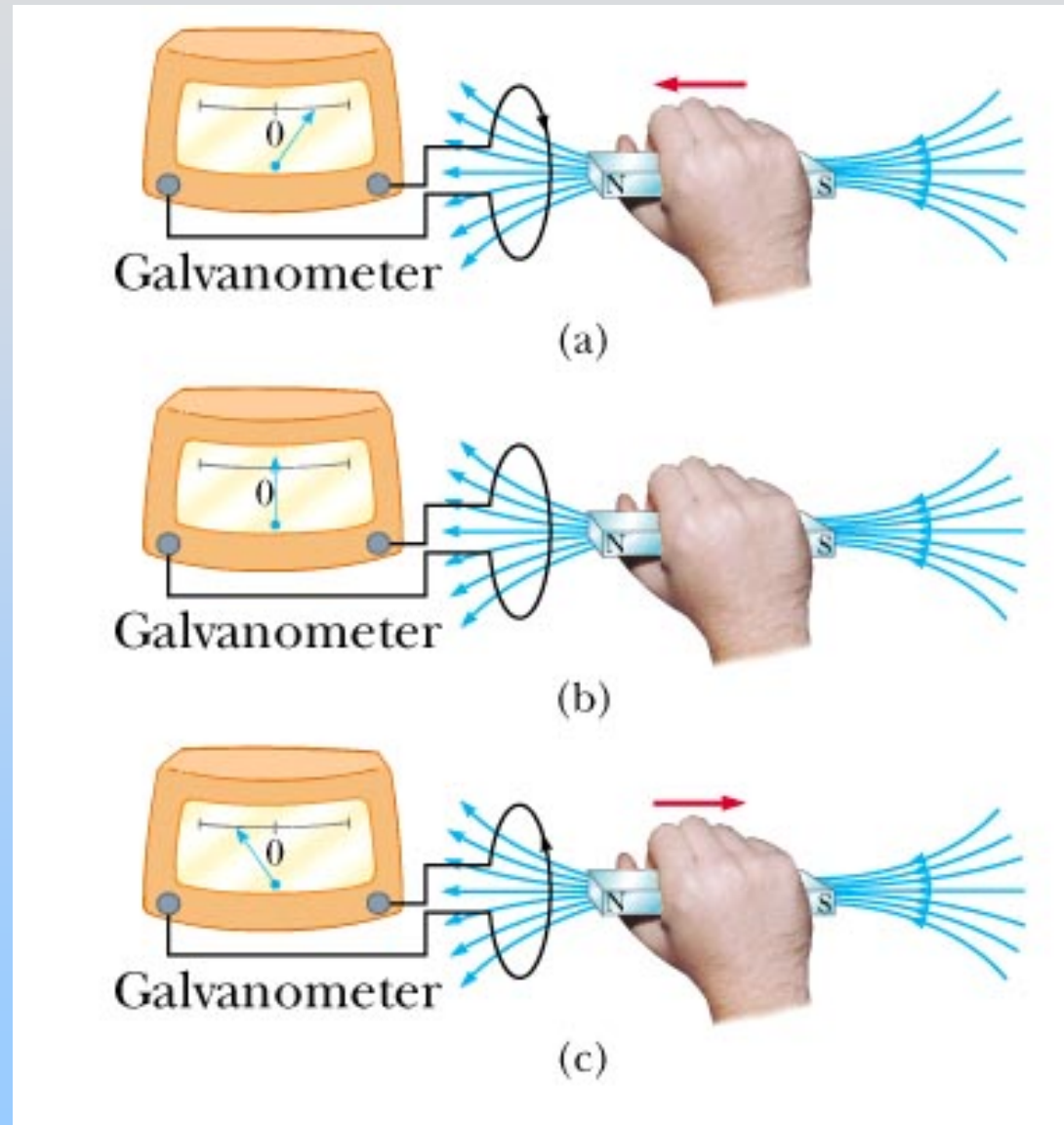


Faraday's Law

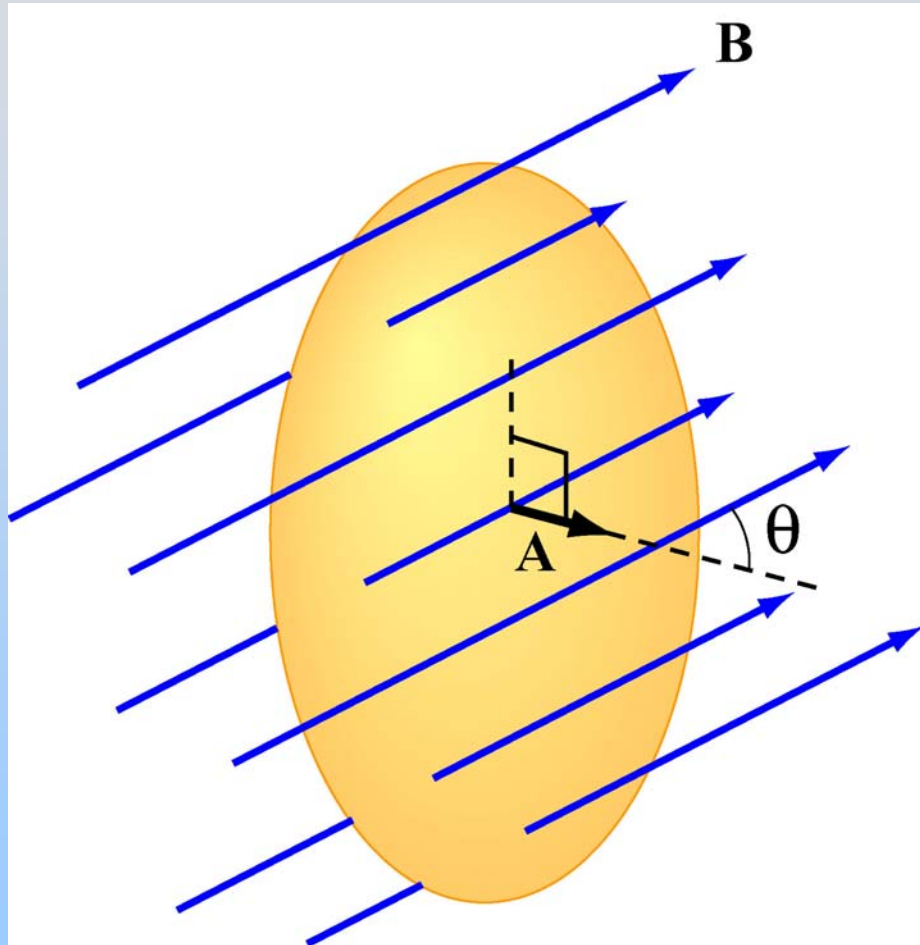
Induction Applet and Demonstration

Electromagnetic Induction



Magnetic Flux Thru Wire Loop

Analogous to Electric Flux (Gauss' Law)



(1) Uniform \vec{B}

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

(2) Non-Uniform \vec{B}

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

What is EMF?

