Module 21:
Faraday's Law

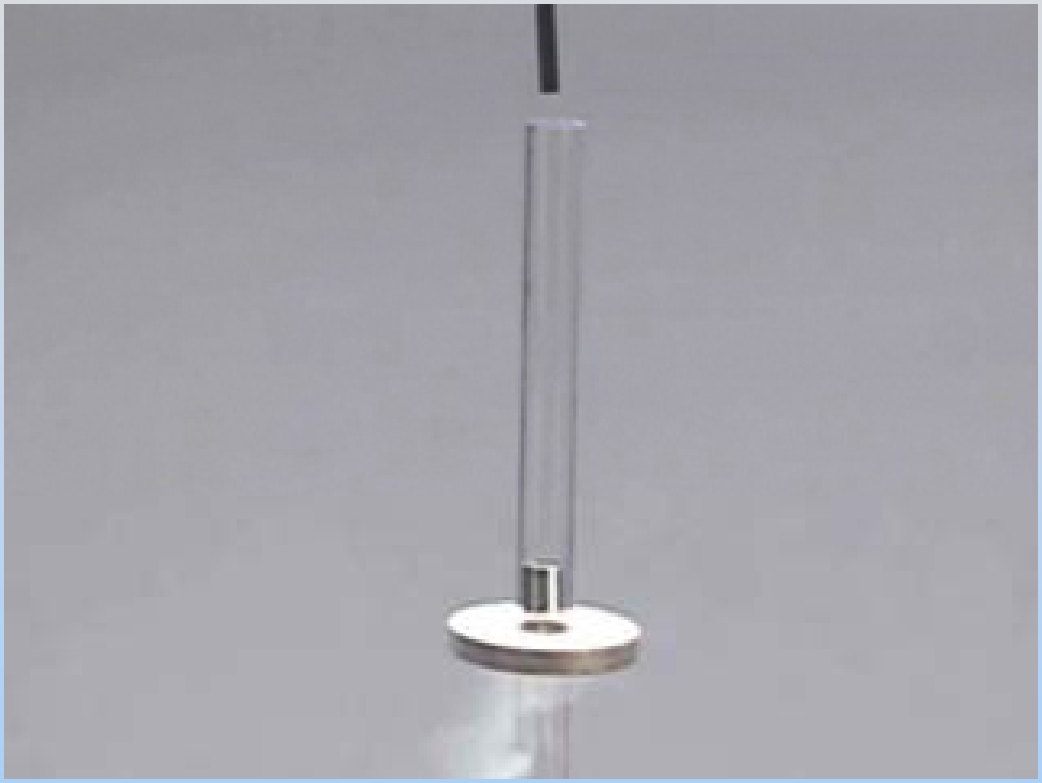
Faraday's Law

Fourth (Final) Maxwell's Equation

Underpinning of Much Technology

Demonstration: Falling Magnet

Magnet Falling Through a Ring



Link to movie

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

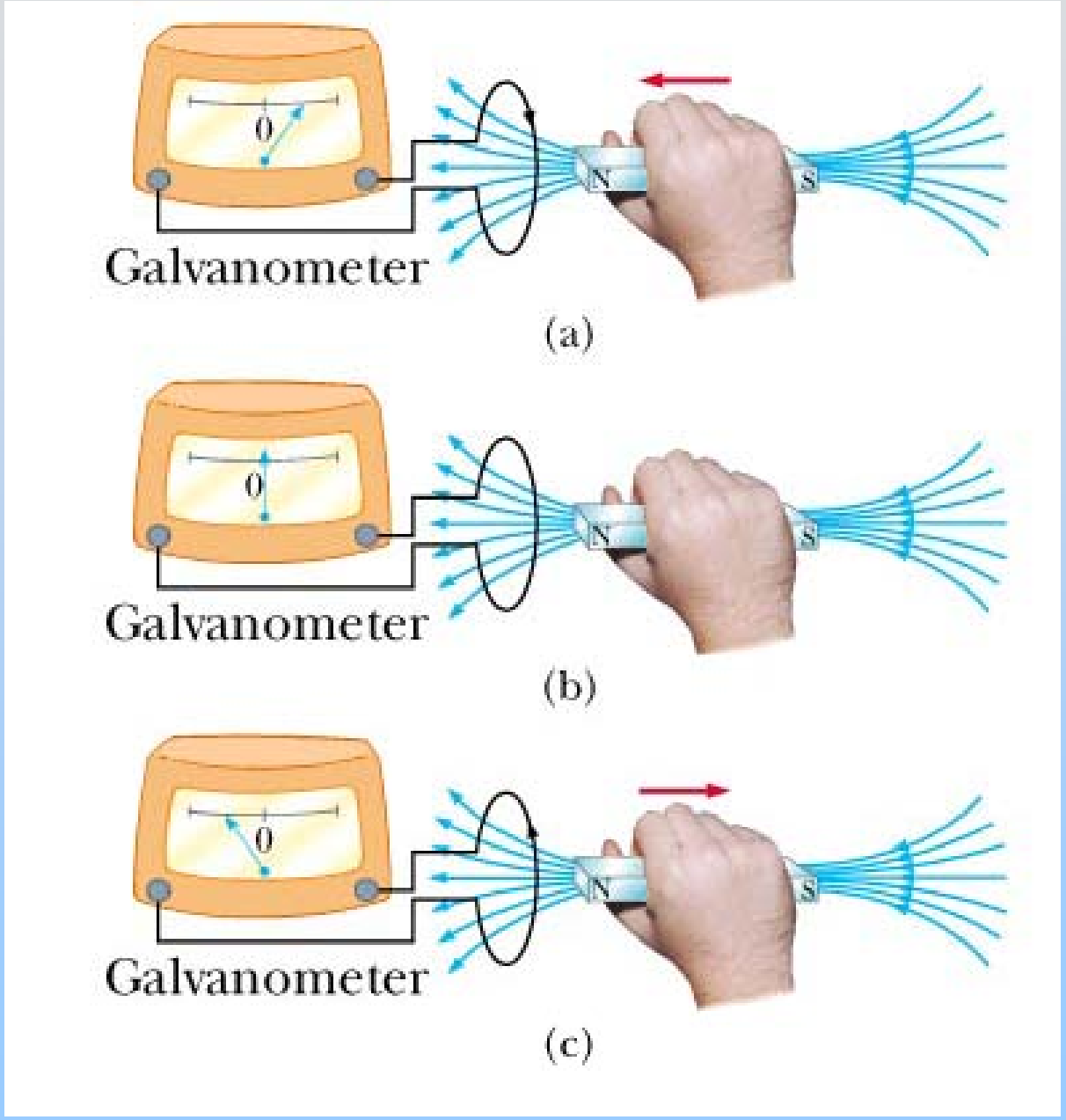
What is Going On?

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

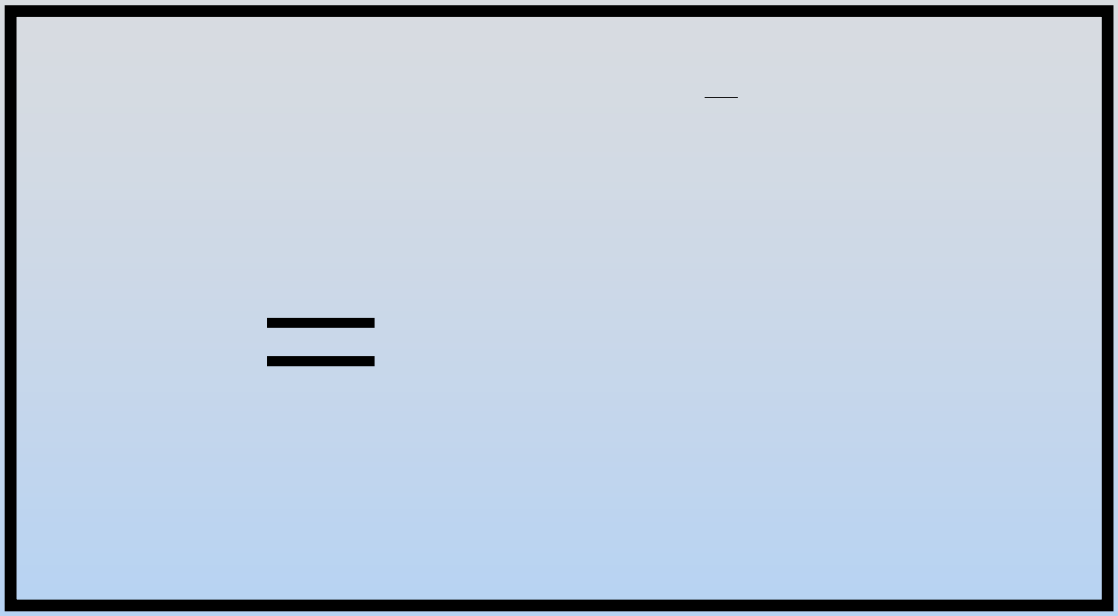
Demonstration: Induction

Link to movie

Electromagnetic Induction



Faraday's Law of Induction



A changing magnetic flux
induces an EMF

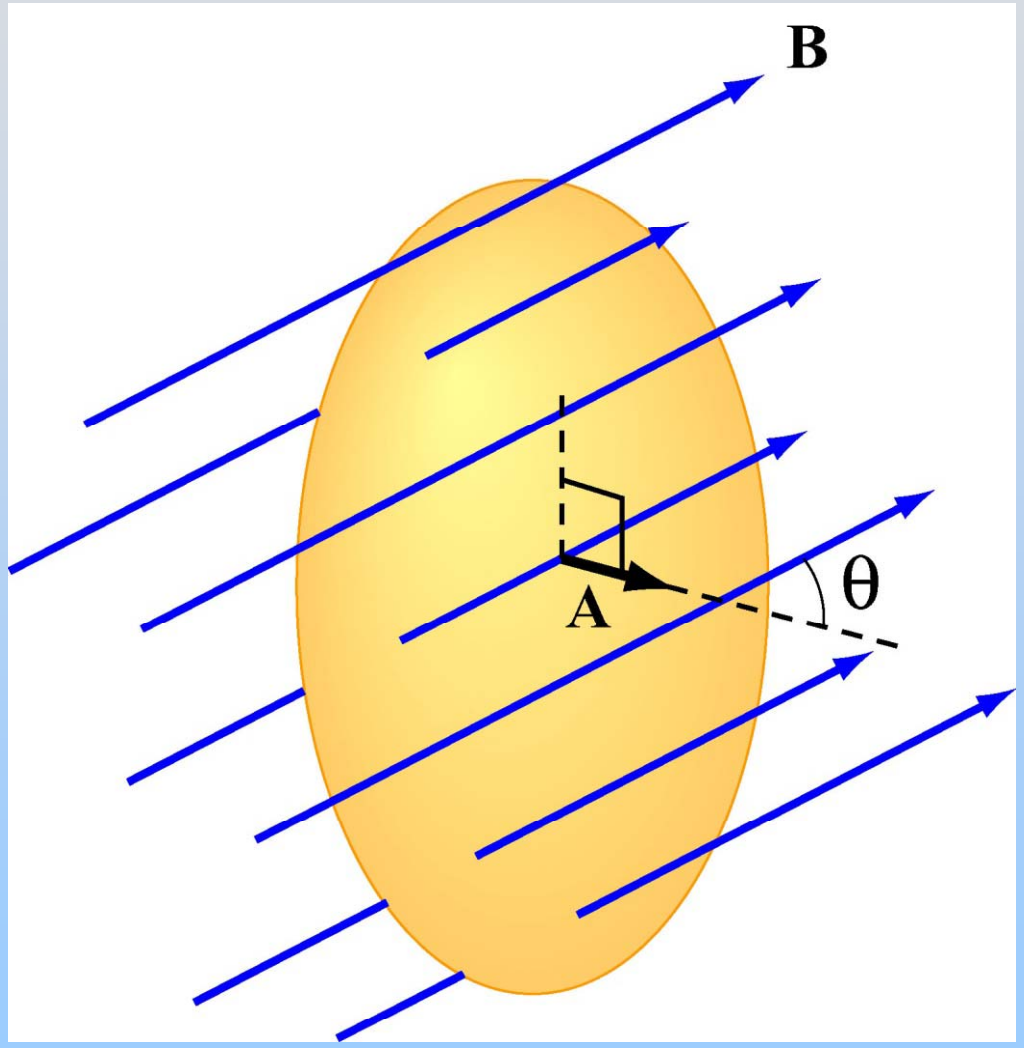
What is EMF?

