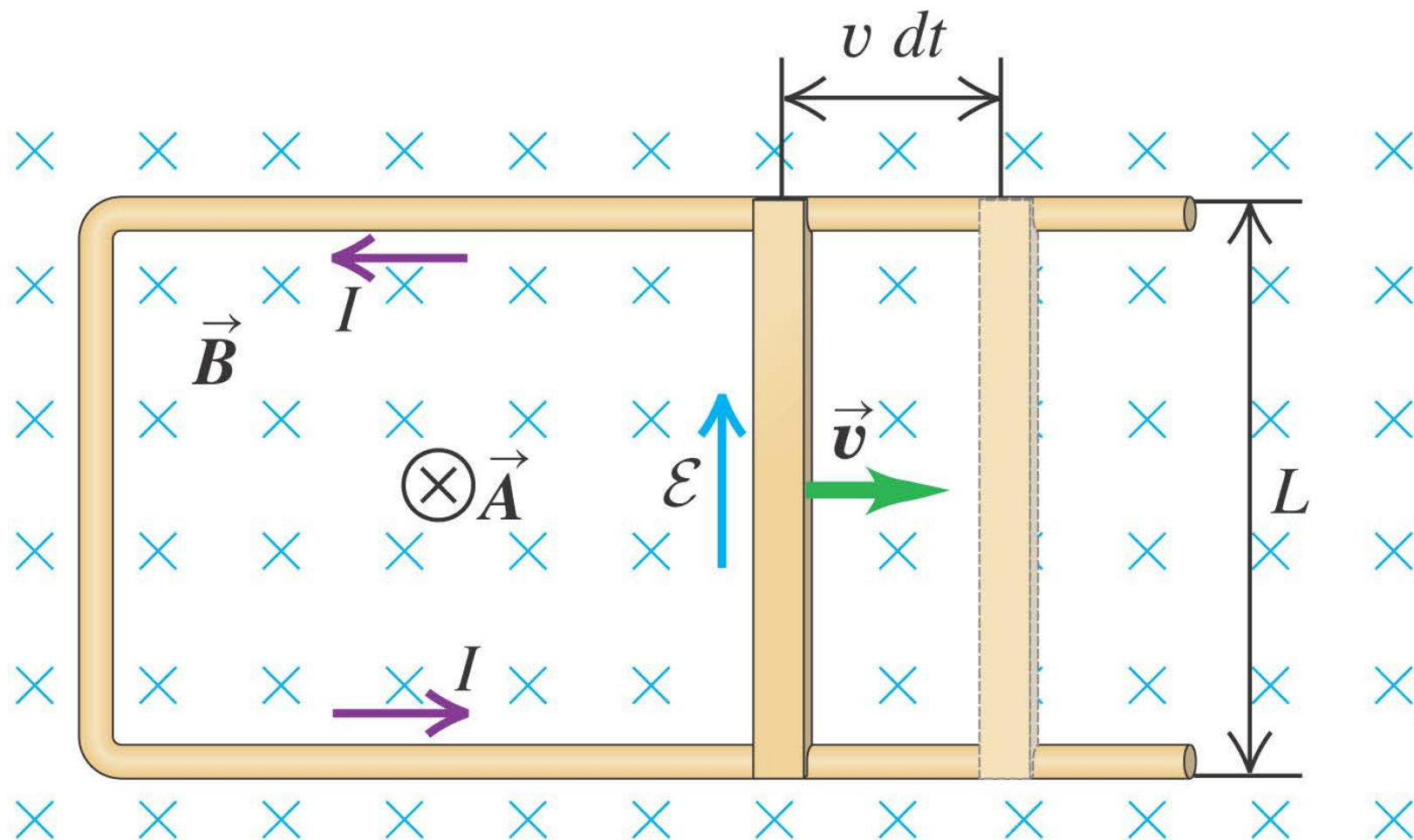
(b) Rod connected to stationary conductor



