Class 20: Outline

Hour 1:

Faraday's Law

Hour 2:

Faraday's Law: Applications

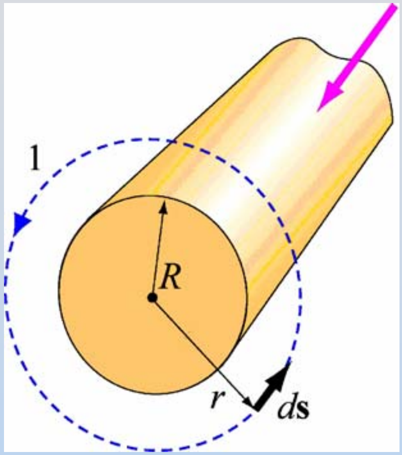
Previously:
Force on Magnetic Dipole

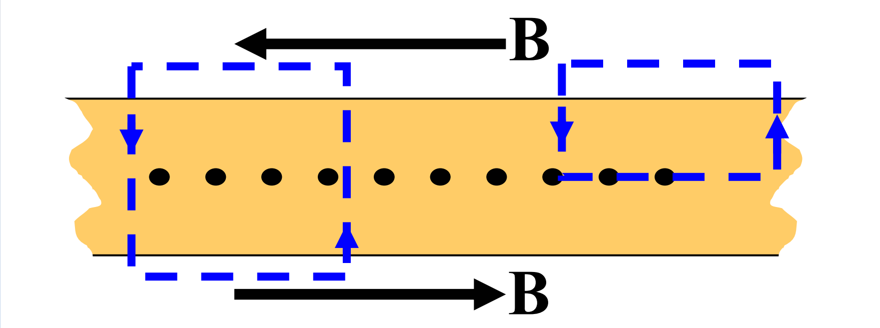
PRS Question:
Force on Magnetic Dipole

Last Time:
Ampere’s Law

Ampere's Law: $\oint \vec{\mathbf{B}} \cdot d\vec{\mathbf{s}} = \mu_0 I_{enc}$

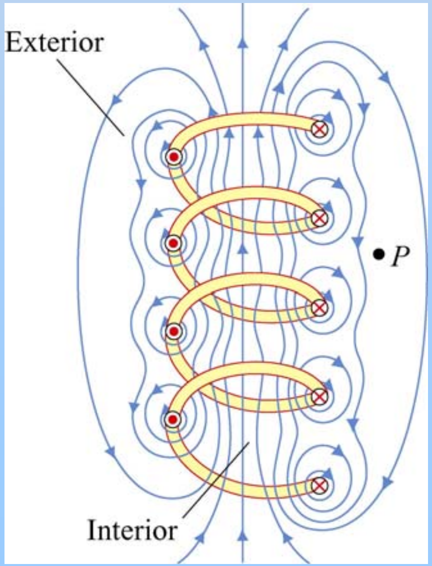
Long Circular Symmetry

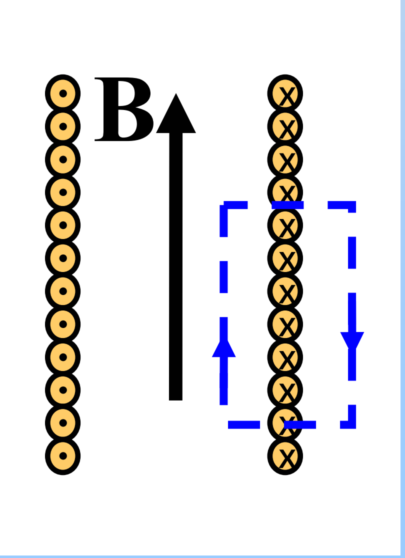


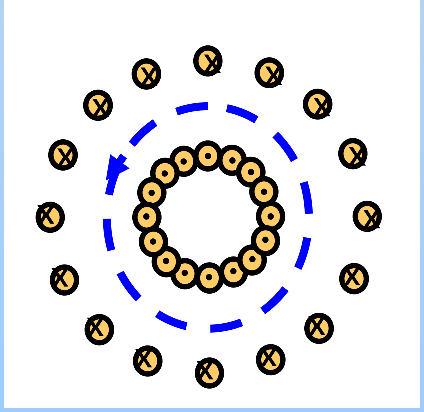


(Infinite) Current Sheet

Solenoid = 2 Current Sheets

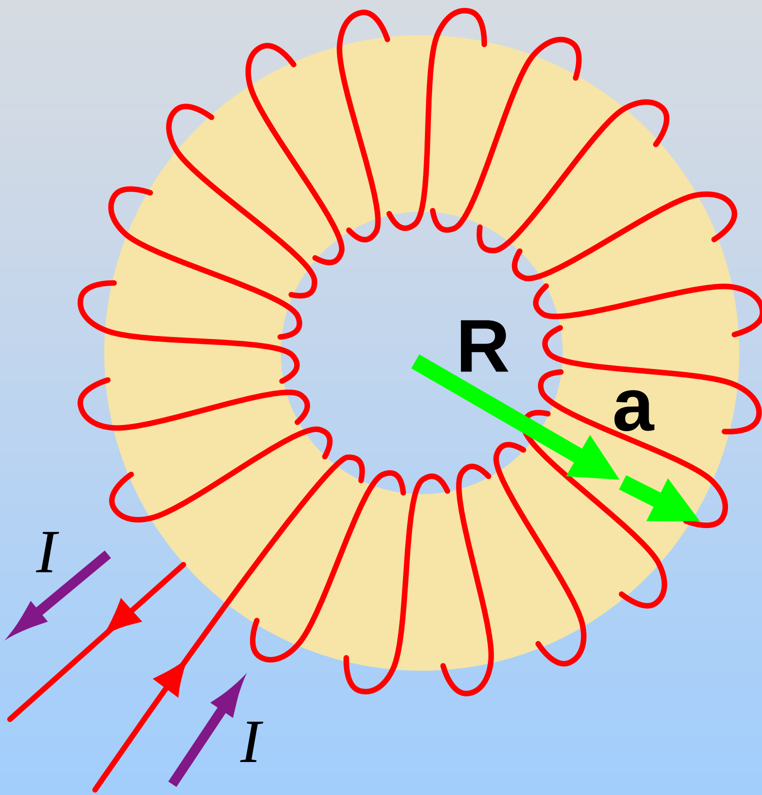






Torus

Group Problem: Torus



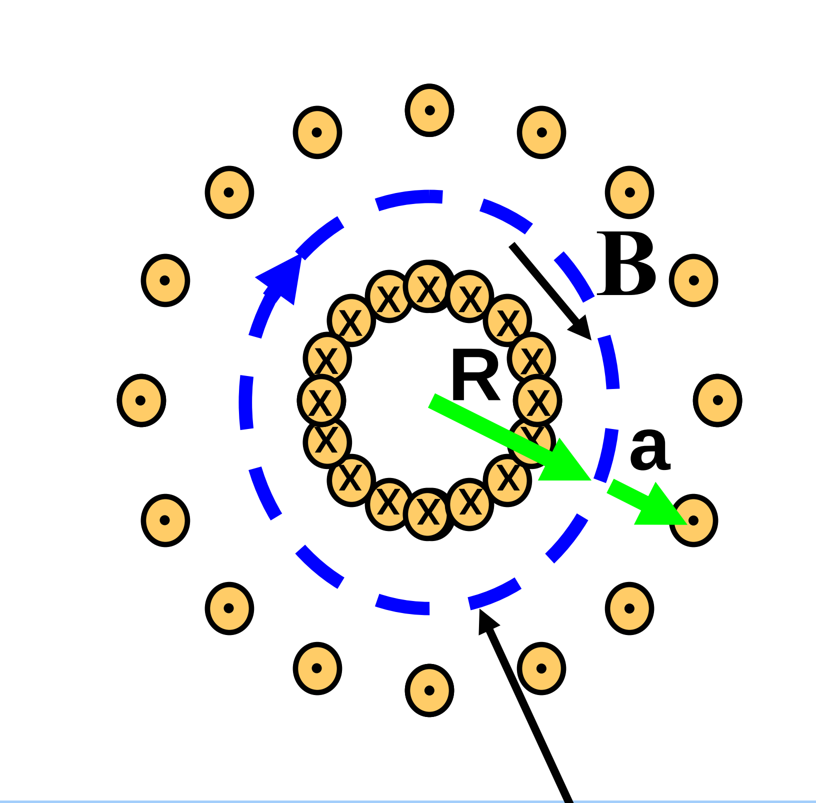
A torus (a solenoid of radius a and *n* turns/meter whose ends are bent around to make a donut of radius *R*) carries a uniform current I.