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

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

Faraday's Law of Induction

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

Changing magnetic flux *induces* an EMF

Lenz: Induction ***opposes*** change

PRS Question: Faraday's Law

Ways to Induce EMF

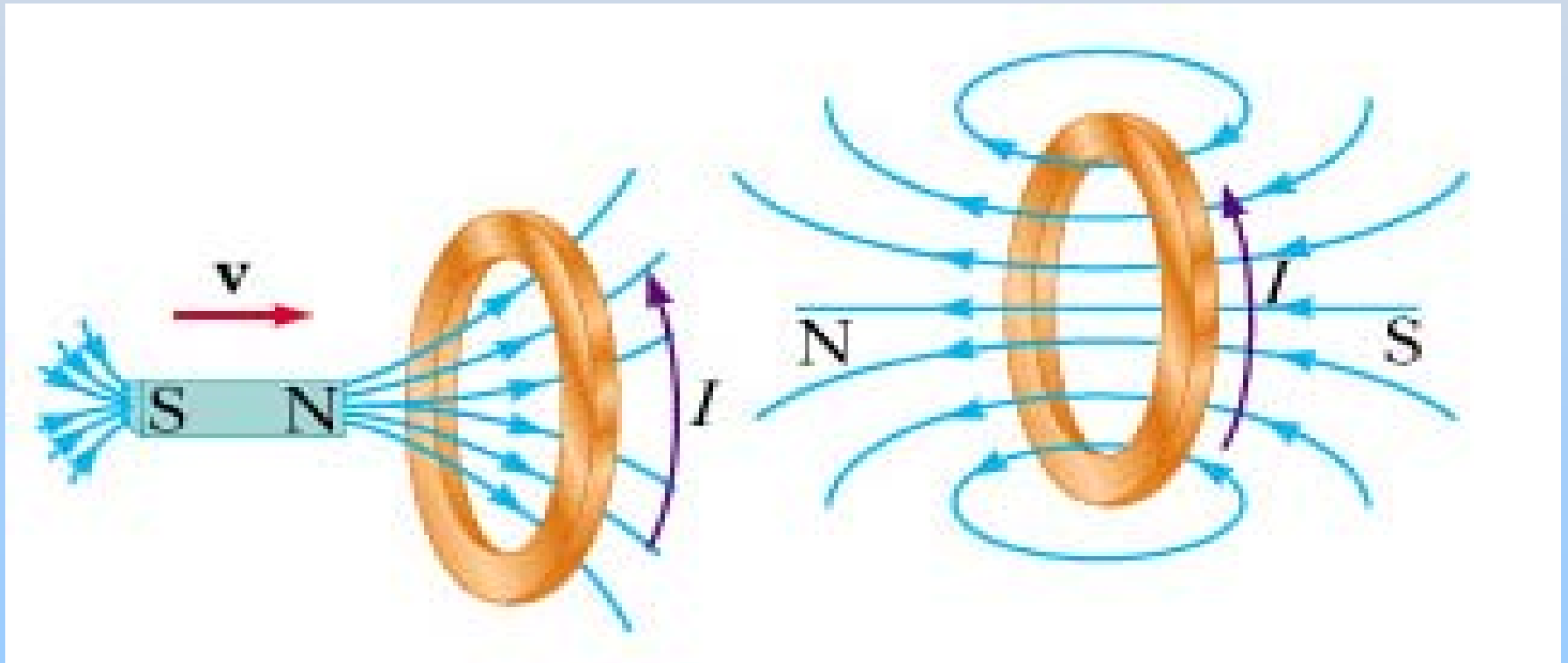
$$\mathcal{E} = -\frac{d}{dt} (BA \cos \theta)$$

Quantities which can vary with time:

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

Minus Sign? Lenz's Law

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



PRS Questions: Lenz' Law

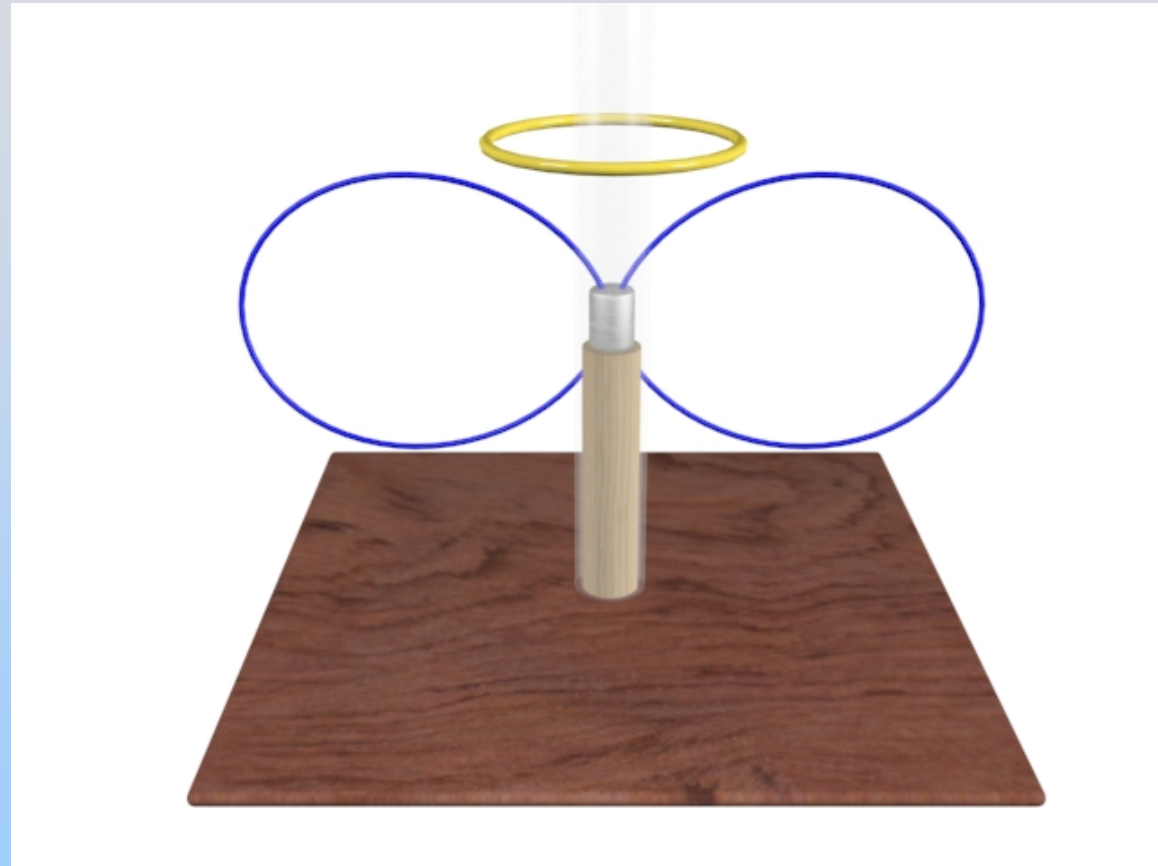
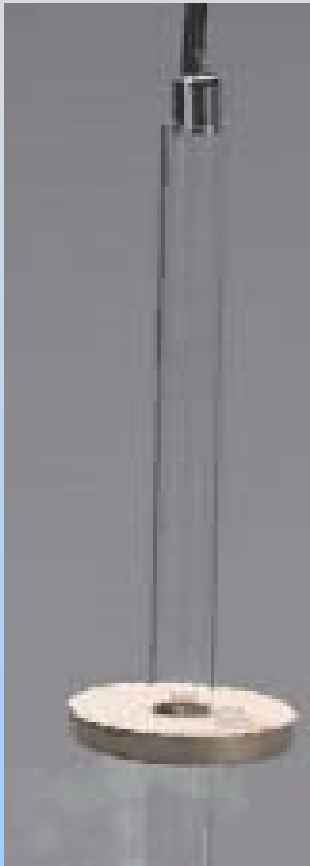
Demonstration: Falling Magnet