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

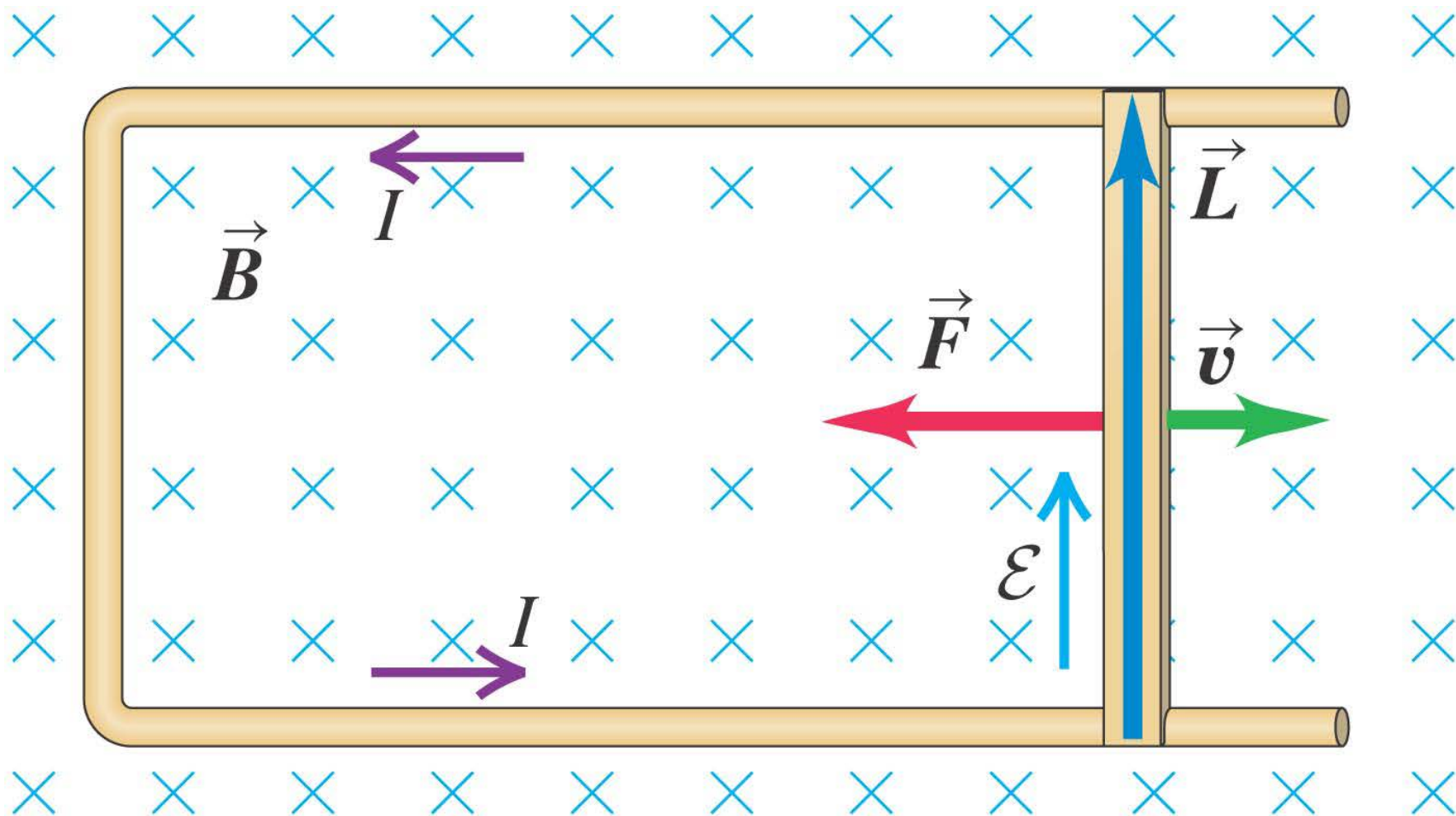
Slidewire generator

- 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.





Maxwell's Equations To Date

$$\oint \vec{E} \cdot d\vec{A} = \frac{Q_{enc}}{\epsilon_o}$$

Gauss' Law

$$\oint \vec{B} \cdot d\vec{A} = 0$$

"No Name Law"