Find B on what was the central axis of the solenoid

Ampere's Law: Torus

Picture:

Solenoid (slinky) curved around & joined end to end



Amperian Loop:

B is Constant & Parallel

I Penetrates

This Time: Faraday's Law

Fourth (Final) Maxwell's Equation

(but we still have to go back and add another term to Ampere's Law!)

Underpinning of Much Technology

Demonstration: Falling Magnet

Magnet Falling Through a Ring

http://ocw.mit.edu/ans7870/8/8.02T/f04/visualizations/faraday/07-FallingMagnetResistive/07-FallMAgRes_f54_320.html

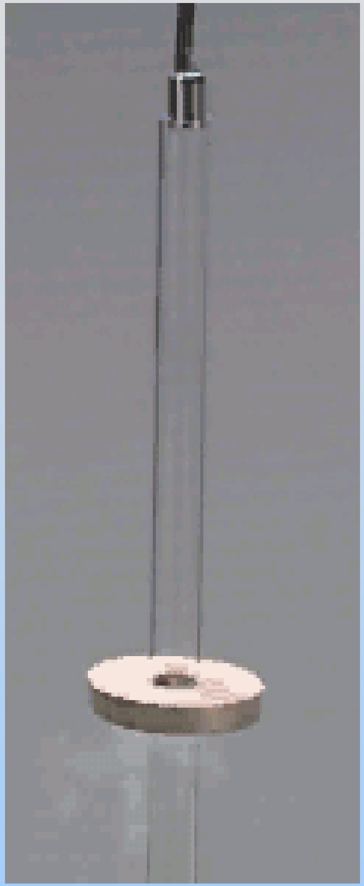
Falling magnet slows as it approaches a copper ring which has been immersed in liquid nitrogen.

Demonstration: Jumping Rings

Jumping Ring

An aluminum ring jumps into the air when the solenoid beneath it is energized

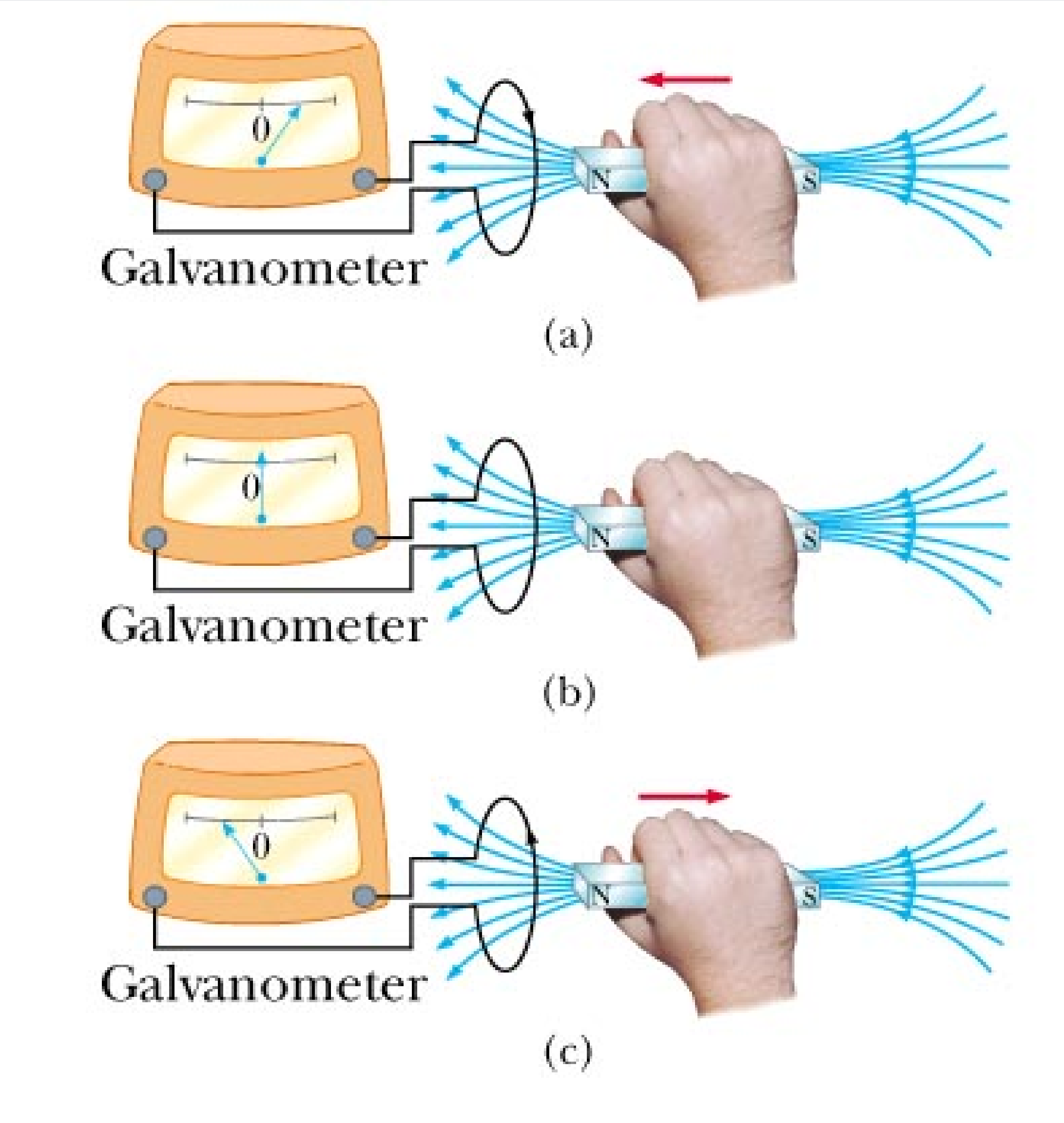
What is Going On?