Magnet Falling Through a Ring



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

Example: Magnitude of B Magnet Falling Through a Ring



Falling magnet approaches a copper ring
or Copper Ring approaches Magnet

Ways to Induce EMF

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

Quantity which can vary with time:

- **Loop moves through a non-uniform magnetic field**

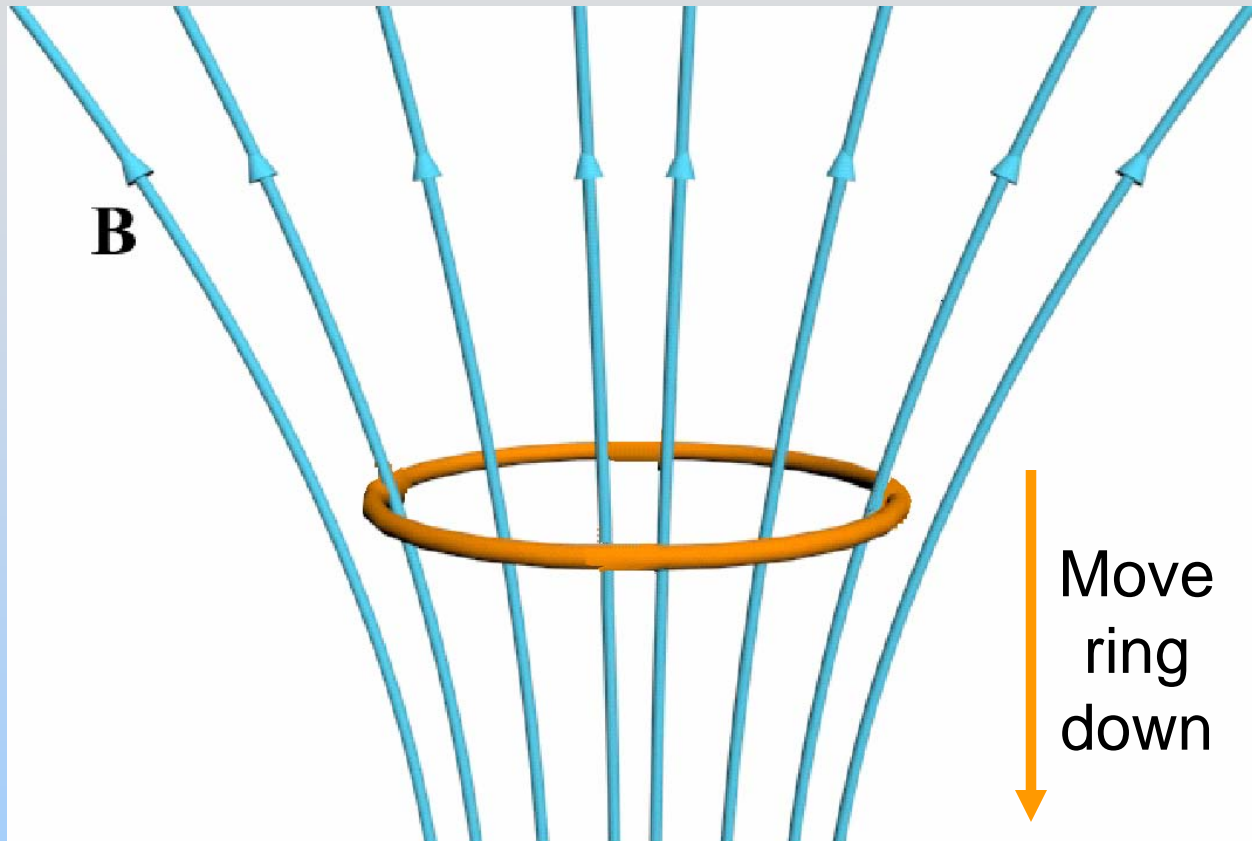
Relativity Principle

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

Quantity which can vary with time:

- **Loop moves through a non-uniform magnetic field is equivalent to a stationary loop in a time changing magnetic field**

Moving Towards Dipole



As ring approaches, what happens to flux?

Flux up increases

PRS Question: Force on Loop Below Magnet

Ways to Induce EMF

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

Quantity which can vary with time:

- **Magnitude of B**

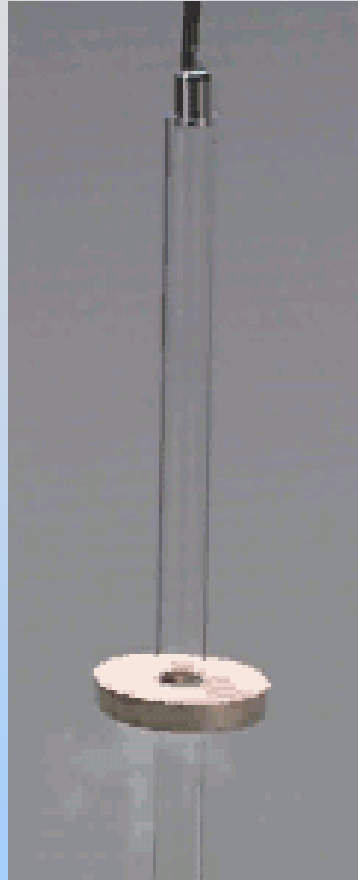
Demonstration: Jumping Rings

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

Ways to Induce EMF

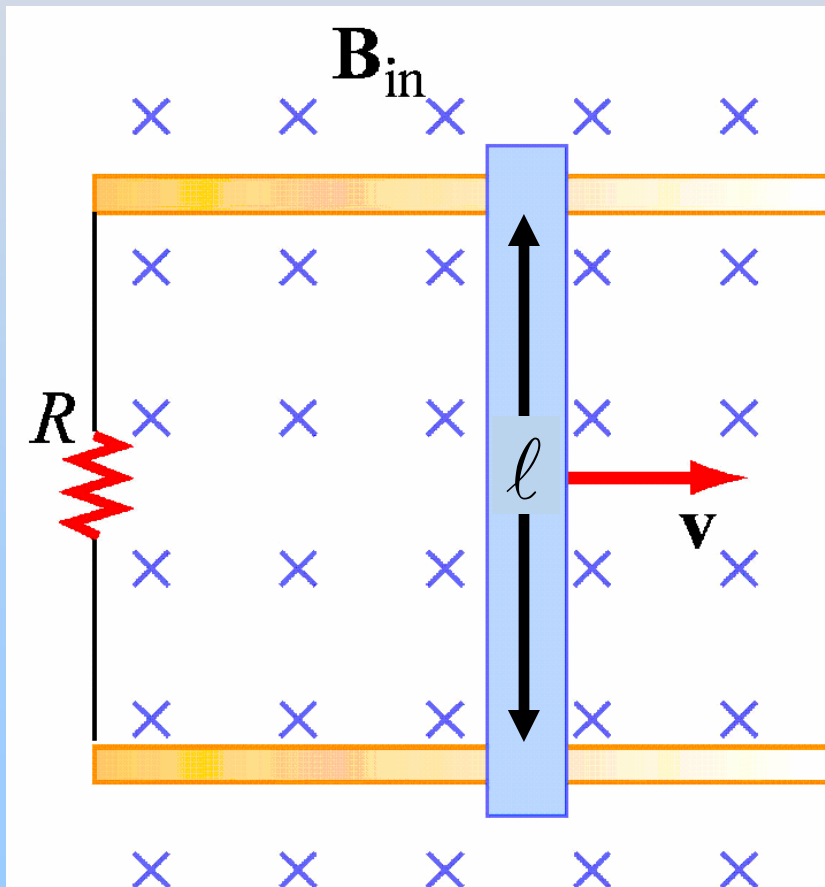
$$\mathcal{E} = -\frac{d}{dt} (BA \cos \theta)$$