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

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

Magnetic Flux Thru Wire Loop

Analogous to Electric Flux (Gauss' Law)

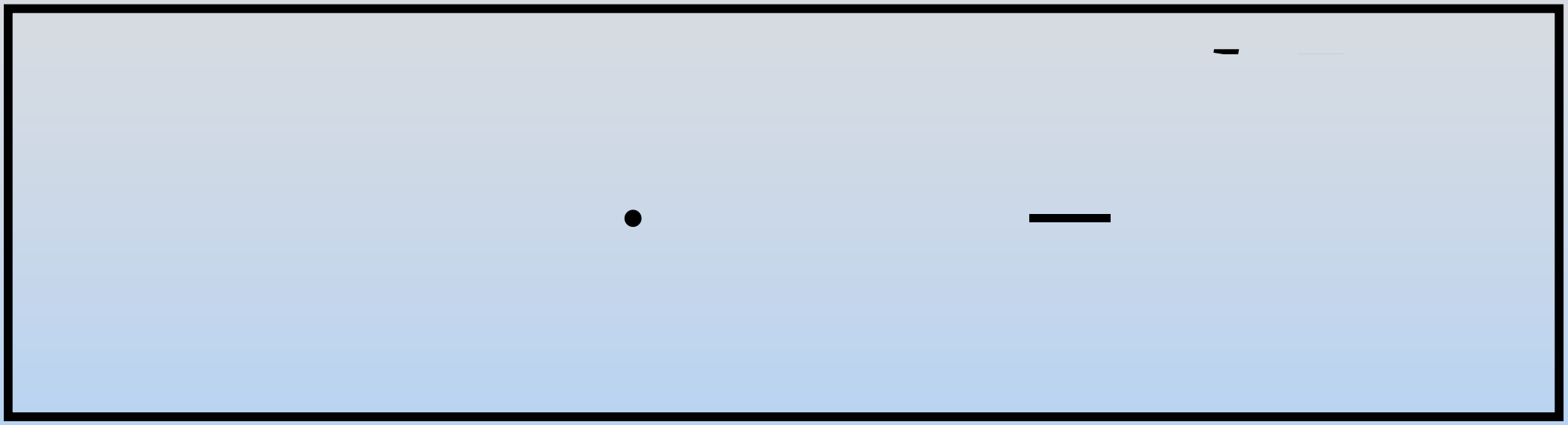


(1) Uniform **B**

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

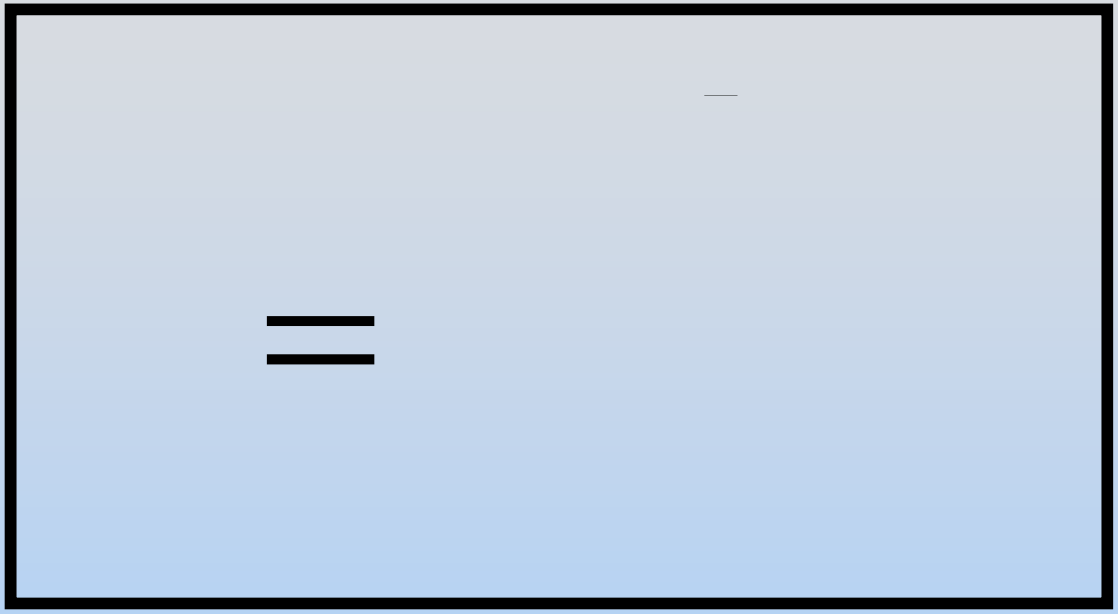
(2) Non-Uniform **B**

Faraday's Law of Induction



A changing magnetic flux *induces* an EMF, a curling E field

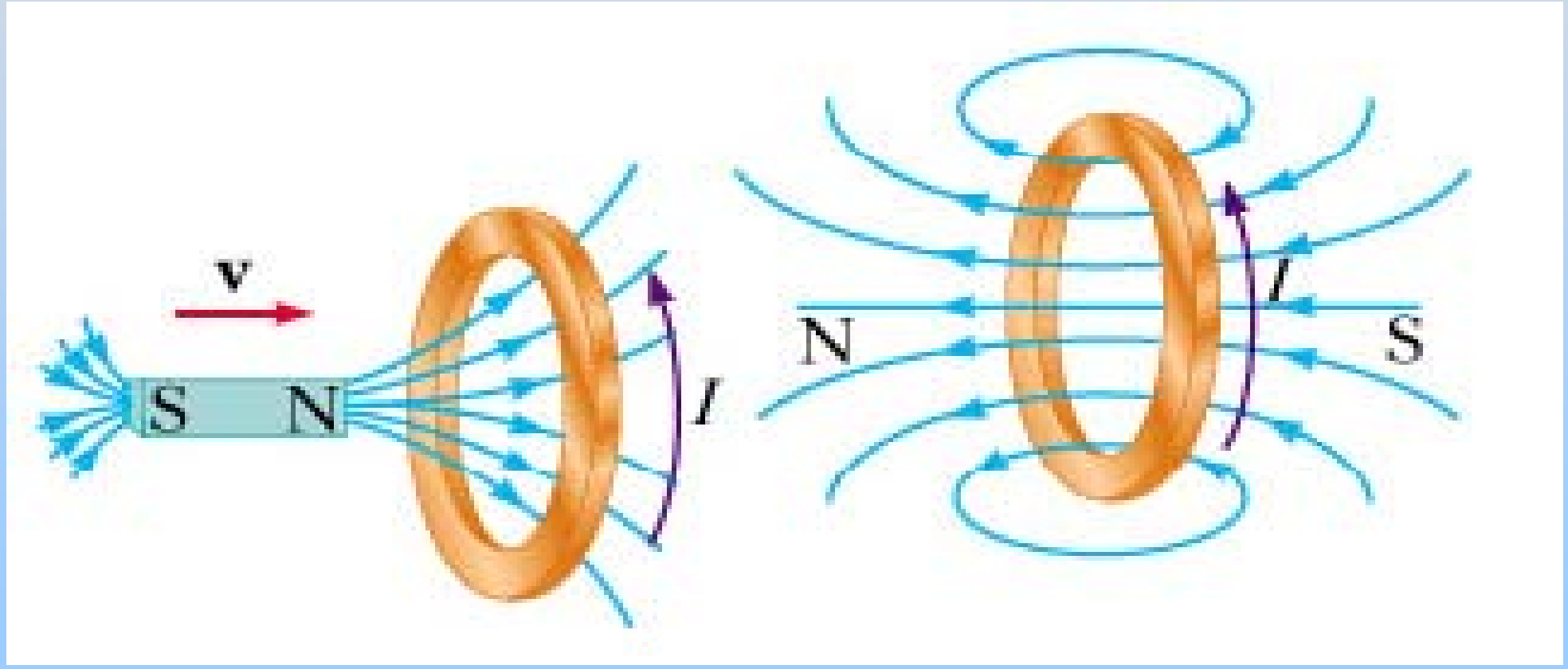
Faraday's Law of Induction



A changing magnetic flux
induces an EMF

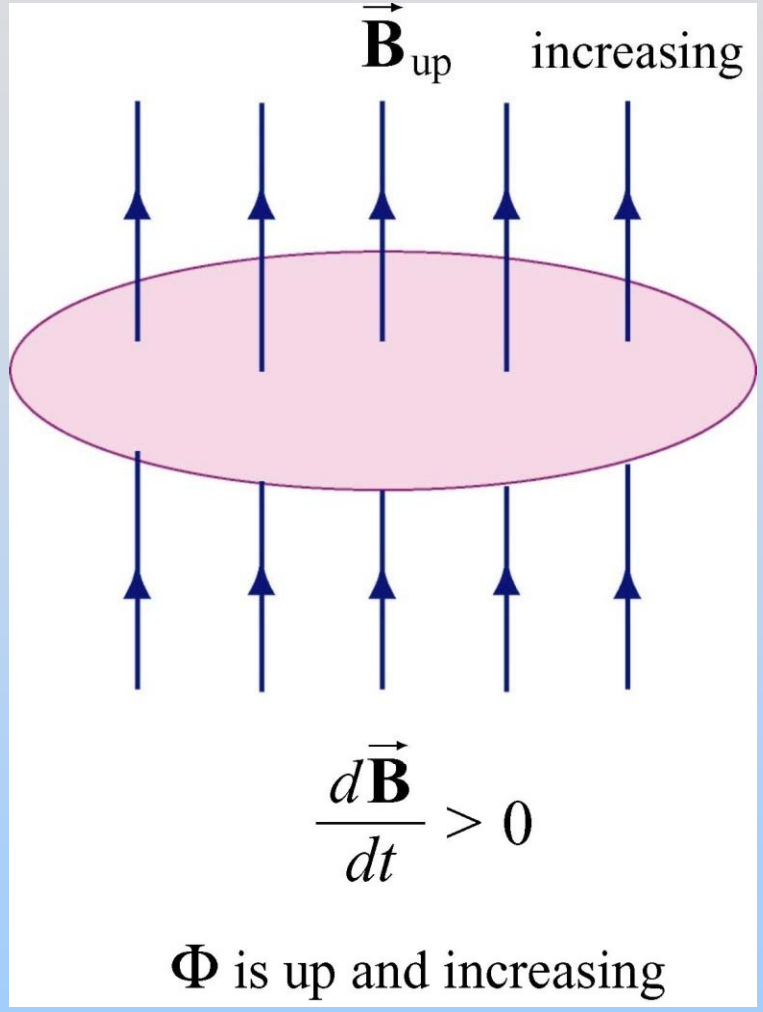
Minus Sign? Lenz's Law

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



Concept Question: Loop

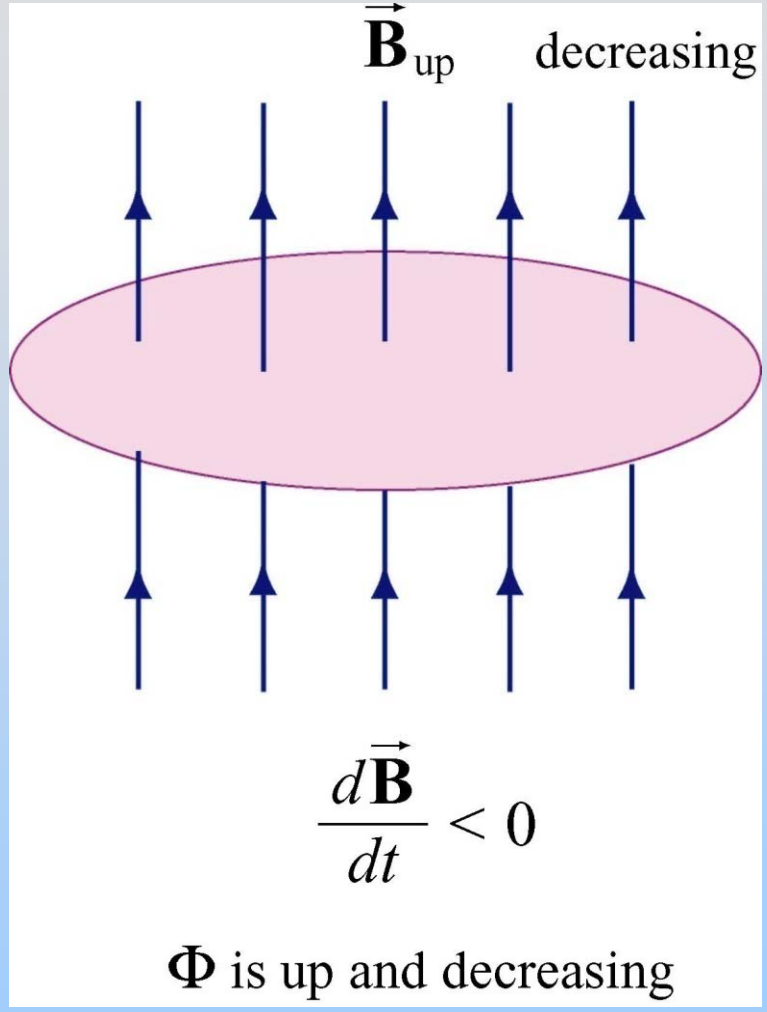
The magnetic field through a wire loop is pointed upwards and *increasing* with time. The induced current in the coil is



1. Clockwise as seen from the top
2. Counterclockwise

Concept Question: Loop

The magnetic field through a wire loop is pointed upwards and *decreasing* with time. The induced current in the coil is



1. Clockwise as seen from the top
2. Counterclockwise