It looks as though the conducting loops have current in them (they behave like magnetic dipoles) even though they aren't hooked up

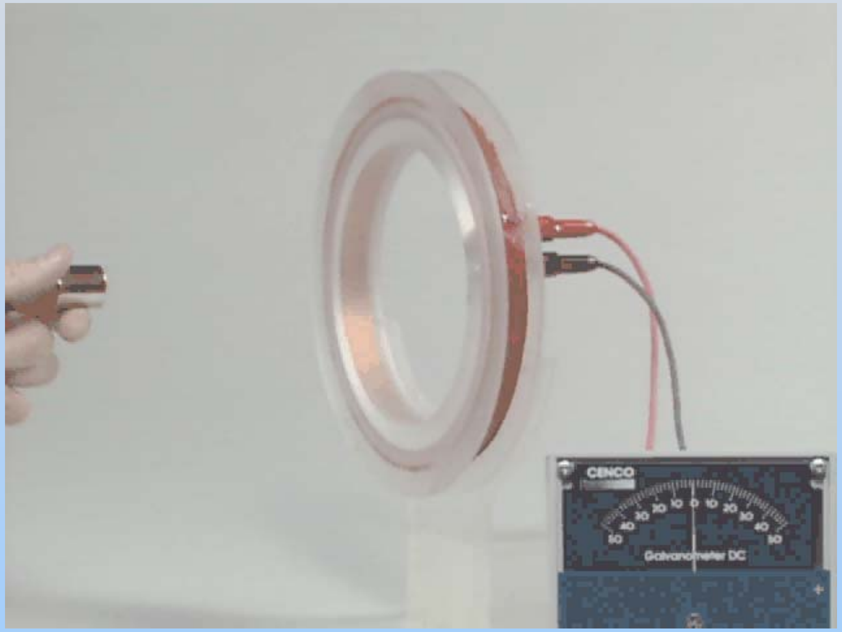
Demonstration: Induction

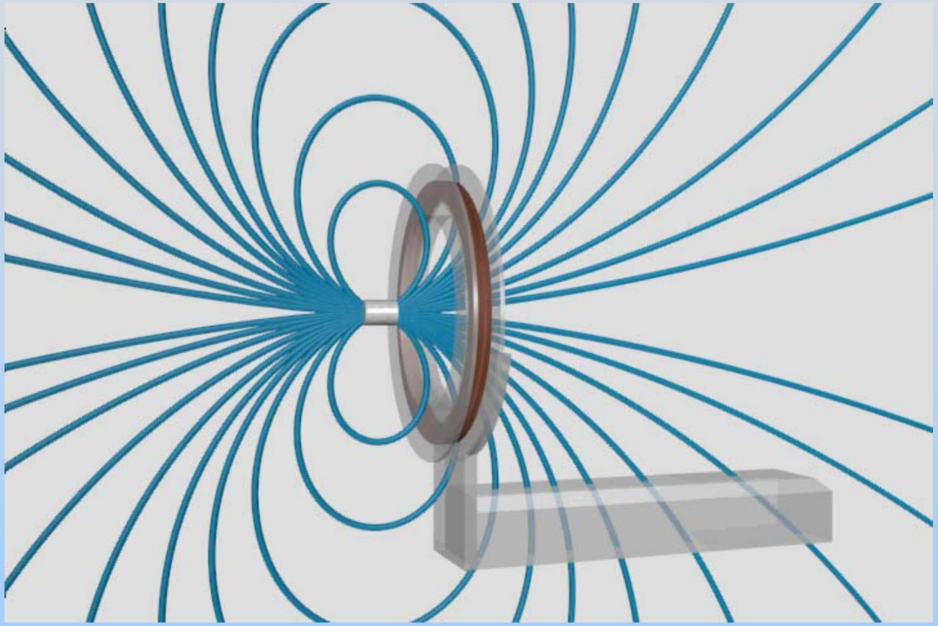
Electromagnetic Induction



Movie and Visualization: Induction

http://ocw.mit.edu/ans7870/8/8.02T/f04/visualizations/faraday/15-inductance/15-1_wmv320.html





Lenz's Law says that the flux tries to remain the same, so the field lines get "hung up" at the coil.

Faraday's Law of Induction

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

A changing magnetic flux
induces an EMF

What is EMF?