Quantity which can vary with time:

- **Area A enclosed by the loop**

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 ?

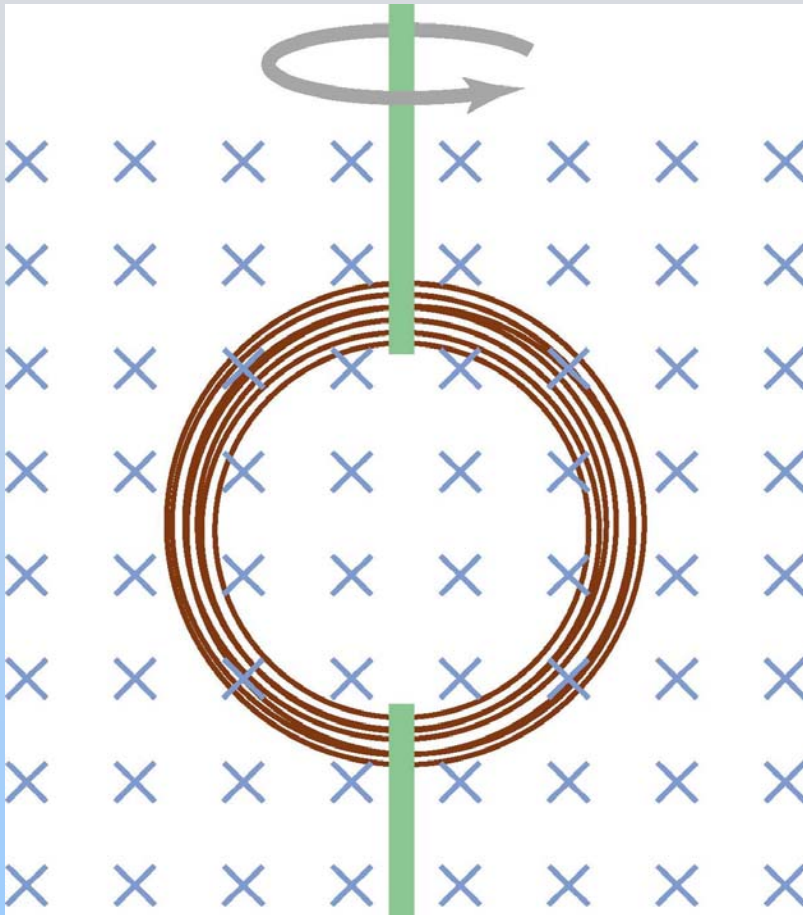
Ways to Induce EMF

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

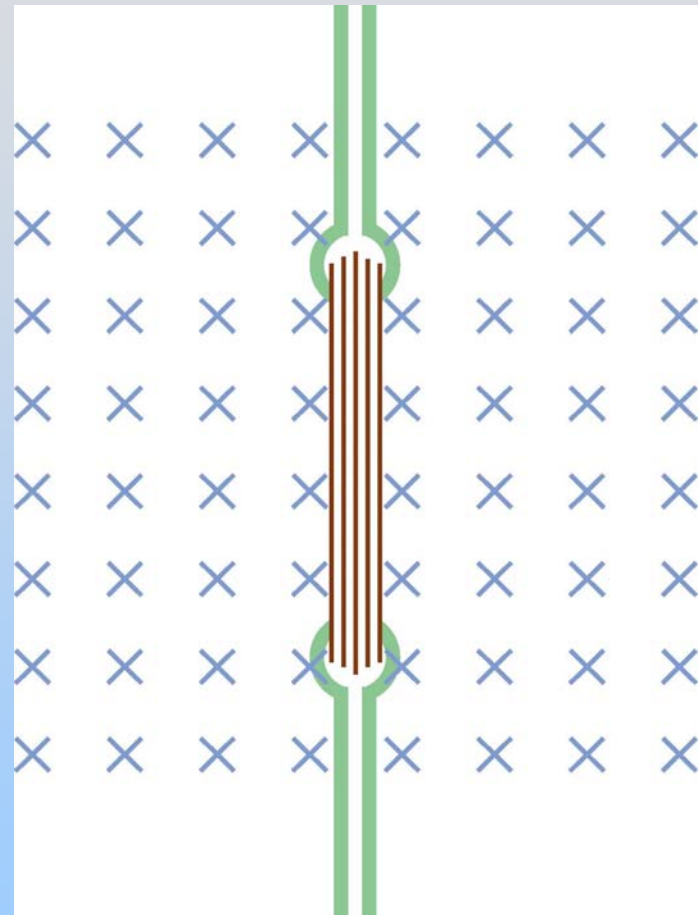
Quantities which can vary with time:

- **Angle θ between \mathbf{B} and loop normal**

Changing Angle



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



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

Maxwell's Equations

Creating Electric Fields

$$\oiint_S \vec{\mathbf{E}} \cdot d\vec{\mathbf{A}} = \frac{Q_{in}}{\epsilon_0} \quad (\text{Gauss's Law})$$