$$\oint \vec{B} \cdot d\vec{\ell} = \mu_o I_{enc}$$

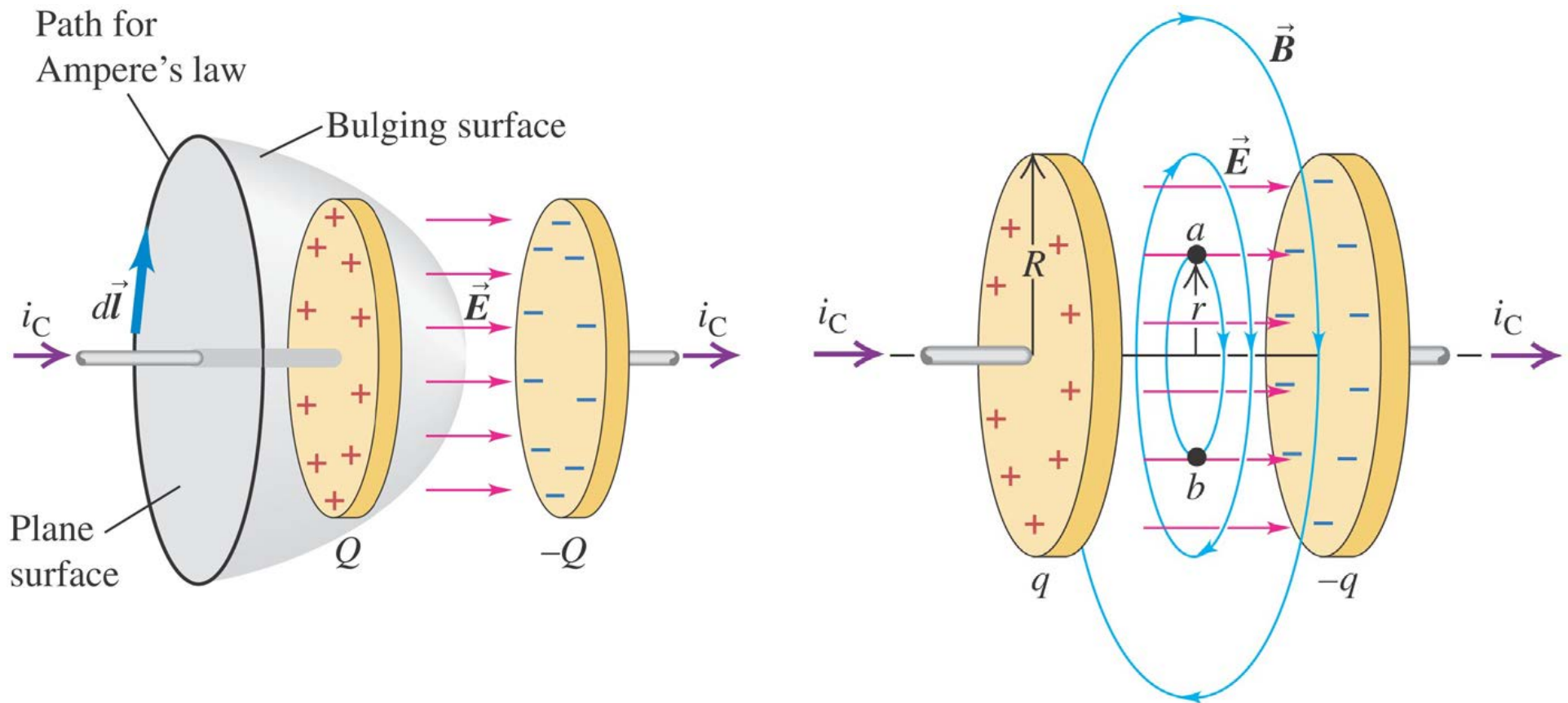
Ampere's Law

$$\oint \vec{E} \cdot d\vec{\ell} = -\frac{\delta}{\delta t} \int \vec{B} \cdot d\vec{A}$$

Faraday's Law

Displacement current

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



Maxwell's Equations To Date

$$\oint \vec{E} \cdot d\vec{A} = \frac{Q_{enc}}{\epsilon_o}$$

Gauss' Law

$$\oint \vec{B} \cdot d\vec{A} = 0$$

"No Name Law"

$$\oint \vec{B} \cdot d\vec{\ell} = \mu_o I_{enc}$$

Ampere's Law

$$\oint \vec{E} \cdot d\vec{\ell} = -\frac{\delta}{\delta t} \int \vec{B} \cdot d\vec{A}$$

Faraday's Law

Maxwell's Equations To Date

$$\oint \vec{E} \cdot d\vec{A} = \frac{Q_{e_enc}}{\epsilon_o}$$

Gauss' Law

$$\oint \vec{B} \cdot d\vec{A} = 0$$

"No Name Law"

$$\oint \vec{B} \cdot d\vec{\ell} = \mu_o I_{e_enc}$$

Ampere's Law

$$\oint \vec{E} \cdot d\vec{\ell} = -\frac{\delta}{\delta t} \int \vec{B} \cdot d\vec{A}$$