$$\mathcal{E} = \int \vec{\mathbf{E}} \cdot d\vec{\mathbf{s}}$$

Looks like potential. It's a "driving force" for current

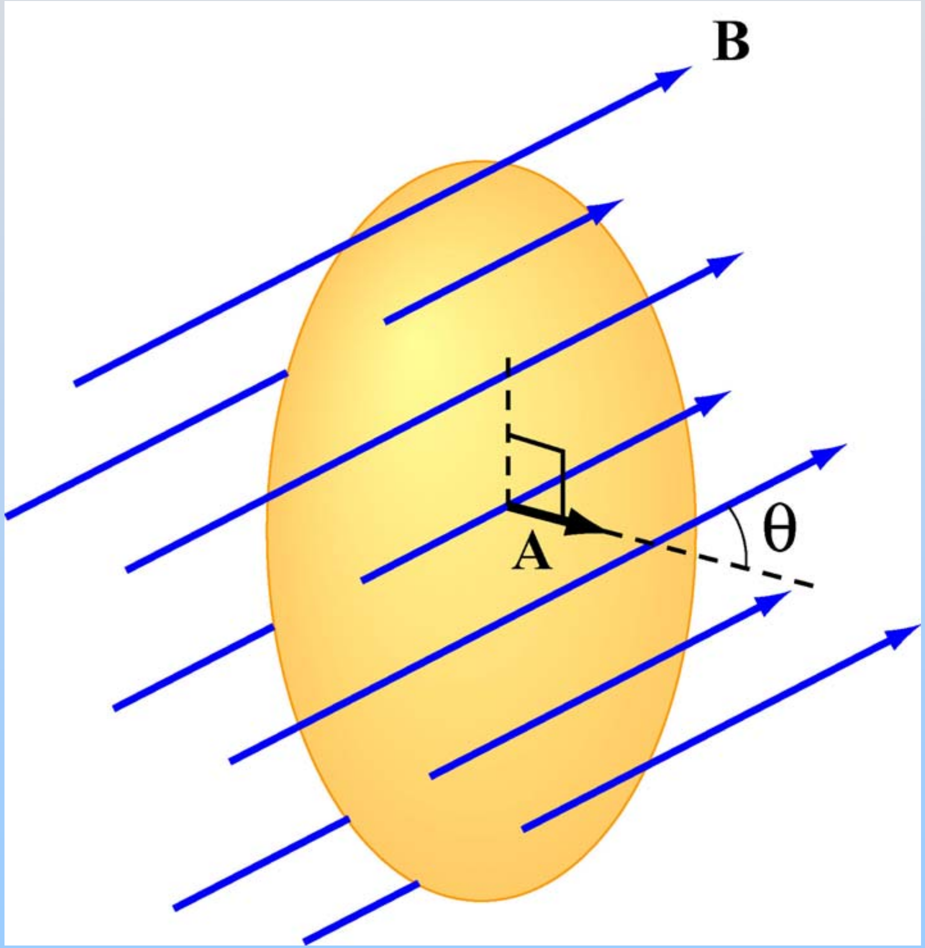
Faraday's Law of Induction

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

A changing magnetic flux
induces an EMF

Magnetic Flux Thru Wire Loop

Analogous to Electric Flux (Gauss' Law)



(1) Uniform **B**

$$\Phi_B = B_\perp A = BA\cos\theta = \vec{\mathbf{B}} \cdot \vec{\mathbf{A}}$$

(2) Non-Uniform **B**

$$\Phi_B = \int_S \vec{\mathbf{B}} \cdot d\vec{\mathbf{A}}$$

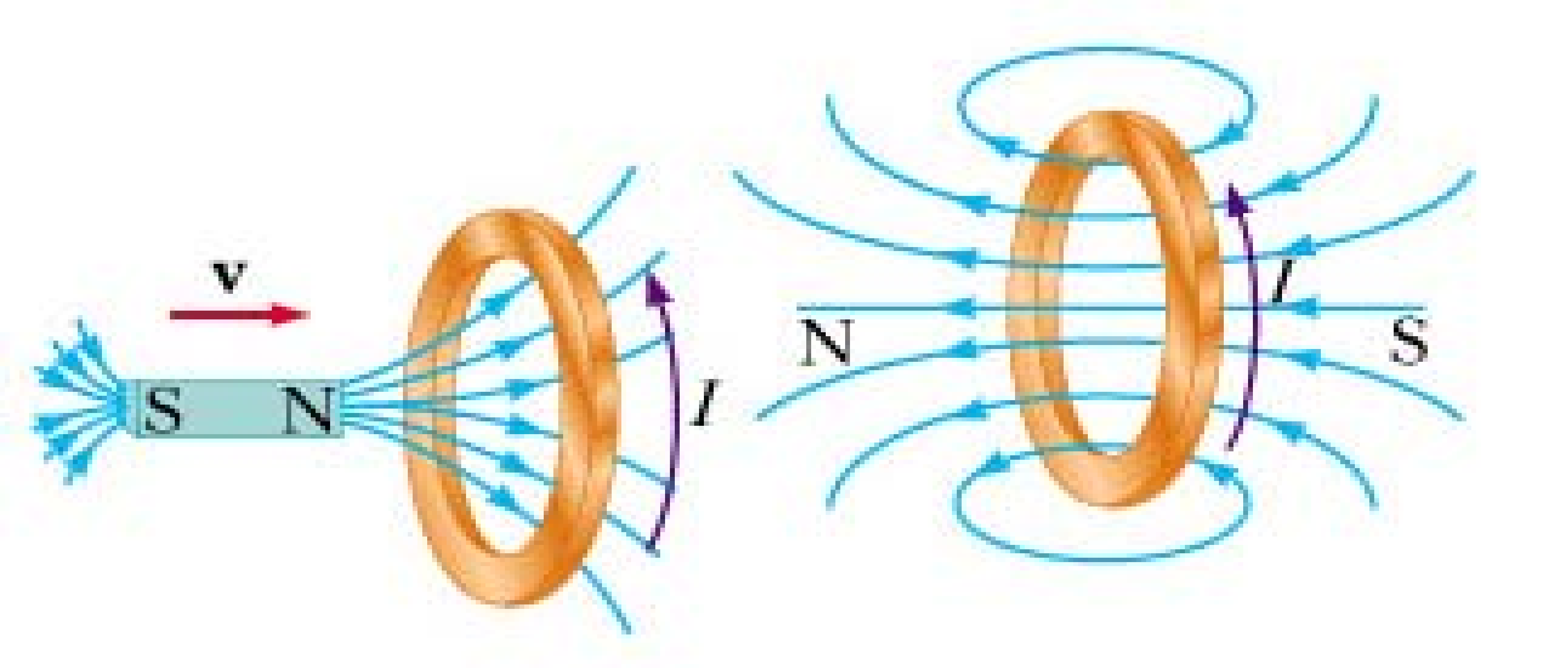
Faraday's Law of Induction

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

A changing magnetic flux
induces an EMF

Minus Sign? Lenz's Law

Induced EMF is in direction that ***opposes*** the change in flux that caused it



Three PRS Questions: Lenz' Law

Faraday's Law of Induction

$$\boxed{\varepsilon = -N\frac{d\Phi_B}{dt}}$$

A changing magnetic flux
induces an EMF

Ways to Induce EMF

$$\mathcal{E} = -N\frac{d}{dt}\left(BA\cos\theta\right)$$

Quantities which can vary with time:

- Magnitude of B
- Area A enclosed by the loop
- Angle θ between B and loop normal

Ways to Induce EMF

$$\mathcal{E} = -N \frac{d}{dt}\left(BA\cos\theta \right)$$

Quantities which can vary with time:

- **Magnitude of B**
- Area A enclosed by the loop
- Angle θ between B and loop normal

Group Discussion: Magnet Falling Through a Ring

Falling magnet slows as it approaches a copper ring which has been immersed in liquid nitrogen.