Ways to Induce EMF

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

Quantities which can vary with time:

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

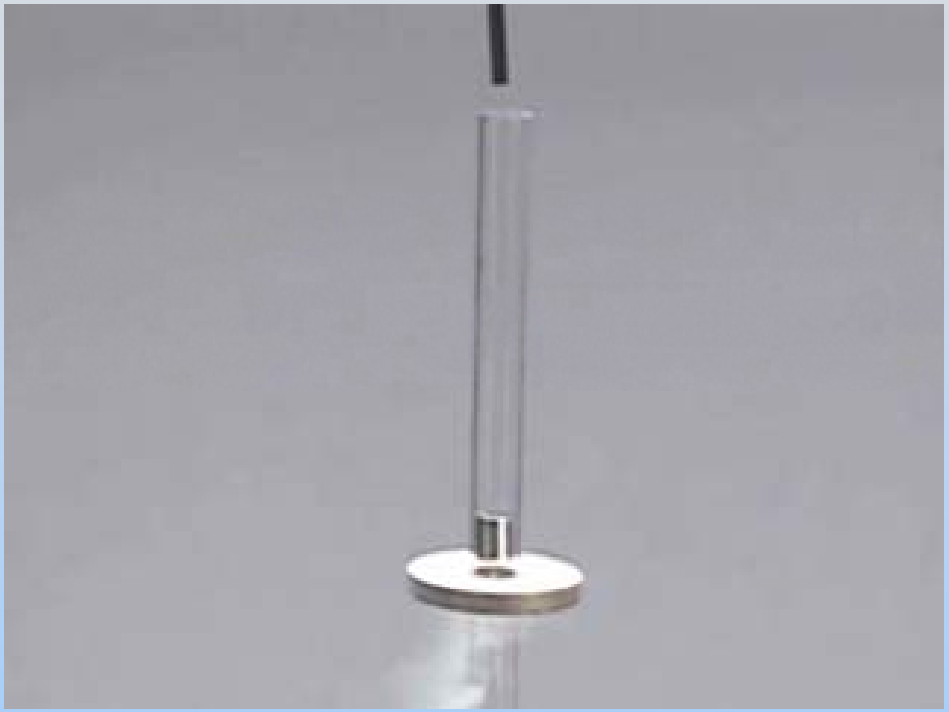
Ways to Induce EMF

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

Quantities which can vary with time:

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

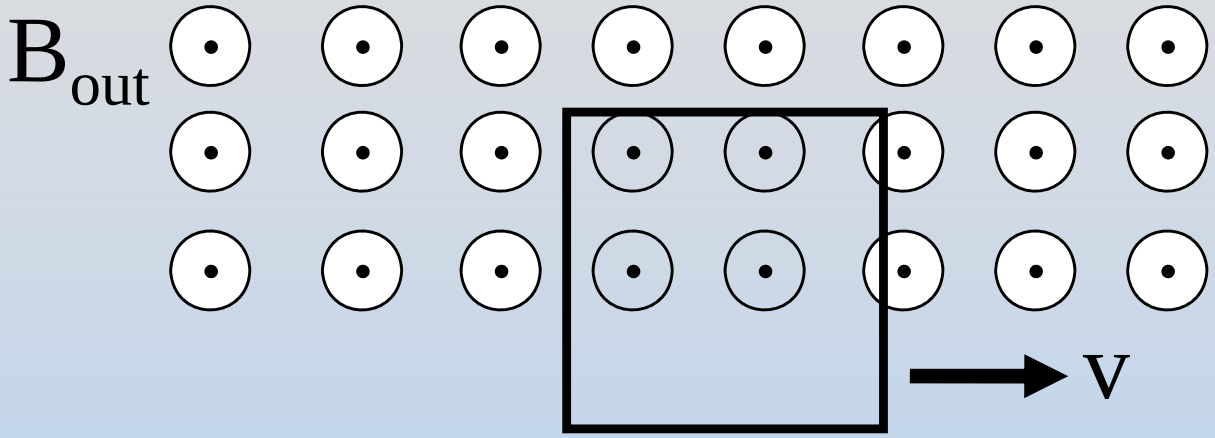
Magnet Falling Through a Ring



Link to movie

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

Concept Question: Loop in Uniform Field

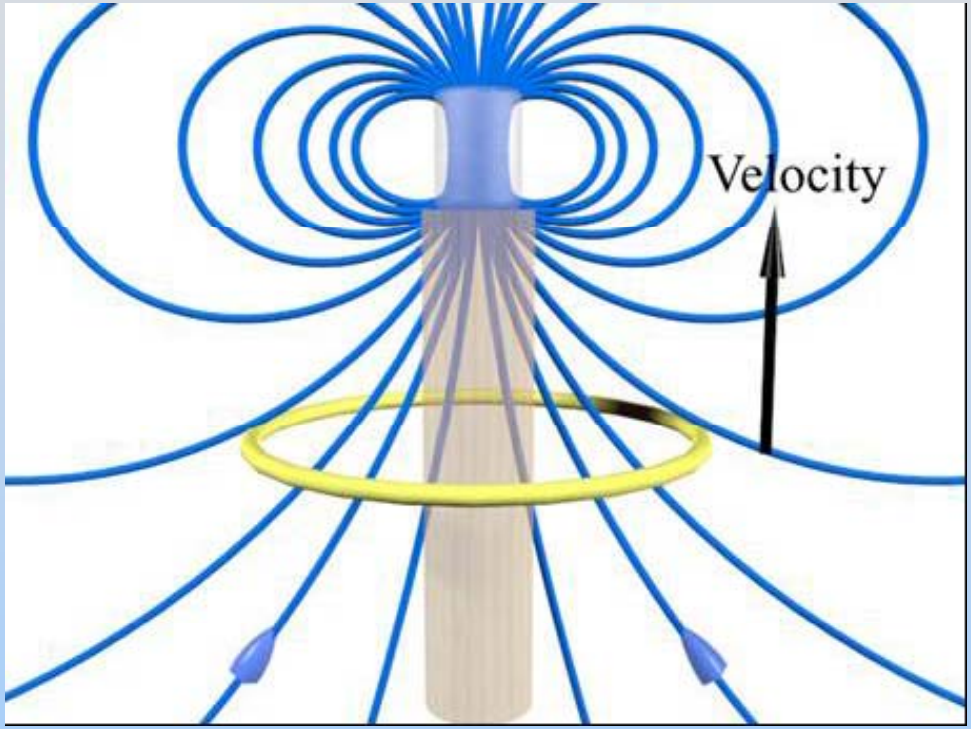


A rectangular wire loop is pulled thru a uniform B field penetrating its top half, as shown. The induced current and the force and torque on the loop are:

1. Current CW, Force Left, No Torque
2. Current CW, No Force, Torque Rotates CCW
3. Current CCW, Force Left, No Torque
4. Current CCW, No Force, Torque Rotates CCW
5. No current, force or torque

Concept Question: Faraday's Law: Loop

A coil moves up from underneath a magnet with its north pole pointing upward. The current in the coil and the force on the coil:

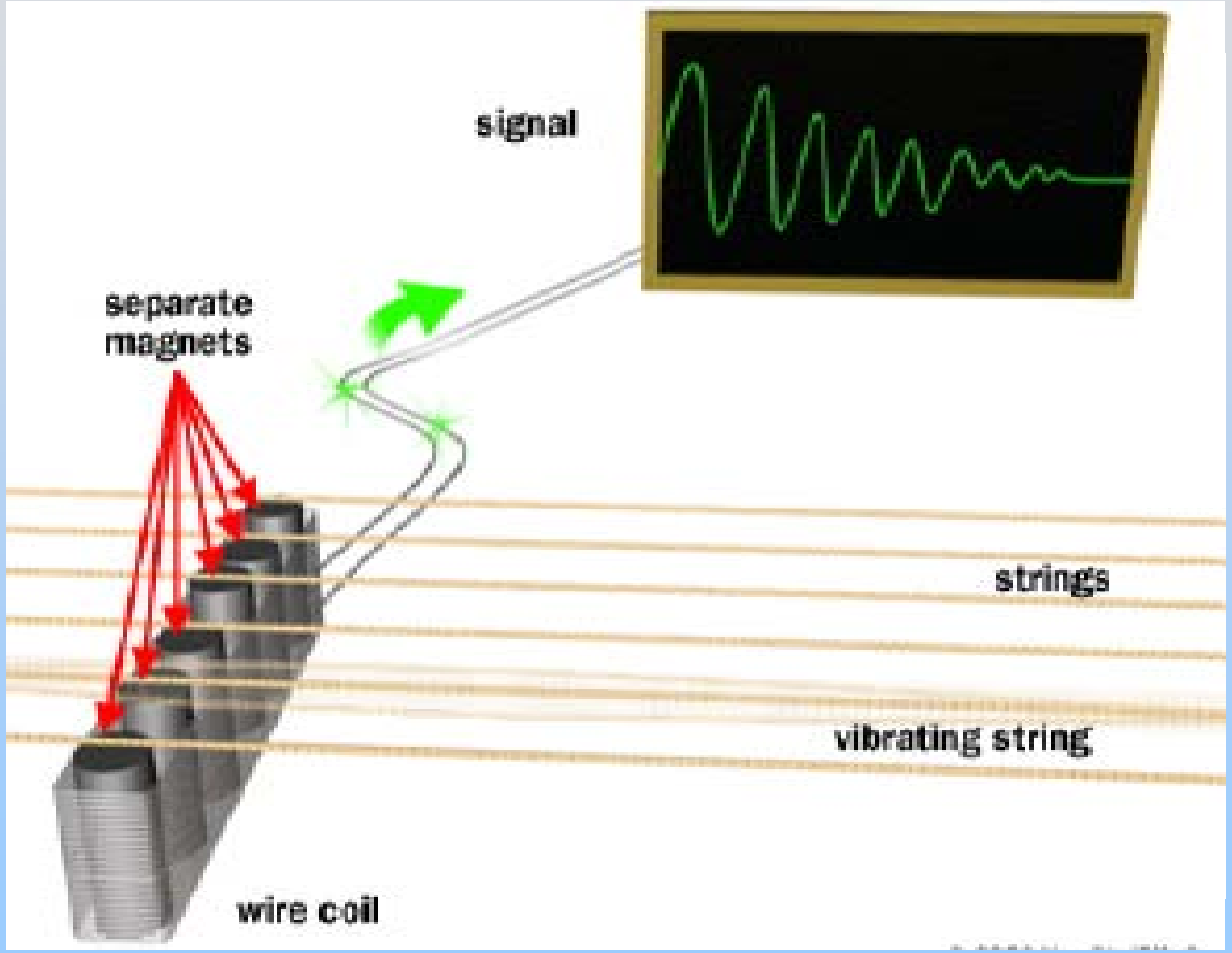


1. Current clockwise; force up
2. Current counterclockwise; force up
3. Current clockwise; force down
4. Current counterclockwise; force down

Technology

Many Applications of Faraday's Law

Electric Guitar



Metal Detector

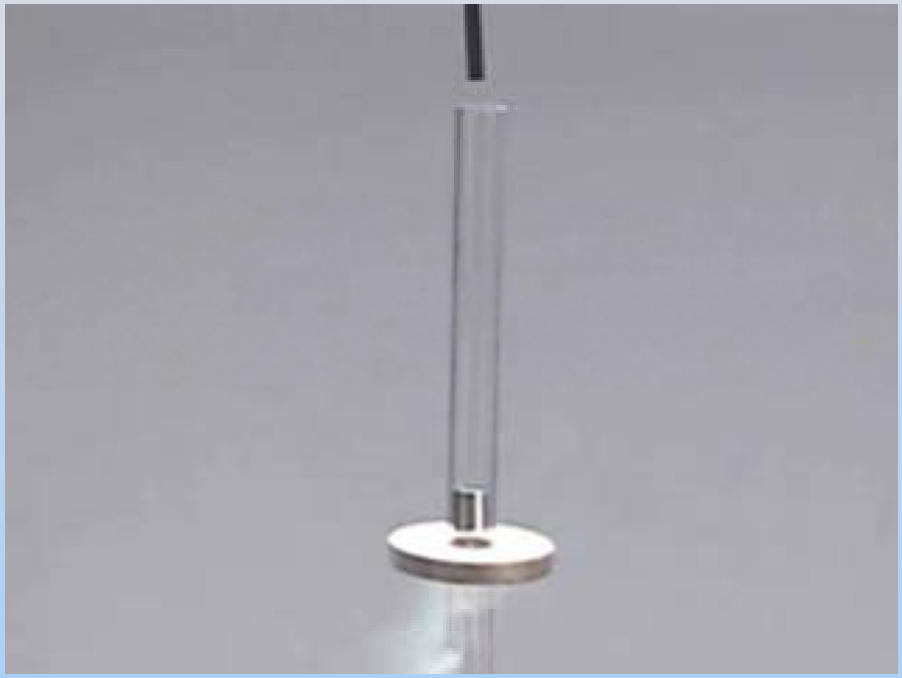
See Animation of how VLF metal detectors work:
http://home.howstuffworks.com/metal-detector2.htm

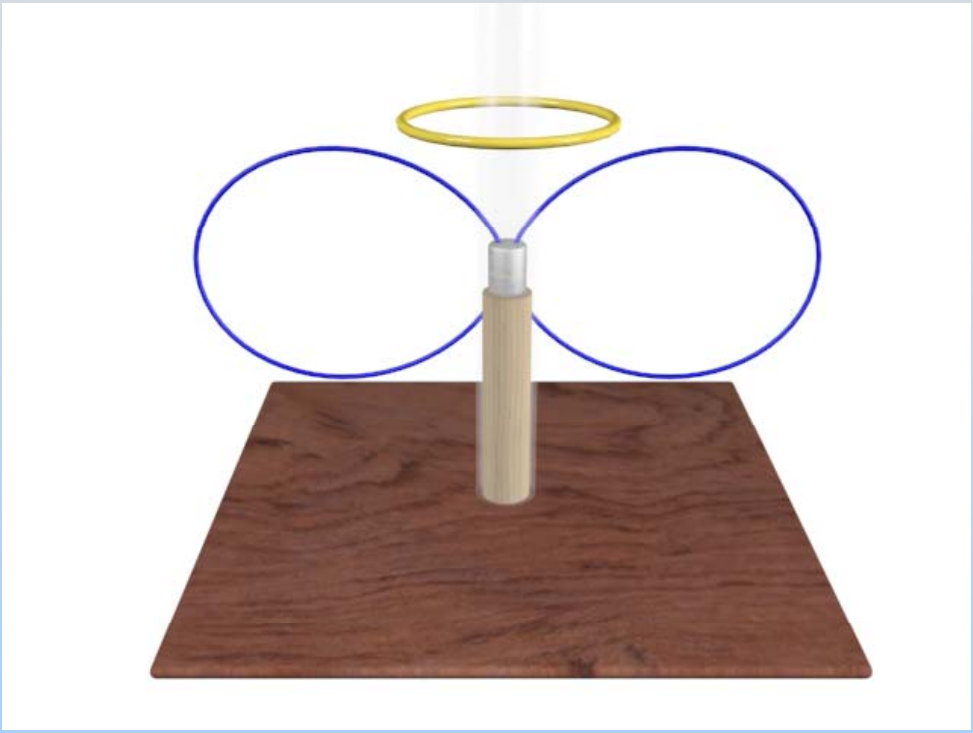
Induction Stovetops

Ground Fault Interrupters (GFI)

Experiment 5:
Faraday's Law of Induction

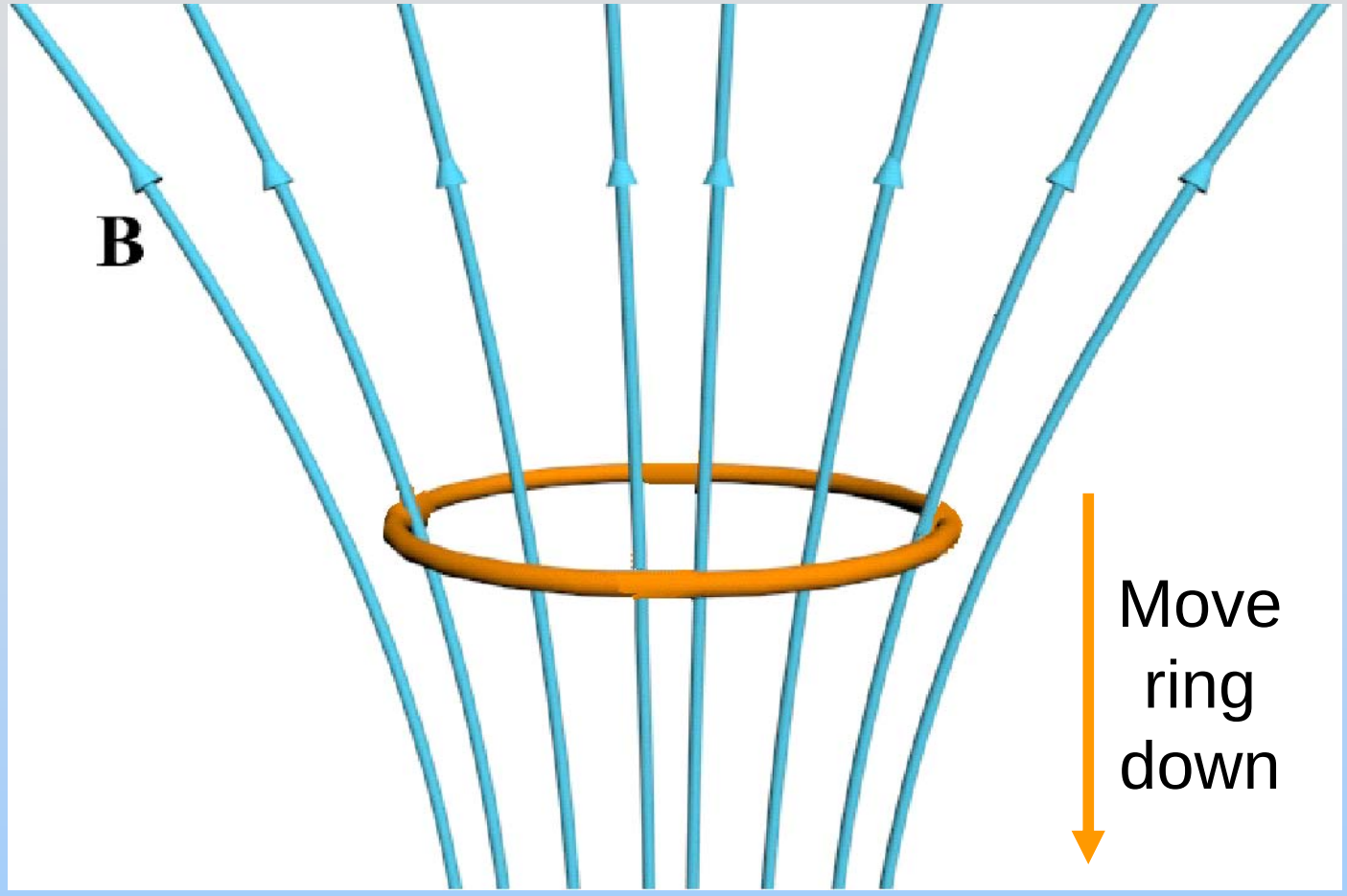
Example: Magnitude of B Magnet Falling Through a Ring