Faraday's Law

Maxwell's Equations To Date

$$\oint \vec{E} \cdot d\vec{A} = \frac{Q_{e_enc}}{\epsilon_o}$$

Gauss' Law

$$\oint \vec{B} \cdot d\vec{A} = \frac{Q_{m_enc}}{\mu_o}$$

"No Name Law"

$$\oint \vec{B} \cdot d\vec{\ell} = \mu_o I_{e_enc}$$

Ampere's Law

$$\oint \vec{E} \cdot d\vec{\ell} = -\frac{\delta}{\delta t} \int \vec{B} \cdot d\vec{A}$$

Faraday's Law

Maxwell's Equations To Date

$$\oint \vec{E} \cdot d\vec{A} = \frac{Q_{e_enc}}{\epsilon_o}$$

Gauss' Law

$$\oint \vec{B} \cdot d\vec{A} = \frac{Q_{m_enc}}{\mu_o}$$

"No Name Law"

$$\oint \vec{B} \cdot d\vec{\ell} = \mu_o I_{e_enc}$$

Ampere's Law

$$\oint \vec{E} \cdot d\vec{\ell} = \epsilon_o I_{m_enc} - \frac{\delta}{\delta t} \int \vec{B} \cdot d\vec{A}$$

Faraday's Law

Maxwell's Equations To Date

$$\oint \vec{E} \cdot d\vec{A} = \frac{Q_{e_enc}}{\epsilon_o}$$

Gauss' Law

$$\oint \vec{B} \cdot d\vec{A} = \frac{Q_{m_enc}}{\mu_o}$$

"No Name Law"

$$\oint \vec{B} \cdot d\vec{\ell} = \mu_o I_{e_enc} - \frac{\delta}{\delta t} \int \vec{E} \cdot d\vec{A}$$

Ampere's Law

$$\oint \vec{E} \cdot d\vec{\ell} = \epsilon_o I_{m_enc} - \frac{\delta}{\delta t} \int \vec{B} \cdot d\vec{A}$$

Faraday's Law

Maxwell's Equations To Date

$$\oint \vec{E} \cdot d\vec{A} = \frac{Q_{e_enc}}{\epsilon_o}$$

Gauss' Law

$$\oint \vec{B} \cdot d\vec{A} = \frac{Q_{m_enc}}{\mu_o}$$

"No Name Law"

$$\oint \vec{B} \cdot d\vec{\ell} = \mu_o I_{e_enc} - \epsilon_o \mu_o \frac{\delta}{\delta t} \int \vec{E} \cdot d\vec{A}$$

Ampere's Law

$$\oint \vec{E} \cdot d\vec{\ell} = \epsilon_o I_{m_enc} - \frac{\delta}{\delta t} \int \vec{B} \cdot d\vec{A}$$

Faraday's Law

Maxwell's Equations To Date

$$\oint \vec{E} \cdot d\vec{A} = \frac{Q_{e_enc}}{\epsilon_o}$$

Gauss' Law

$$\oint \vec{B} \cdot d\vec{A} = \frac{Q_{m_enc}}{\mu_o}$$

"No Name Law"

$$\oint \vec{B} \cdot d\vec{\ell} = \mu_o I_{e_enc} - \epsilon_o \mu_o \frac{\delta}{\delta t} \int \vec{E} \cdot d\vec{A}$$

Ampere's Law

$$\oint \vec{E} \cdot d\vec{\ell} = \epsilon_o I_{m_enc} - \frac{\delta}{\delta t} \int \vec{B} \cdot d\vec{A}$$

Faraday's Law

But no magnetic monopoles have been found!
So no magnetic current!

Maxwell's Equations To Date

$$\oint \vec{E} \cdot d\vec{A} = \frac{Q_{e_enc}}{\epsilon_o}$$

Gauss' Law

$$\oint \vec{B} \cdot d\vec{A} = 0$$

"No Name Law"

$$\oint \vec{B} \cdot d\vec{\ell} = \mu_o I_{e_enc} - \epsilon_o \mu_o \frac{\delta}{\delta t} \int \vec{E} \cdot d\vec{A}$$

Ampere's Law
w/ Maxwell's Correction

$$\oint \vec{E} \cdot d\vec{\ell} = -\frac{\delta}{\delta t} \int \vec{B} \cdot d\vec{A}$$

Faraday's Law

But no magnetic monopoles have been found!
So no magnetic current!