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

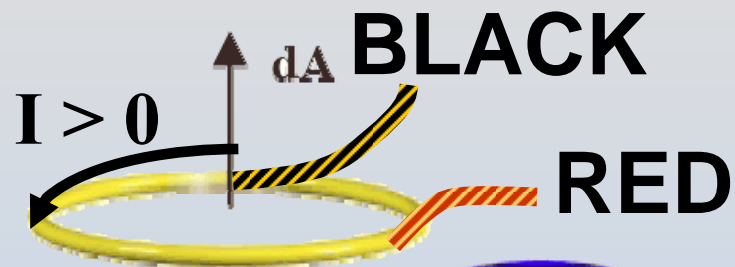
Creating Magnetic Fields

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

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

Experiment 5: Faraday's Law of Induction

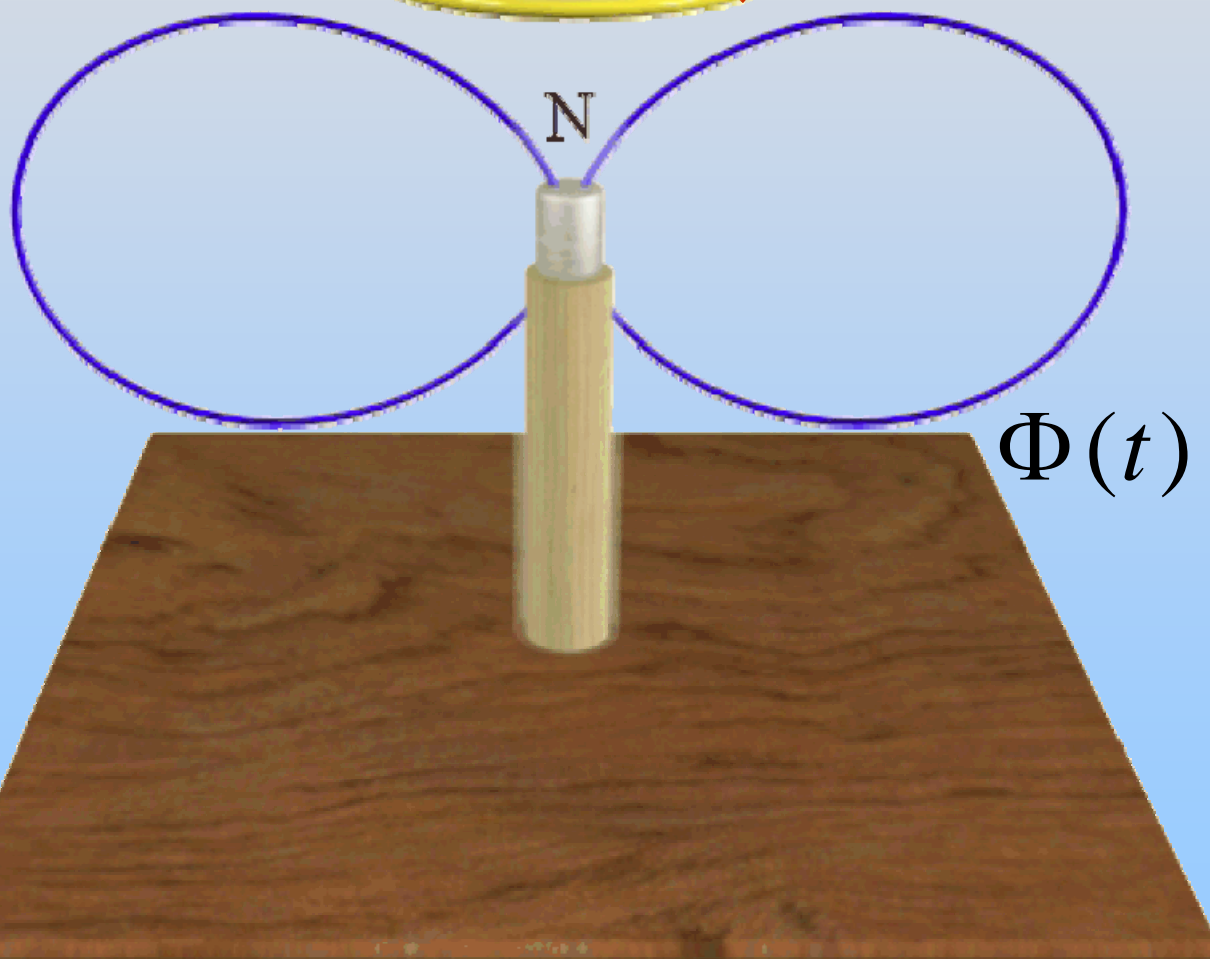
Part 1: Current & Flux



Current?

Flux?

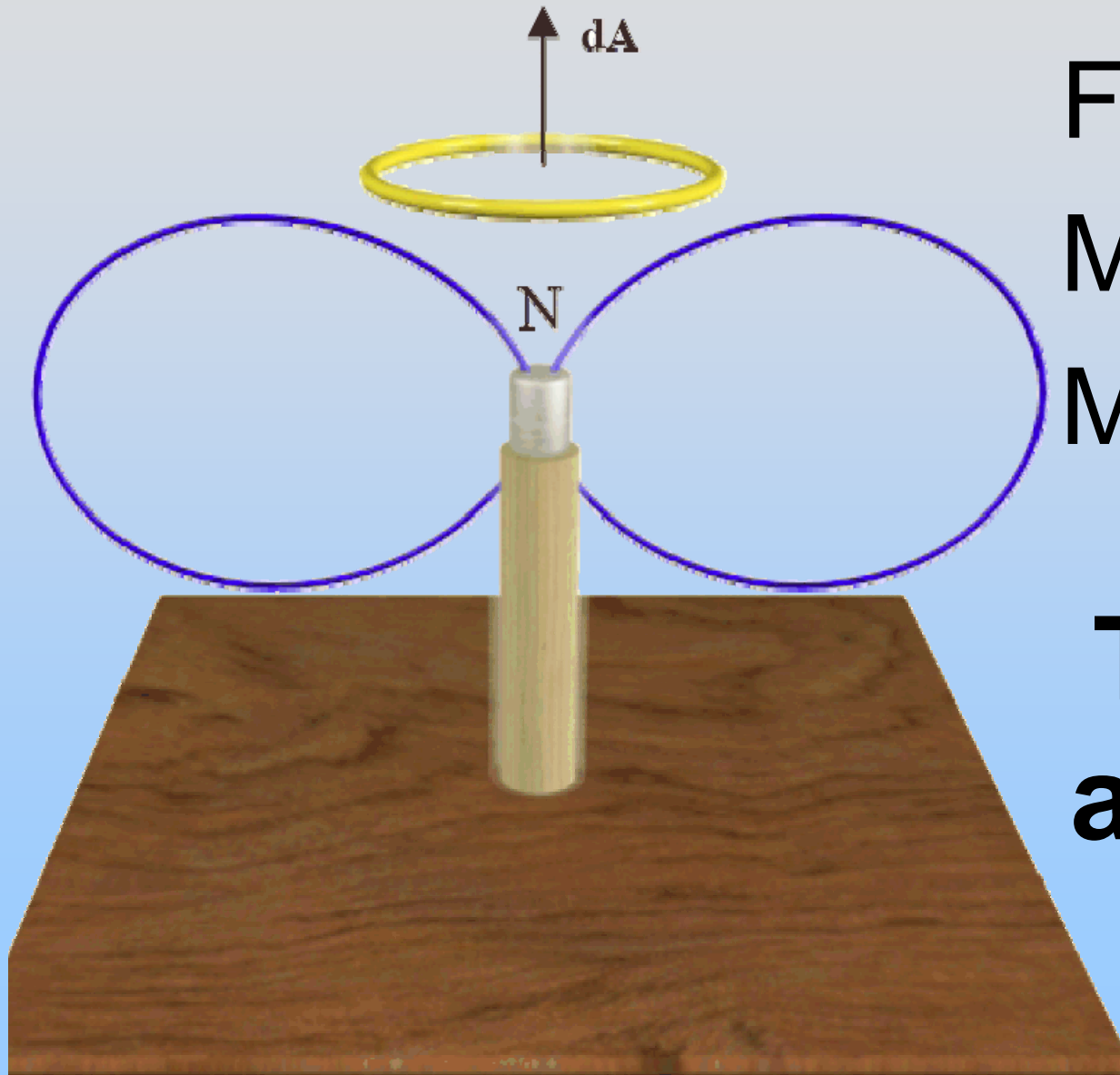
$$\Phi(t) = -R \int_0^t I(t') dt'$$



PRS Predictions: Flux & Current

PRS Confirming Predictions? Flux & Current

Part 2: Force Direction



Force when
Move Down?
Move Up?