PRS Question:
Force on Loop Below Magnet

Ways to Induce EMF

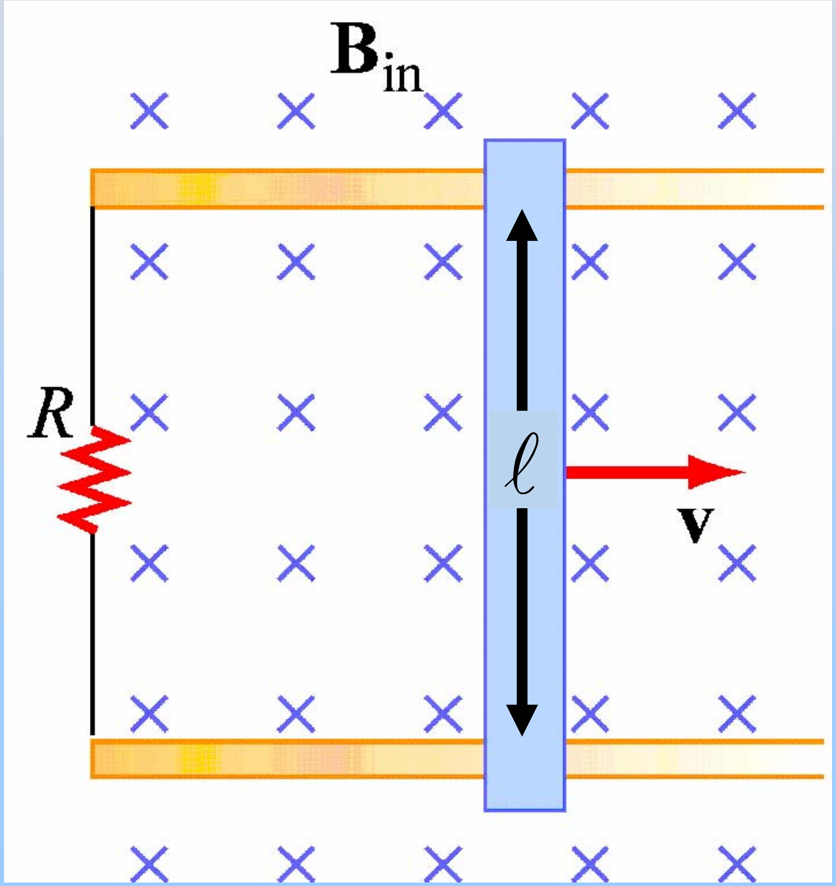
$$\mathcal{E} = -N\frac{d}{dt}\left(BA\cos\theta\right)$$

Quantities which can vary with time:

- Magnitude of B **e.g. Falling Magnet**
- **Area A enclosed by the loop**
- Angle θ between B and loop normal

Group Problem: Changing Area

Conducting rod pulled along two conducting rails in a uniform magnetic field B at constant velocity v



1. Direction of induced current?
2. Direction of resultant force?
3. Magnitude of EMF?
4. Magnitude of current?
5. Power externally supplied to move at constant v?

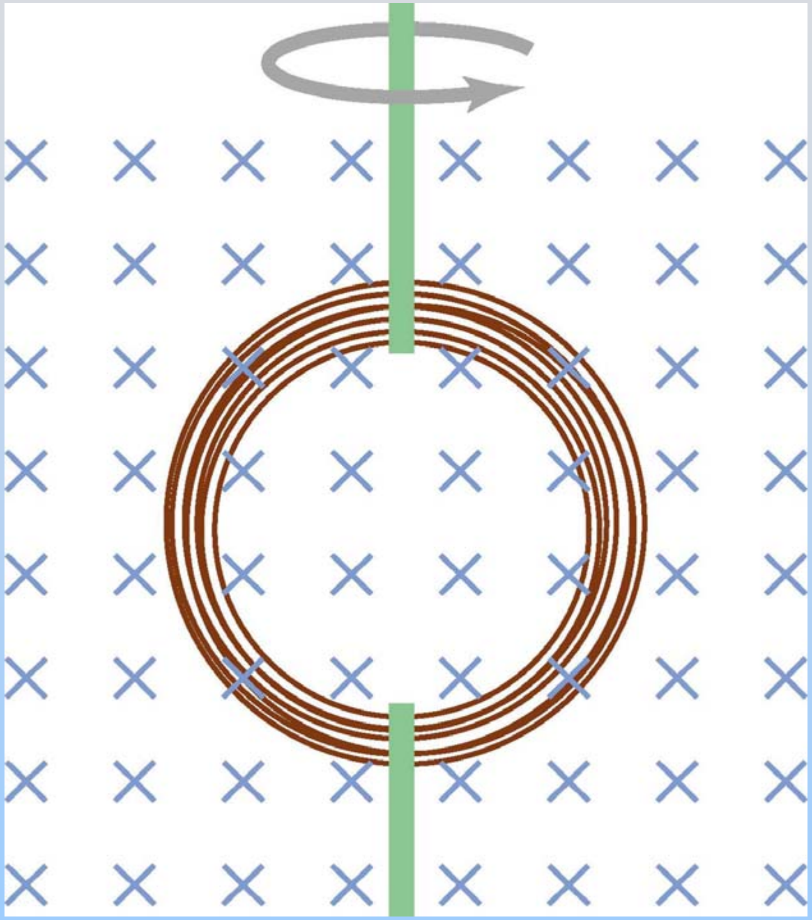
Ways to Induce EMF

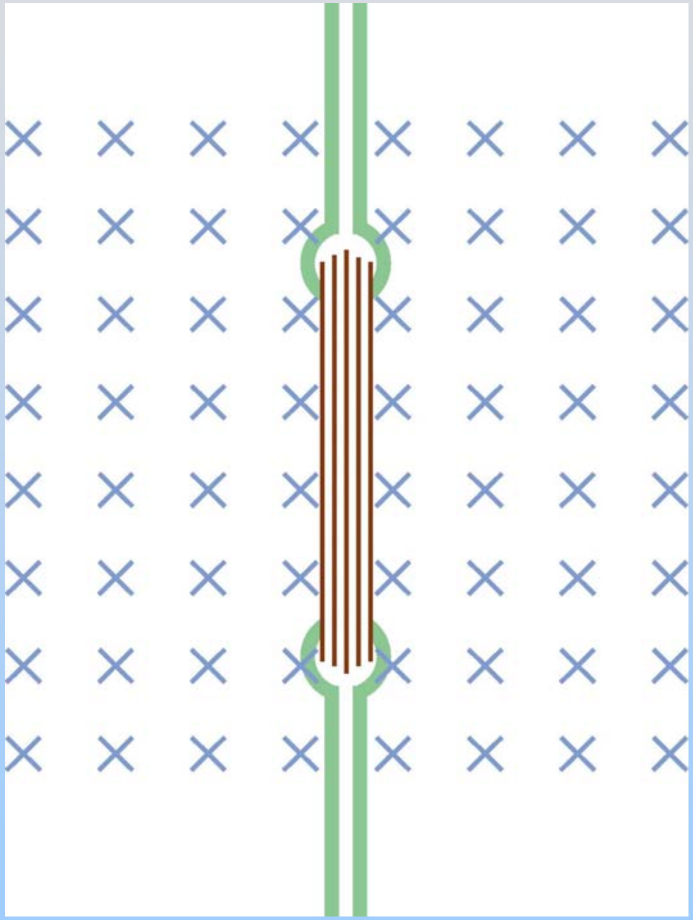
$$\mathcal{E} = -N\frac{d}{dt}\left(BA\cos\theta\right)$$