Falling magnet approaches a copper ring
or Copper Ring approaches Magnet

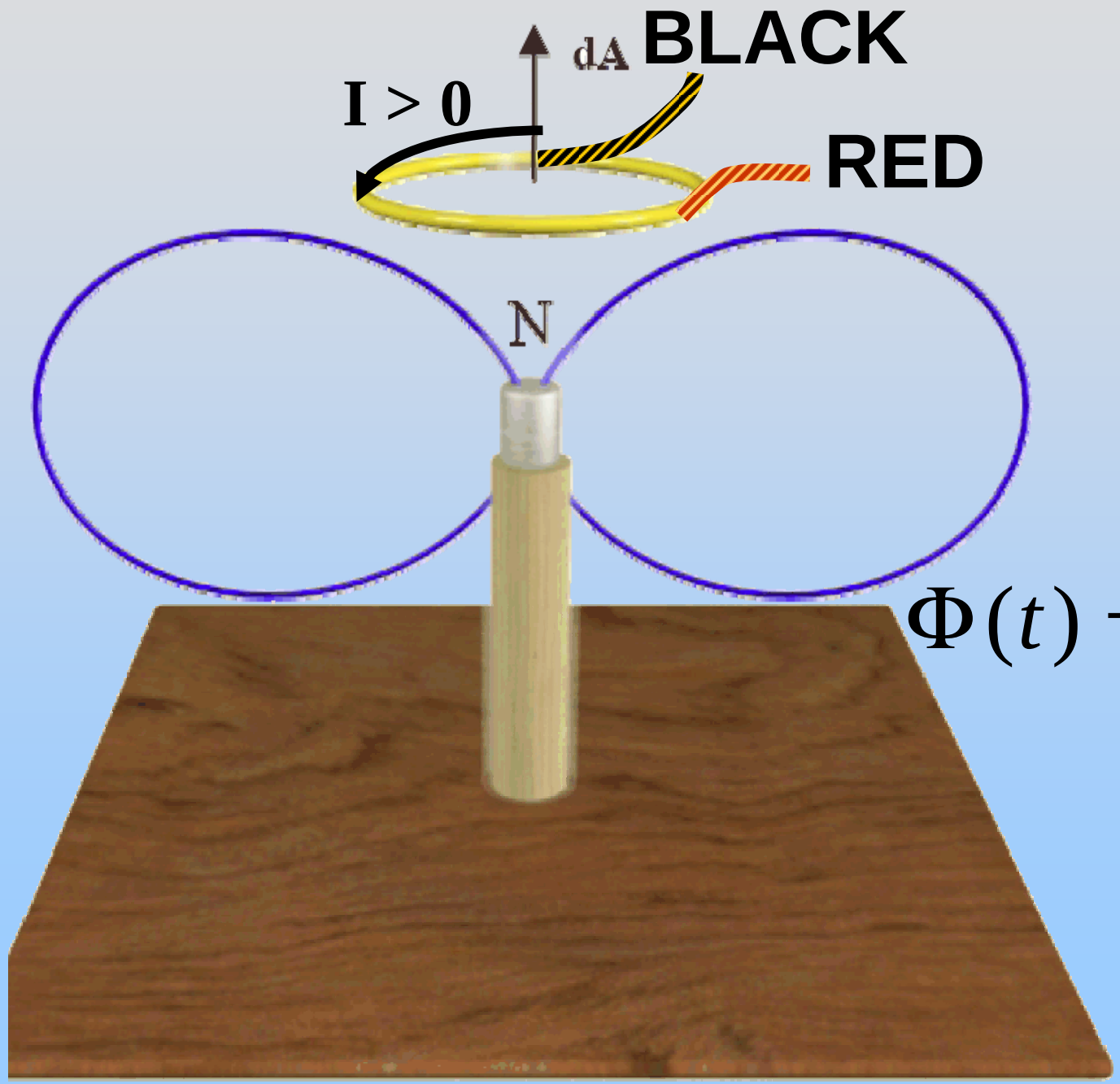
Moving Towards Dipole



As ring approaches, what happens to flux?

Flux up increases

Part 1: Current & Flux



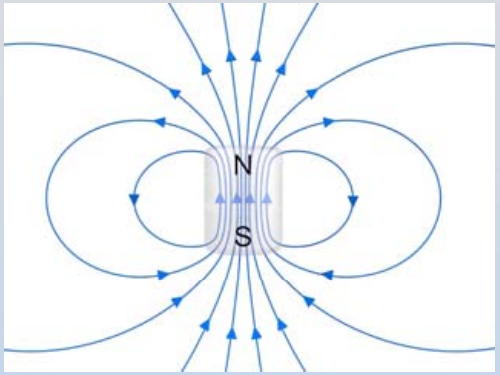
Current?

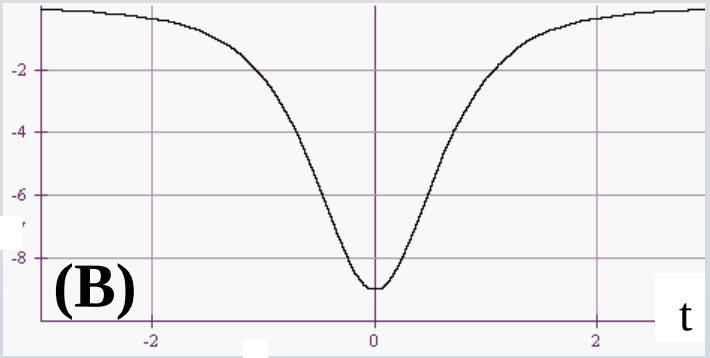
Flux?

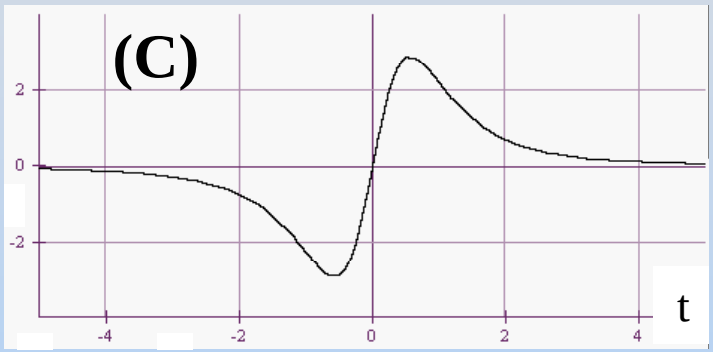
$$\Phi(t) = -R\int_0^t I(t')\,dt'$$

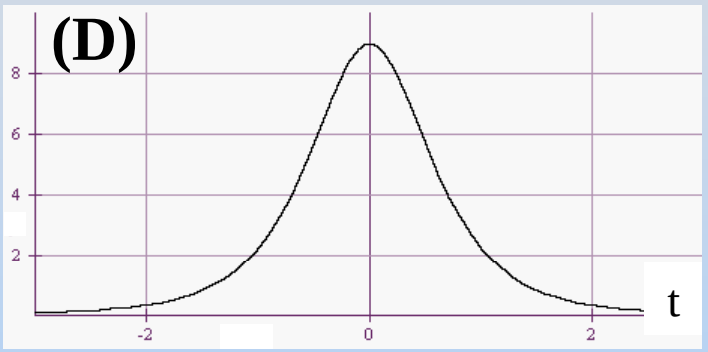
Concept Question Predictions: Flux & Current

Concept Q. : Flux Measurement





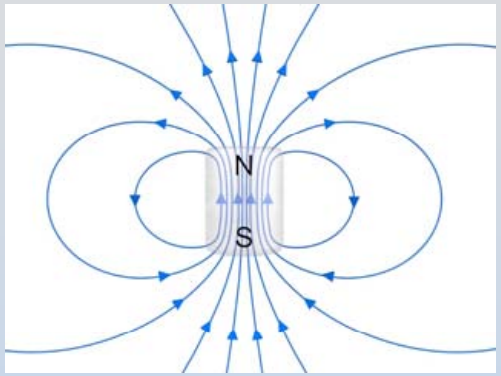


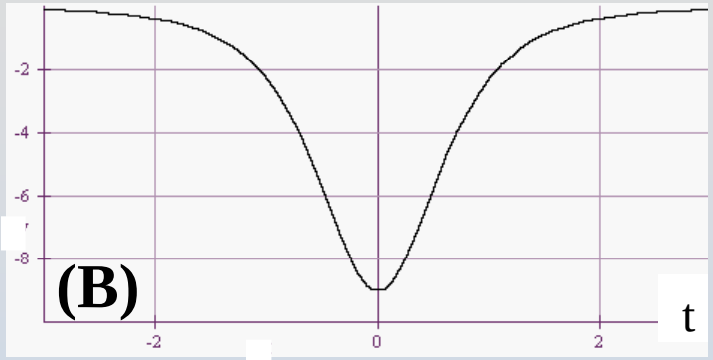


Moving from above to below and back, you will measure a *flux* of:

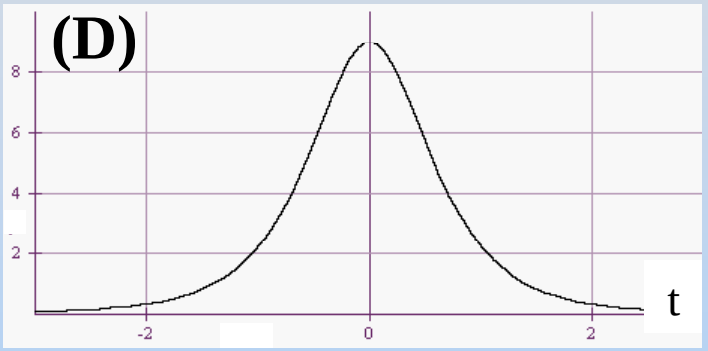
1. A then A
2. C then C
3. A then C
4. C then A
5. B then B
6. D then D
7. B then D
8. D then B

Concept Q.: Current Measurement





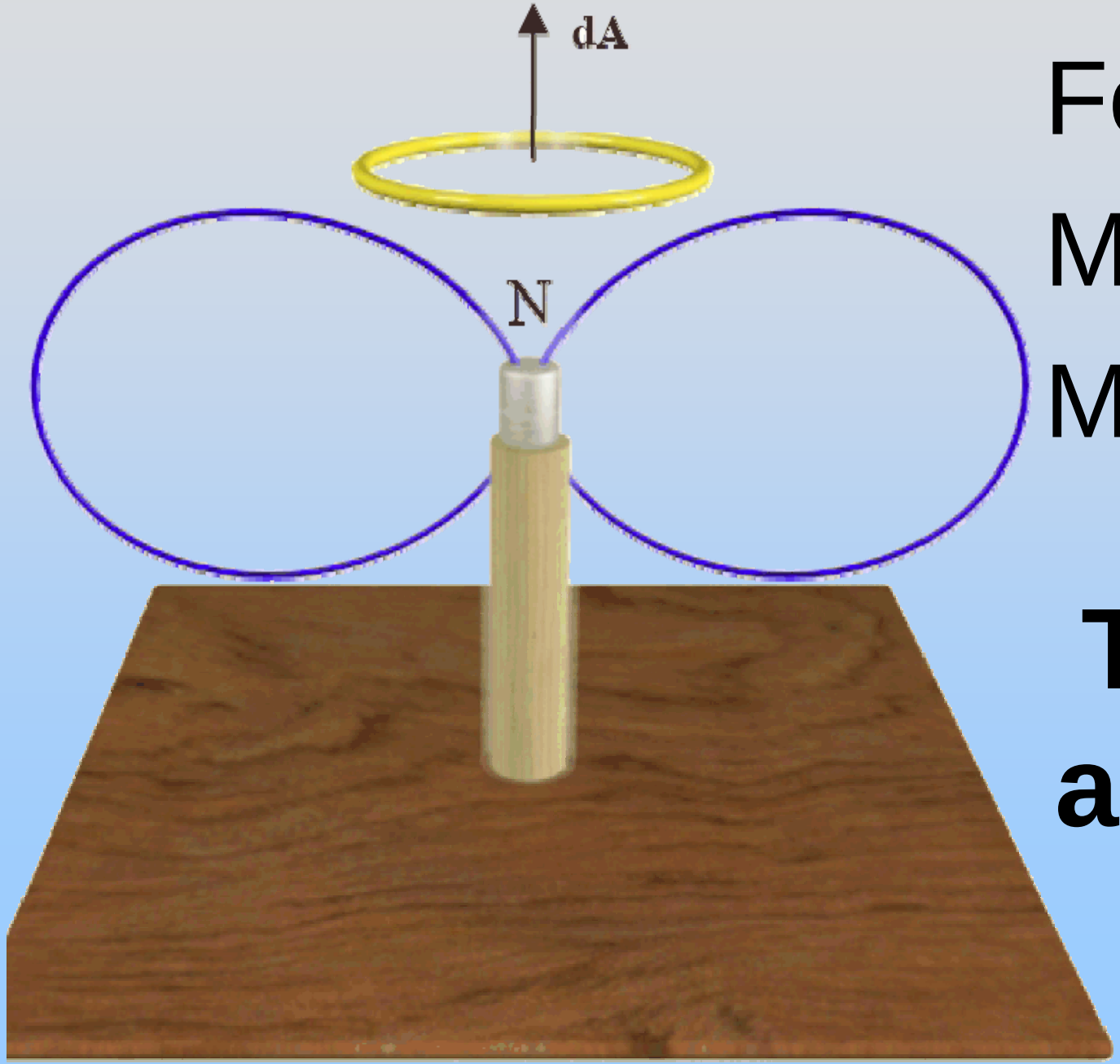
NOTE: CCW is positive!