**Test with
aluminum
sleeve**

**PRS Questions:
Lab Wrap-Up
Faraday's Law**

Technology

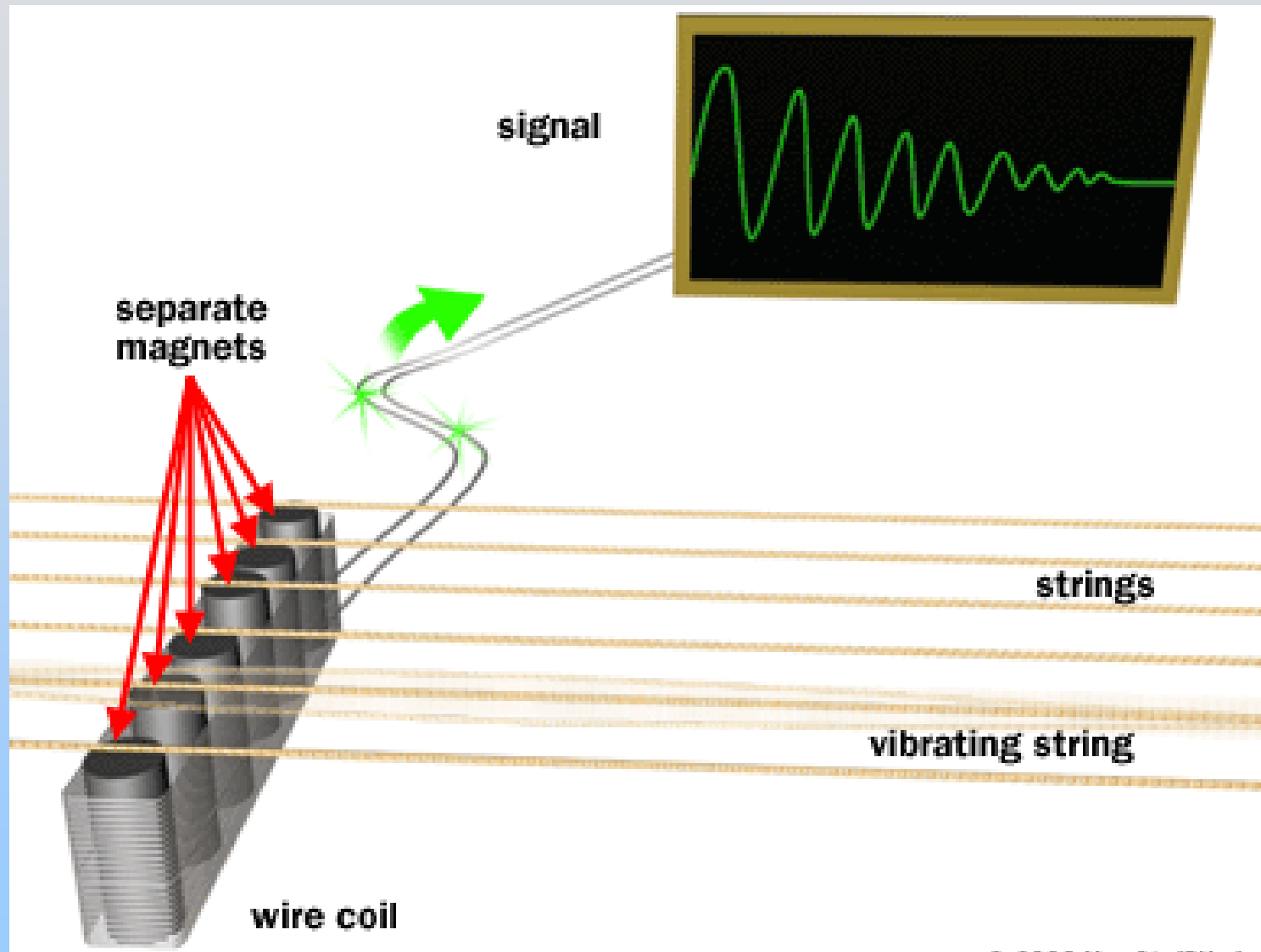
Many Applications of
Faraday's Law

Electric Guitar



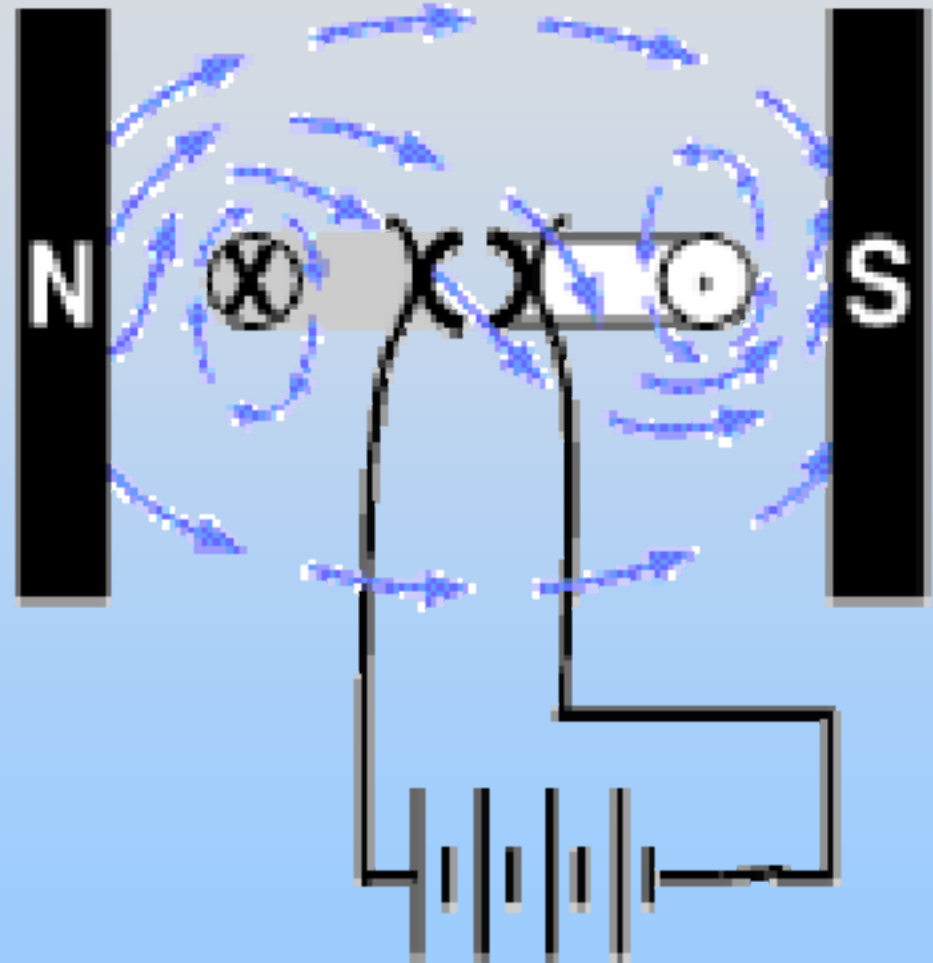
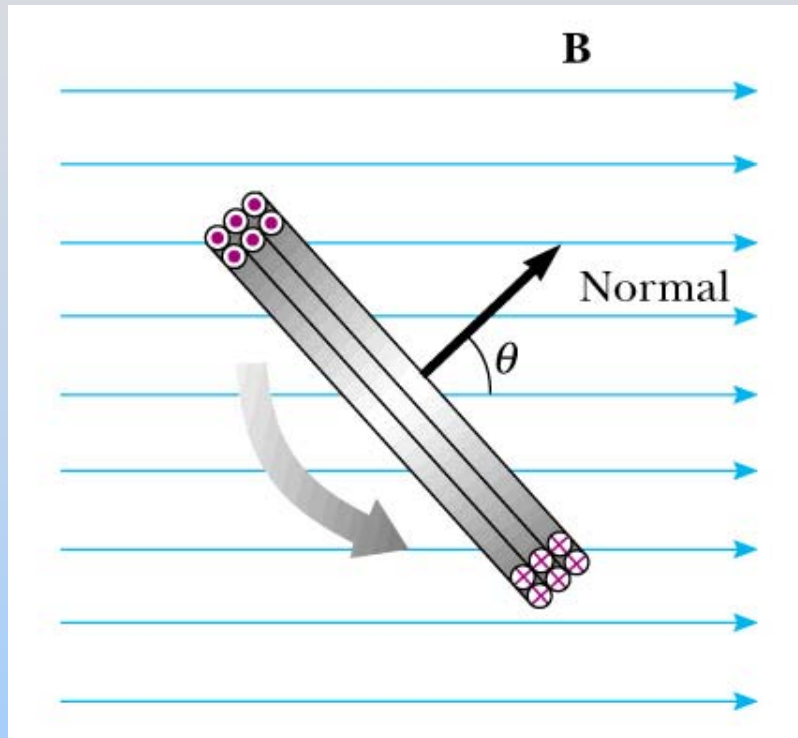
Pickups