Quantities which can vary with time:

- Magnitude of B **e.g. Moving Coil & Dipole**
- Area A enclosed **e.g. Sliding bar**
- **Angle θ between B and loop normal**

Changing Angle

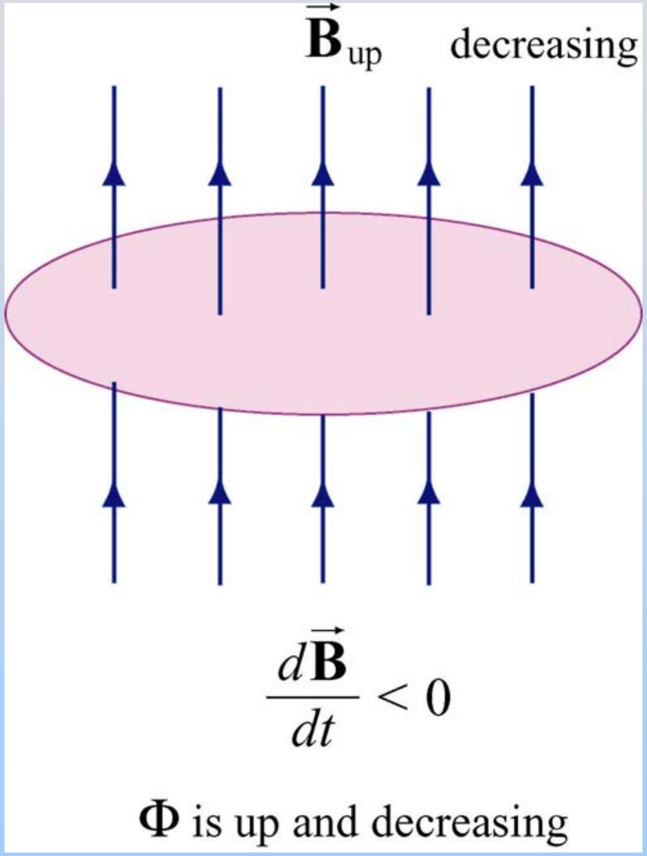


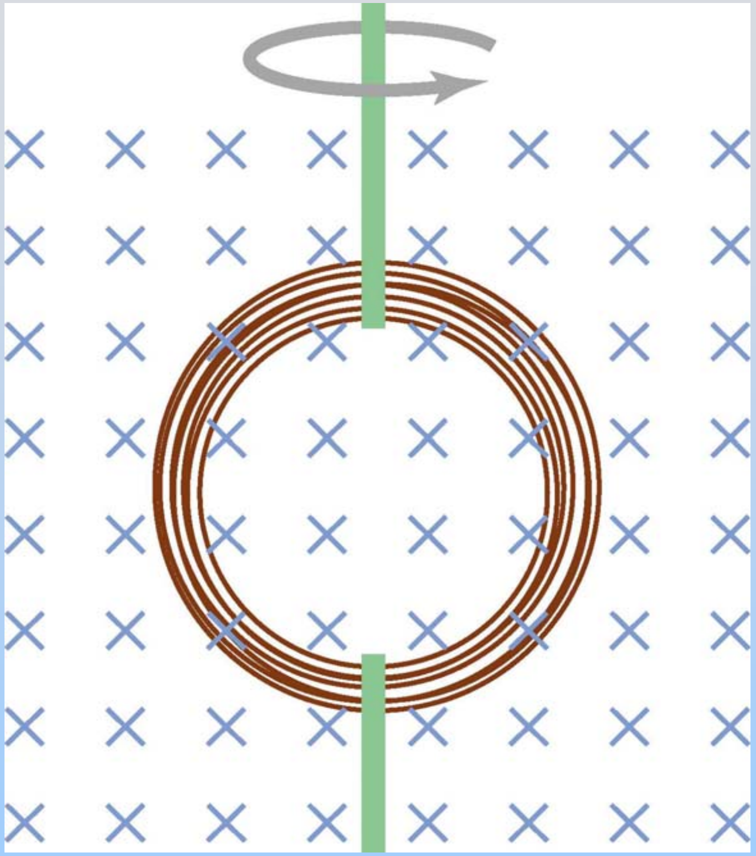


$$\Phi_B = \vec{\mathbf{B}} \cdot \vec{\mathbf{A}} = BA$$

$$\Phi_B = \vec{\mathbf{B}} \cdot \vec{\mathbf{A}} = 0$$

Applets that show these 3 cases





http://ocw.mit.edu/ans7870/8/8.02T/f04/visualizations/faraday/13-faradayapp02/13-faradayapp02_320.html

Faraday's Law
The last of the Maxwell's Equations (Kind of, still need one more term in Ampere's Law)

Maxwell's Equations

Creating Electric Fields

$$\oiint_S \vec{\mathbf{E}} \cdot d\vec{\mathbf{A}} = \frac{Q_{in}}{\varepsilon_0}$$ (Gauss's Law)

$$\oint_C \vec{\mathbf{E}} \cdot d\,\vec{\mathbf{s}} = -\frac{d\Phi_B}{dt}$$ (Faraday's Law)

Creating Magnetic Fields

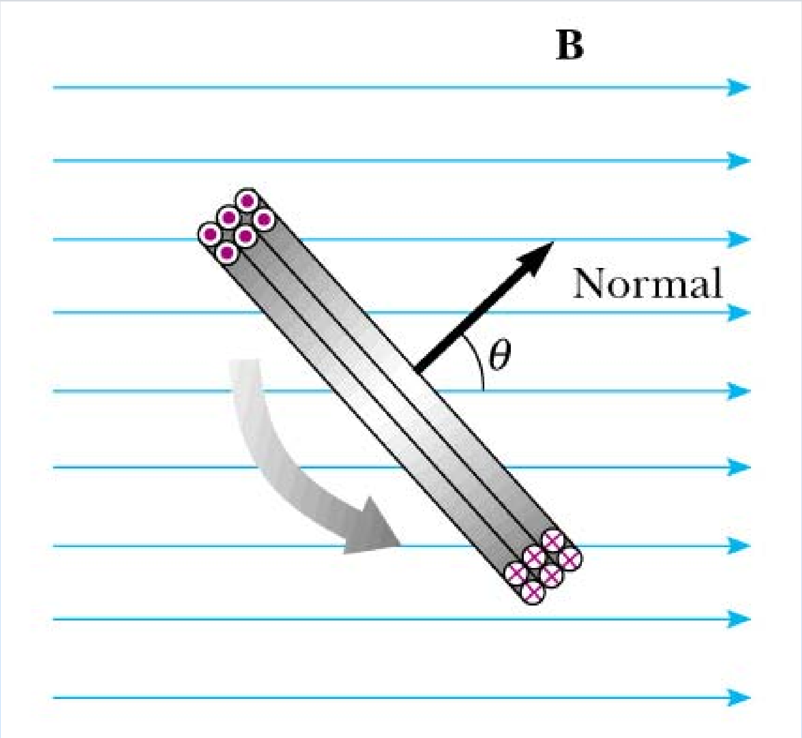
$$\oiint_S \vec{\mathbf{B}} \cdot d\vec{\mathbf{A}} = 0$$ (Magnetic Gauss's Law)