Moving from above to below and back, you will measure a *current* of:

1. A then A
2. C then C
3. A then C
4. C then A
5. B then B
6. D then D
7. B then D
8. D then B

Part 2: Force Direction



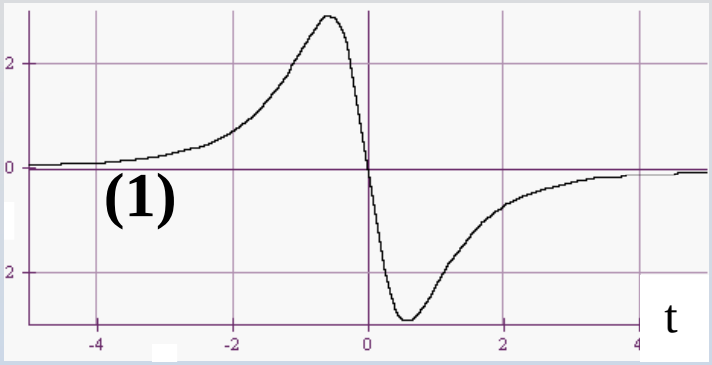
Force when

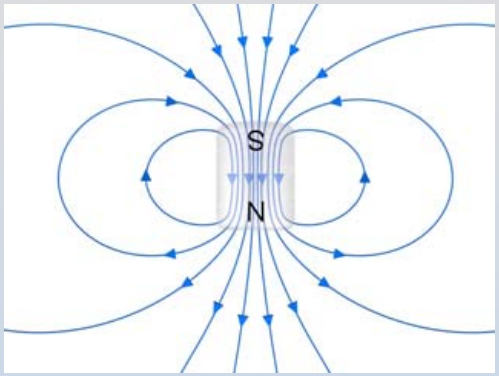
Move Down?

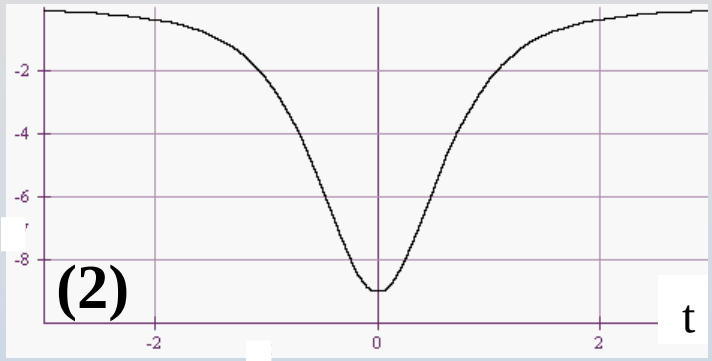
Move Up?

Test with aluminum sleeve

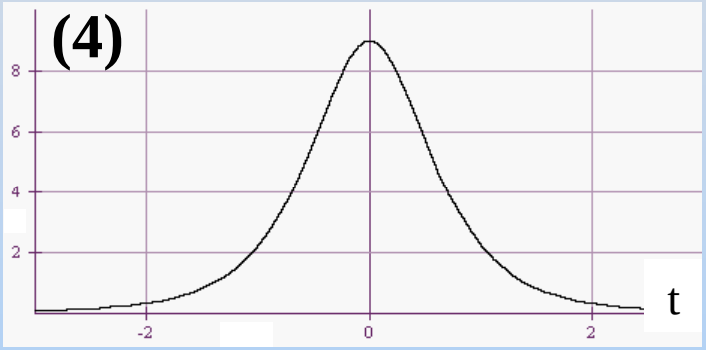
Concept Question: Flux Behavior





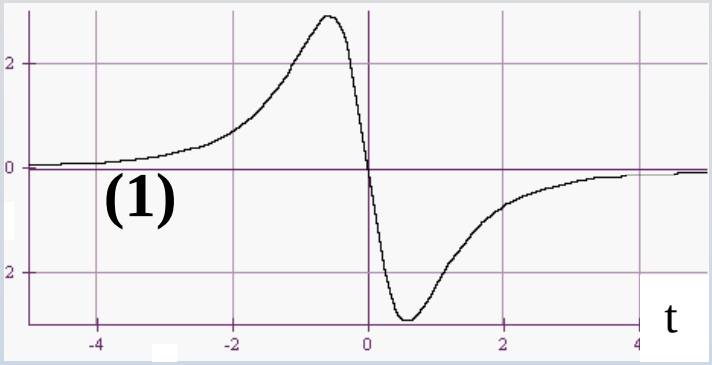


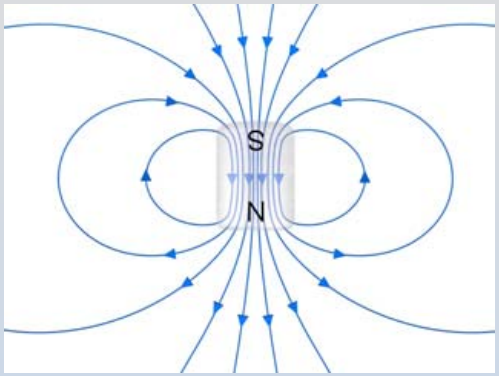
NOTE: Magnet "Upside Down"

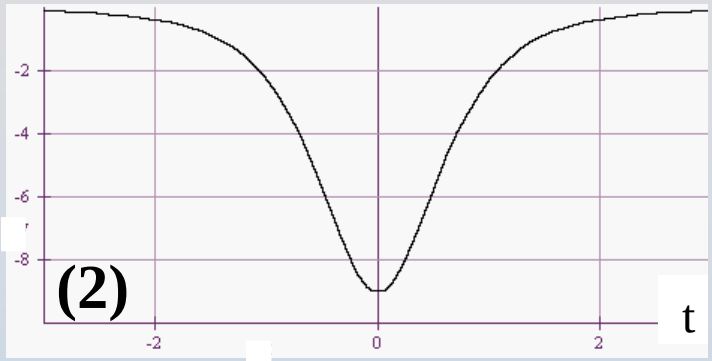


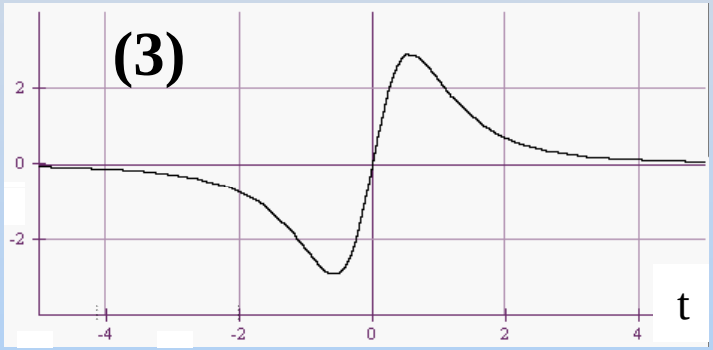
Moving from below to above, you would measure a *flux* best represented by which plot above (taking upward flux as positive)?

Concept Q.: Current Behavior

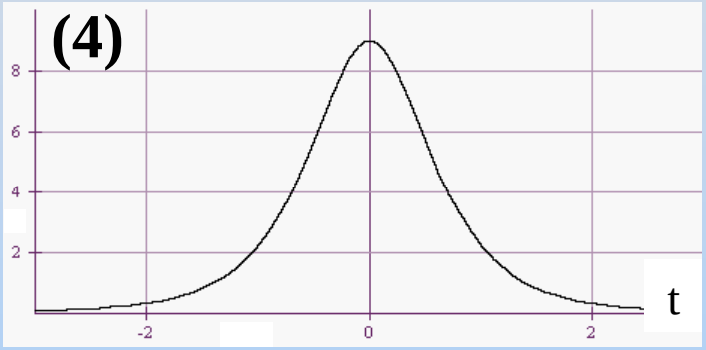








NOTE: Magnet "Upside Down"

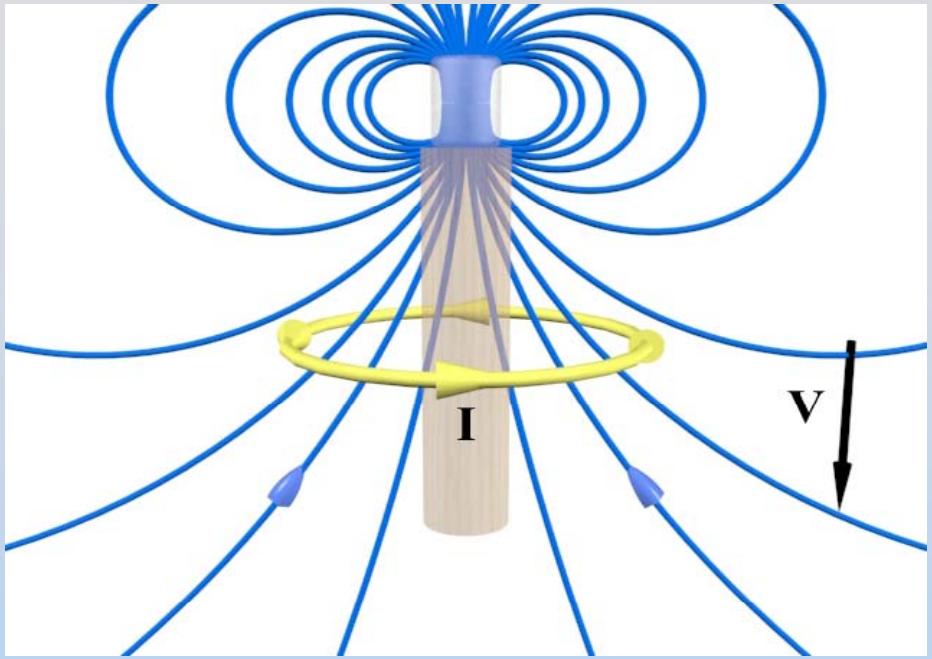


Moving from *above* to *below*, you would measure a *current* best represented by which plot above (taking counterclockwise current as positive)?