Electric Guitar

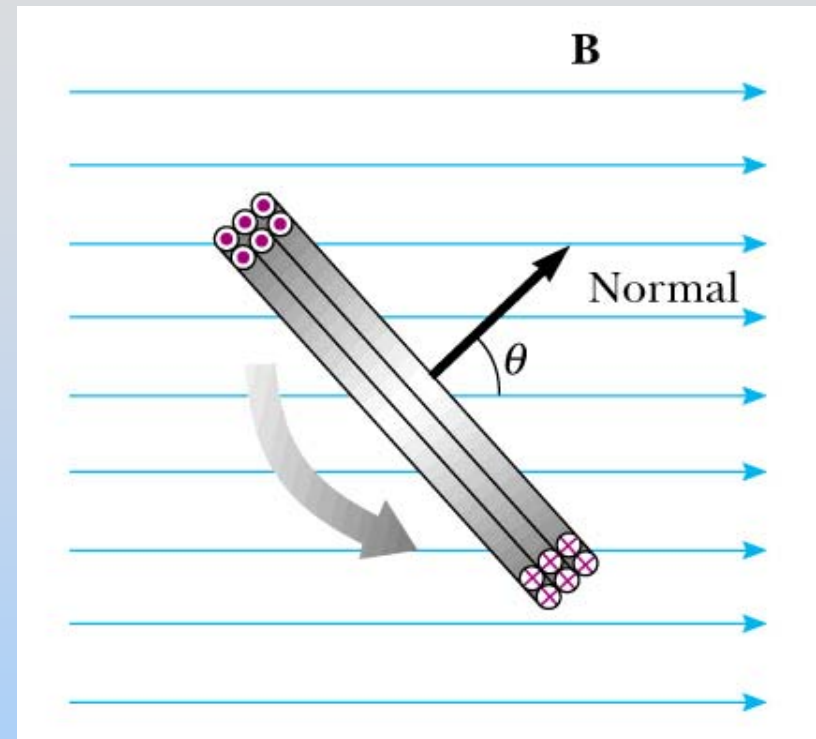
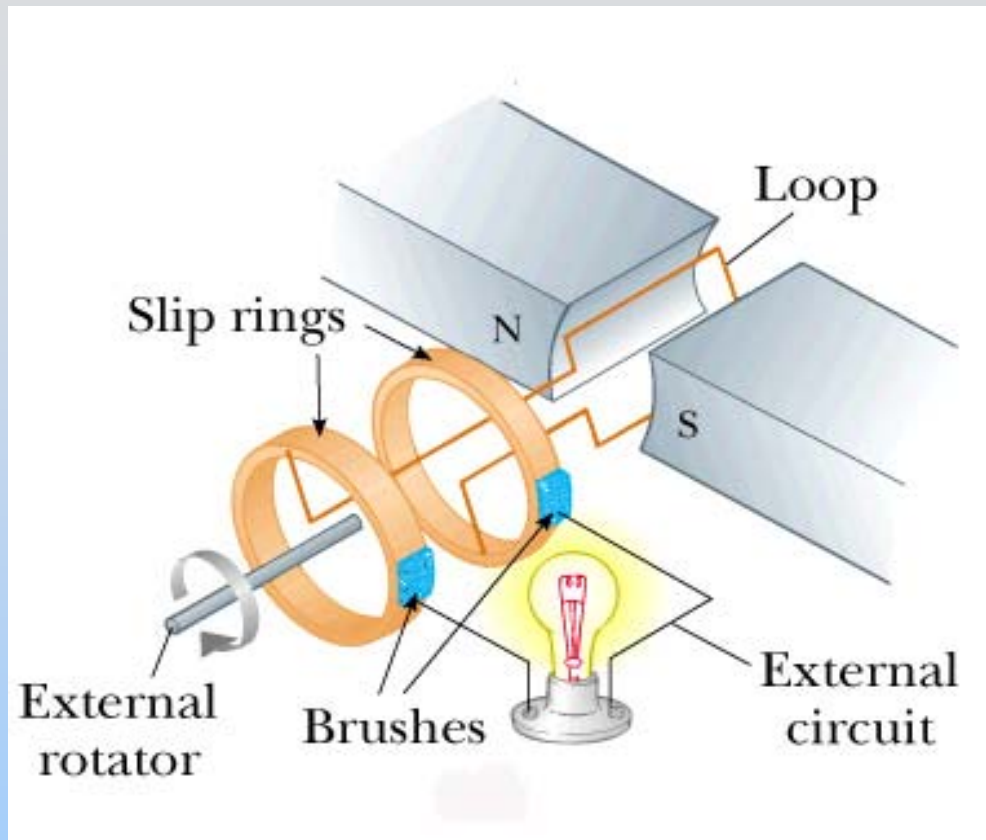