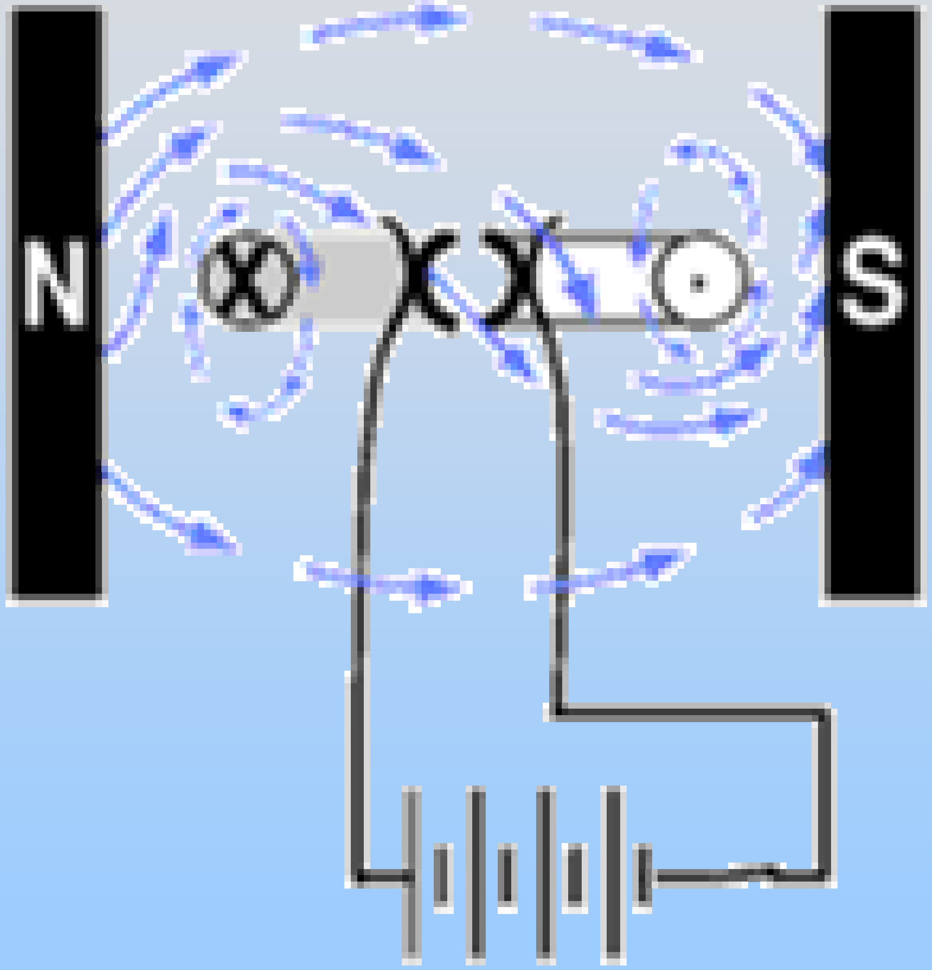
$$\oint_C \vec{\mathbf{B}} \cdot d\,\vec{\mathbf{s}} = \mu_0 I_{enc}$$ (Ampere's Law)

Technology

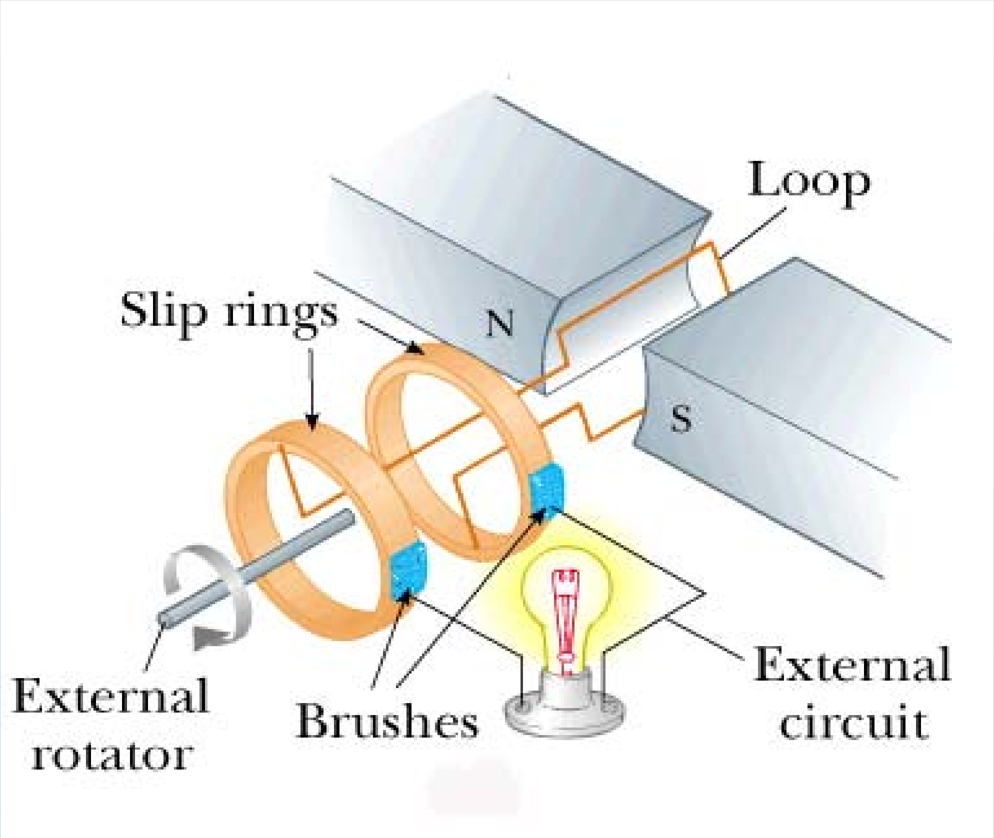
Many Applications of Faraday's Law

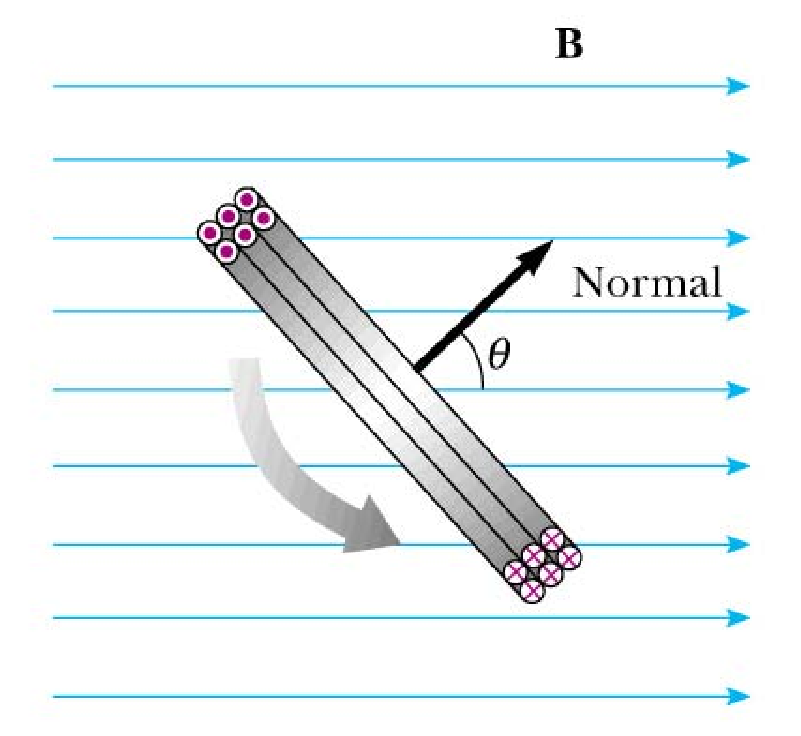
DC Motor (magnetostatics)





Motors & Generators





$$\Phi_B = BA\cos\theta = BA\cos\omega t$$

$$\varepsilon = -N\frac{d\Phi_B}{dt} = -NAB\frac{d}{dt}(\cos\omega t) = NAB\omega\sin\omega t$$

Speakers & Microphones (magnetostatics)

See Diagram:

http://electronics.howstuffworks.com/speaker3.htm

Metal Detector

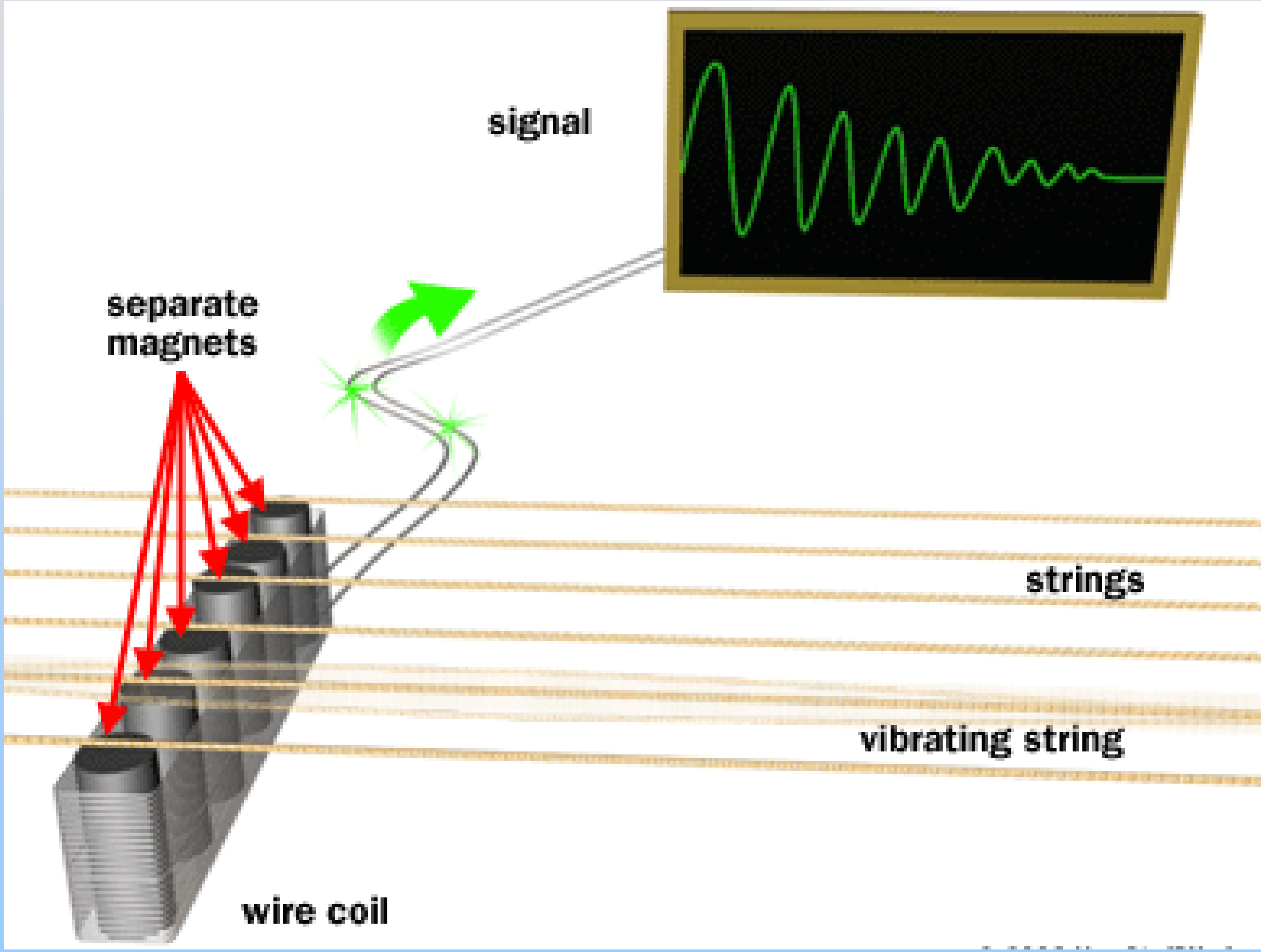
See Animation of how VLF metal detectors work:

http://home.howstuffworks.com/metal-detector2.htm

Induction Stovetops

Ground Fault Interrupters (GFI)

Electric Guitar



Demonstration: Electric Guitar