Demonstration: Electric Guitar

DC Motor



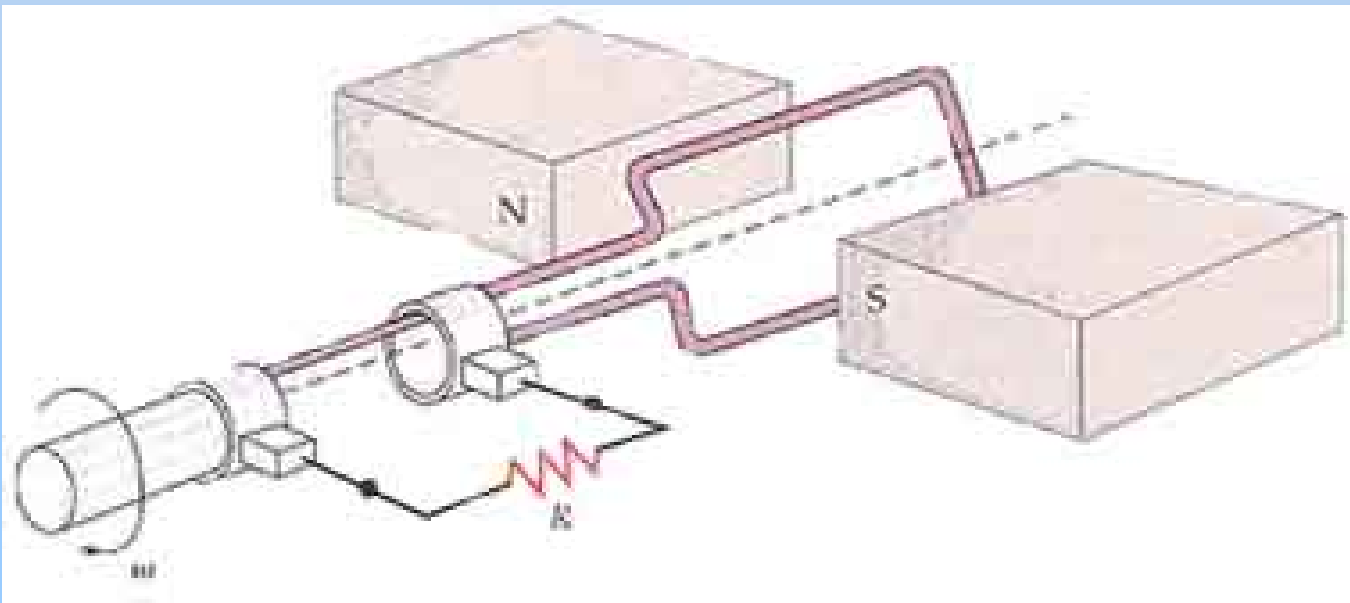
Motors & Generators



Group Problem: Generator

Square loop (side L) spins with angular frequency ω in a field of strength B . It is hooked to a load R .

- 1) Write an expression for current $I(t)$ assuming the loop is vertical at time $t = 0$.
- 2) How much work from generator per revolution?
- 3) To make it twice as hard to turn, what do you do to R ?



Brakes

Magnet Falling Through a Ring



What happened to kinetic energy of magnet?

Demonstration: Eddy Current Braking

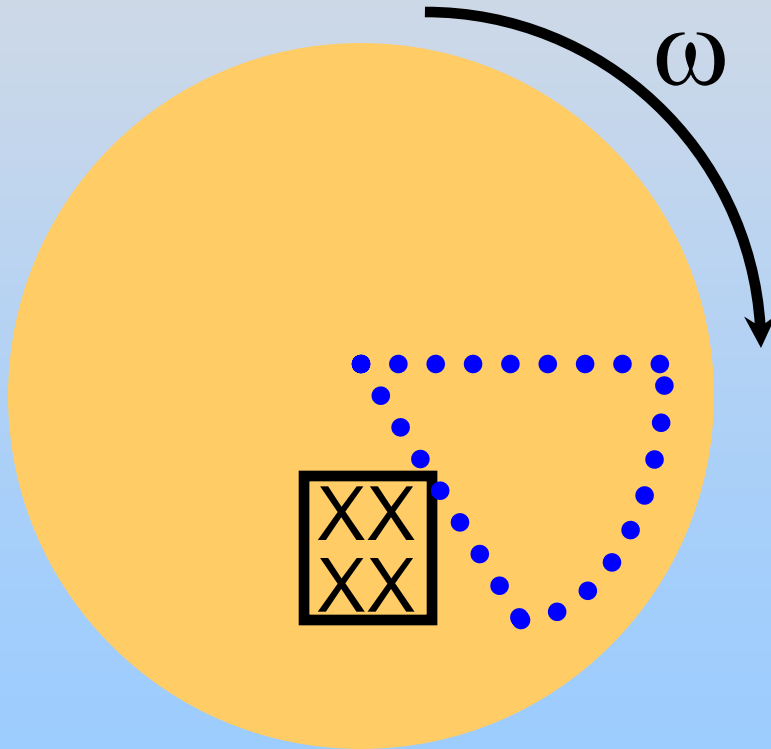
Eddy Current Braking



What happened to kinetic energy of disk?

Eddy Current Braking

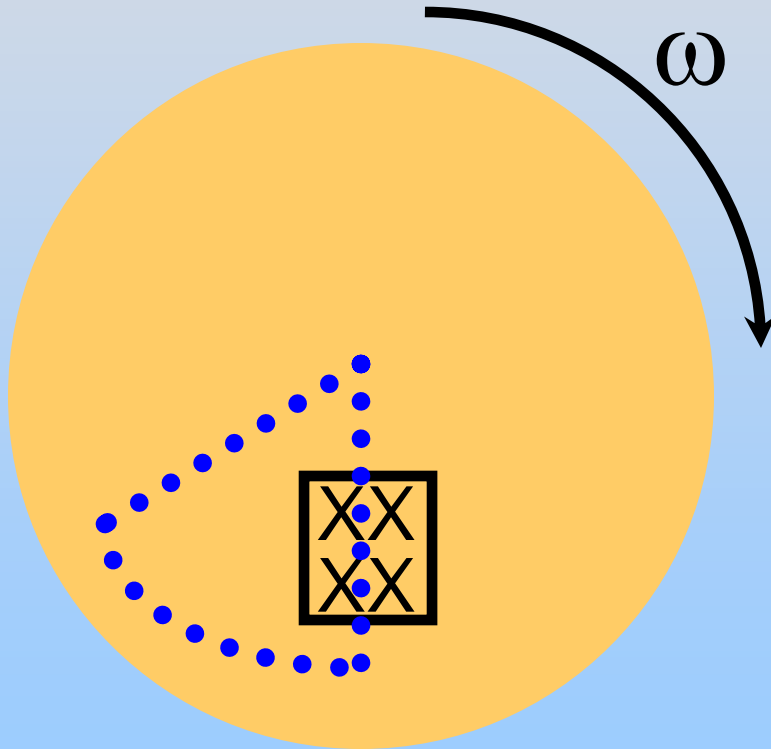
The magnet induces currents in the metal that dissipate the energy through Joule heating:



1. Current is induced counter-clockwise (out from center)
2. Force is opposing motion (creates slowing torque)

Eddy Current Braking

The magnet induces currents in the metal that dissipate the energy through Joule heating:



1. Current is induced clockwise (out from center)
2. Force is opposing motion (creates slowing torque)
3. EMF proportional to ω

$$4. F \propto \frac{\mathcal{E}^2}{R}$$

Demonstration: Levitating Magnet

PRS Question: Loop in Uniform Field