Concept Question Confirming Predictions?
Flux & Current

Concept Question Question:
Wrap-Up
Faraday's Law

Concept Q.: Loop Below Magnet



A conducting loop is below a magnet and moving downwards. This induces a current as pictured. The *I ds x B* force on the coil is

0% 1. Up

0% 2. Down

0% 3. Zero

Ways to Induce EMF

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

Quantities which can vary with time:

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

The last of the Maxwell's Equations (Kind of)

Maxwell's Equations

Creating Electric Fields

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

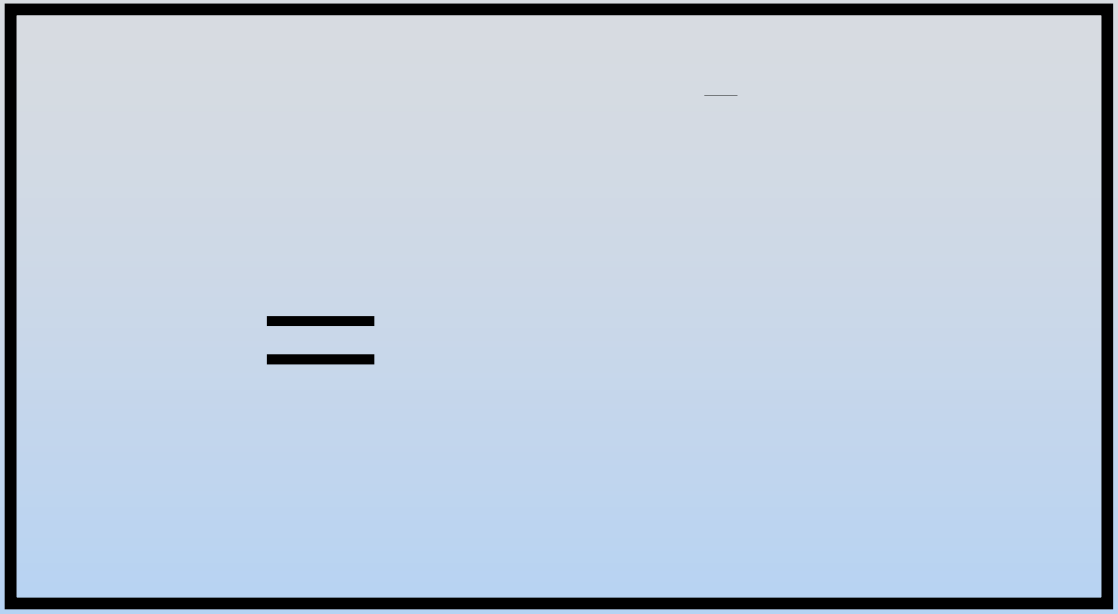
$$\oint_C \vec{\mathbf{E}} \cdot d\,\vec{\mathbf{s}} = -\frac{d\Phi_B}{dt}$$ (Faraday's Law)

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)

Faraday's Law of Induction



Changing magnetic flux *induces* an EMF

Lenz: Induction ***opposes*** change

Faraday's Law
Problem Solving Session

Ways to Induce EMF

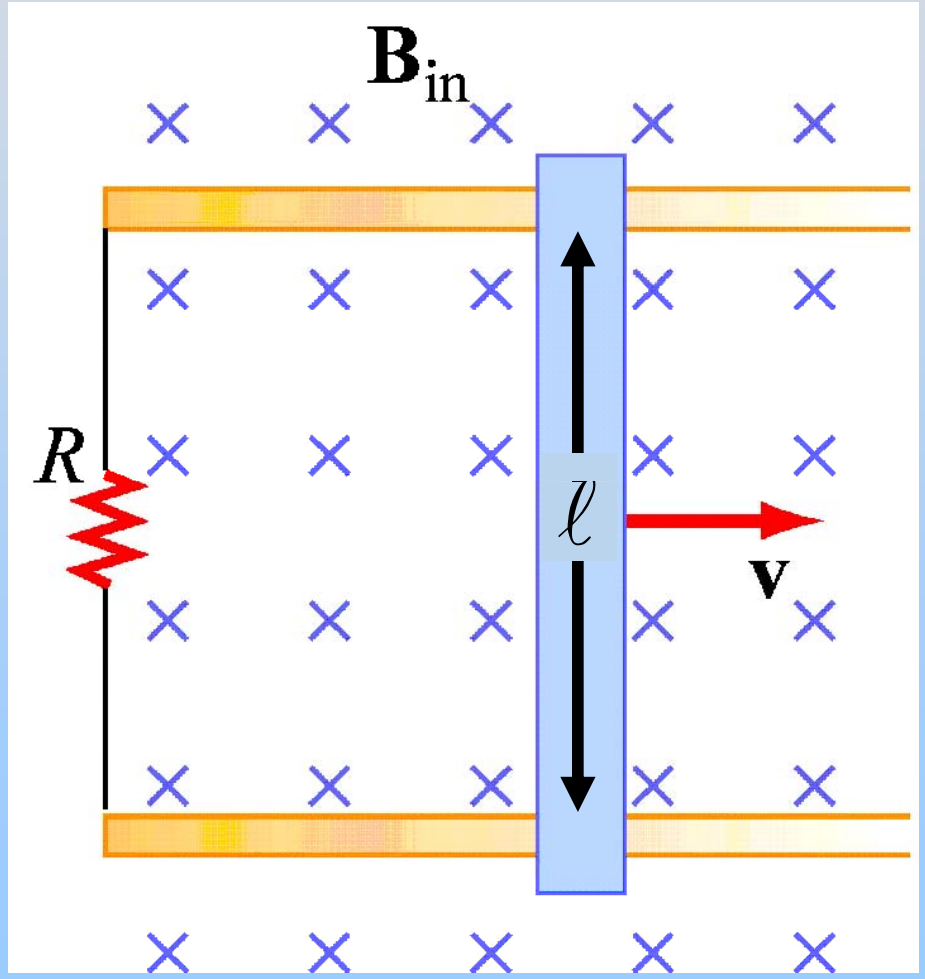
$$\mathcal{E} = - \frac{d}{dt}\left(BA\cos\theta\right)$$

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

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?

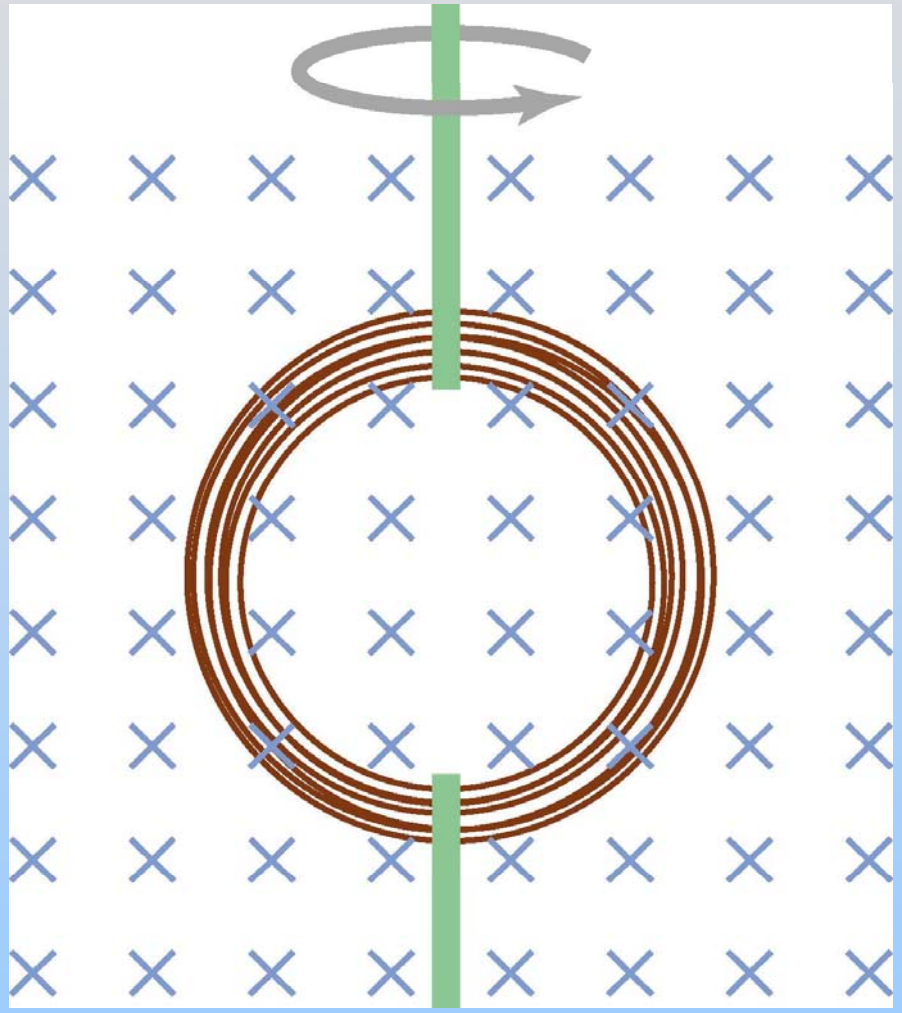
Ways to Induce EMF

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

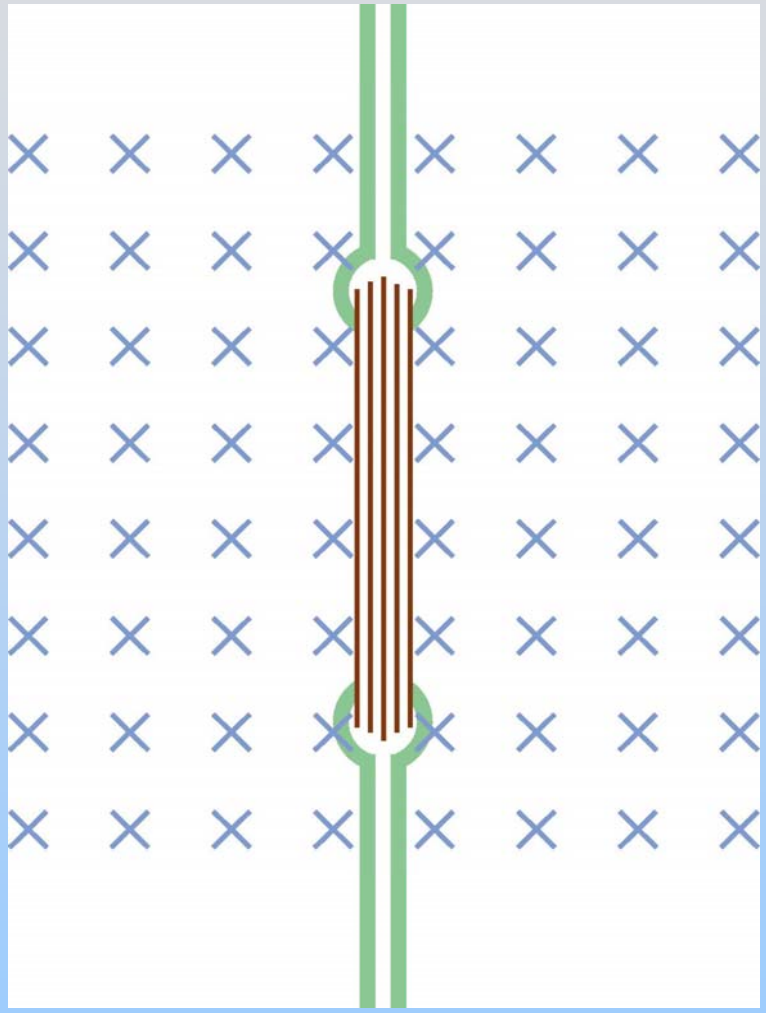
Quantities which can vary with time:

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

Changing Angle

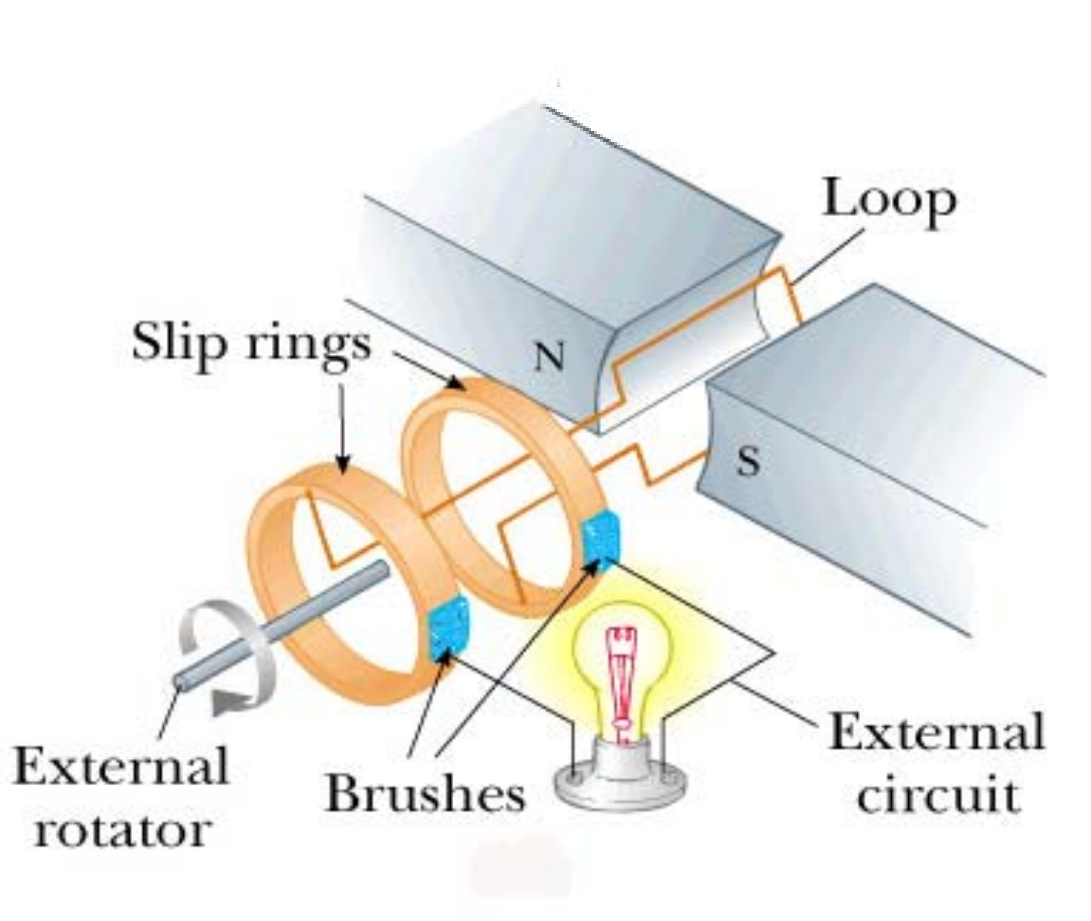


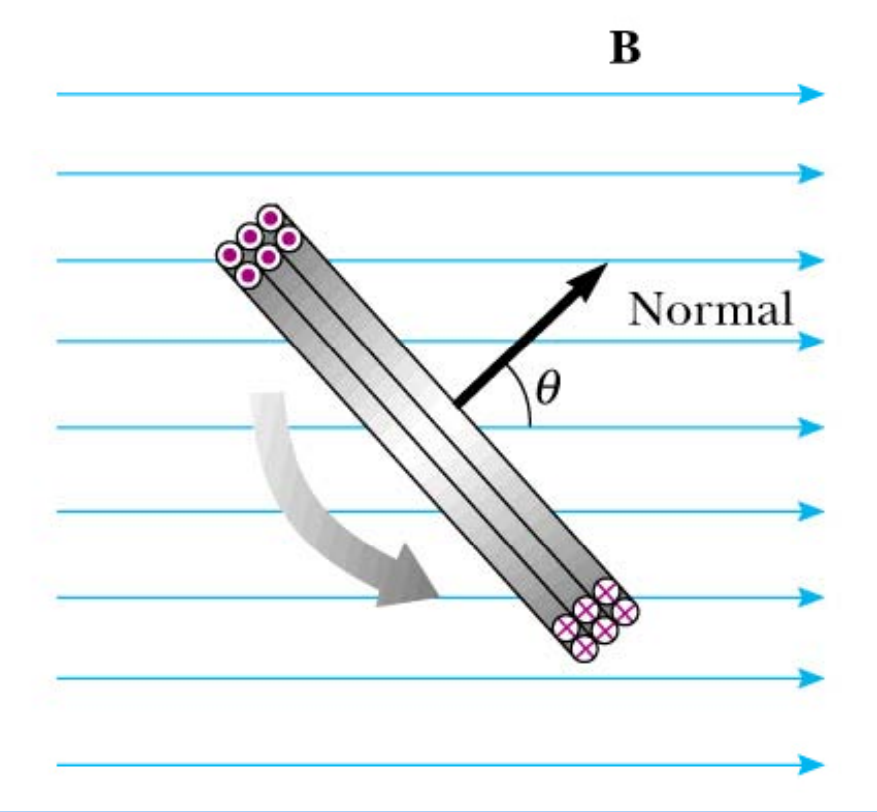
$$\Phi_B = \vec{\mathbf{B}} \cdot \vec{\mathbf{A}} = BA$$



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

Motors & Generators

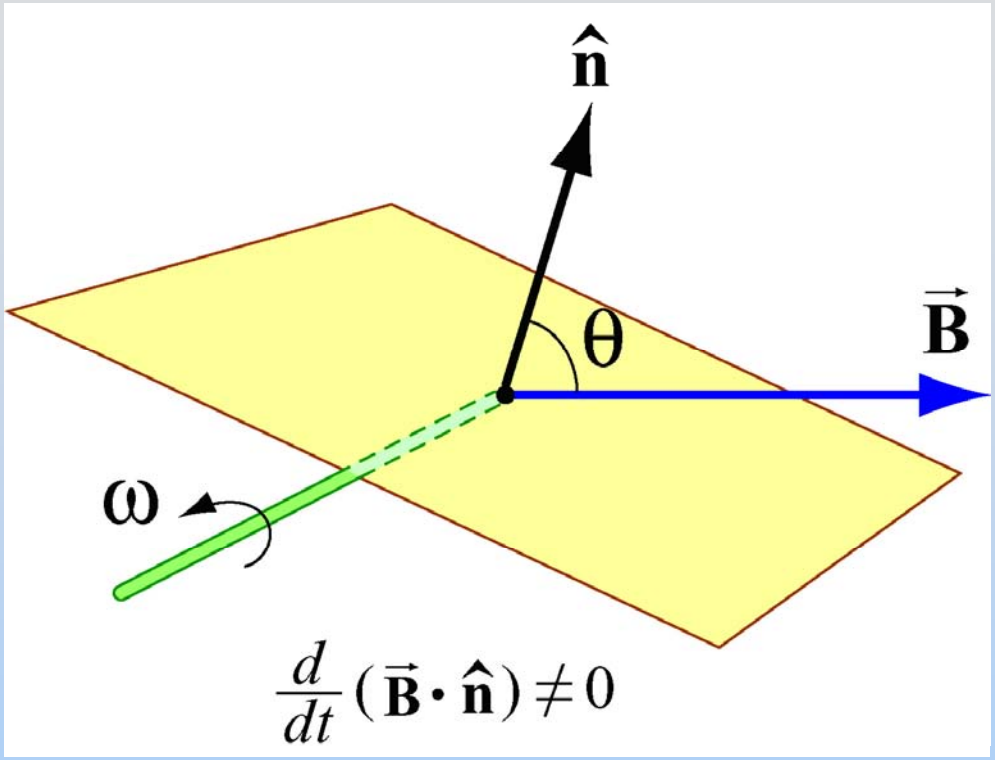




Concept Question Question: Generator

Concept Question: Generator

A square coil rotates in a magnetic field directed to the right. At the time shown, the current in the square, when looking down from the top of the square loop, will be

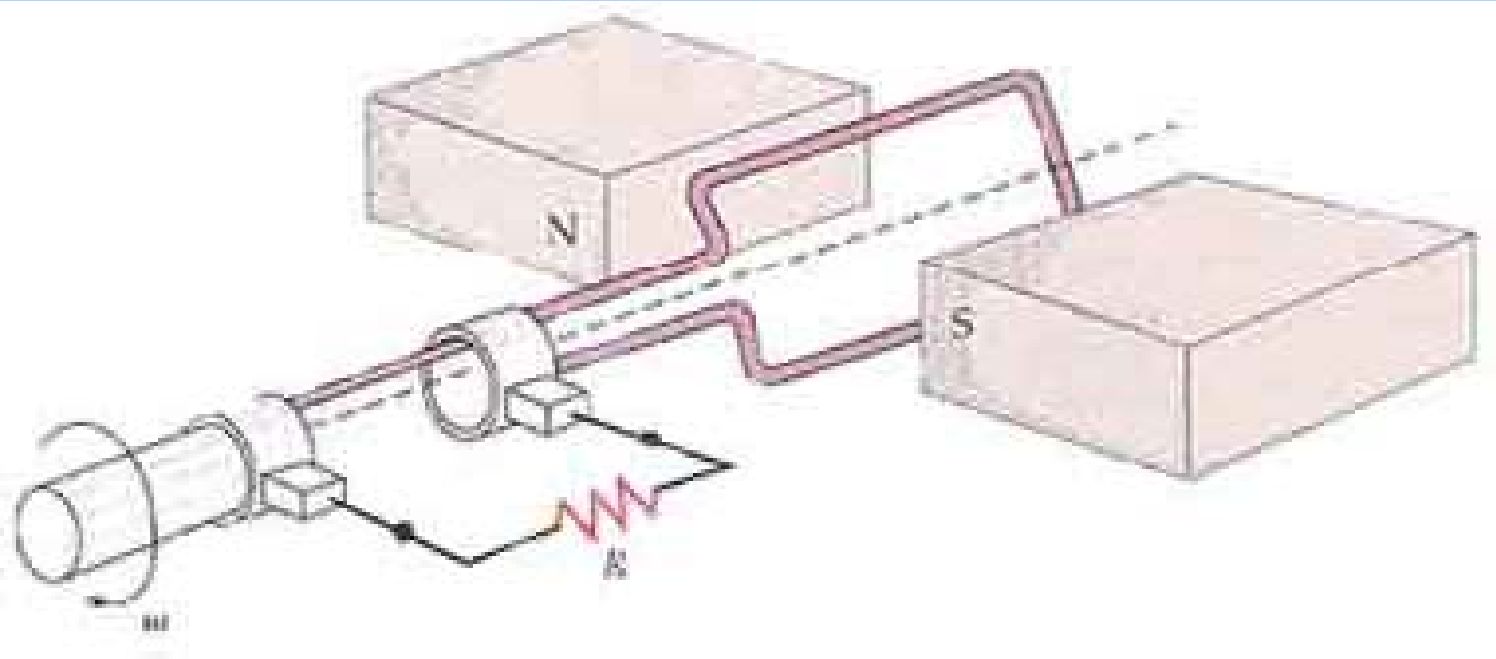


1. Clockwise
2. Counterclockwise
3. Neither, the current is zero
4. I don't know

Problem: Generator

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

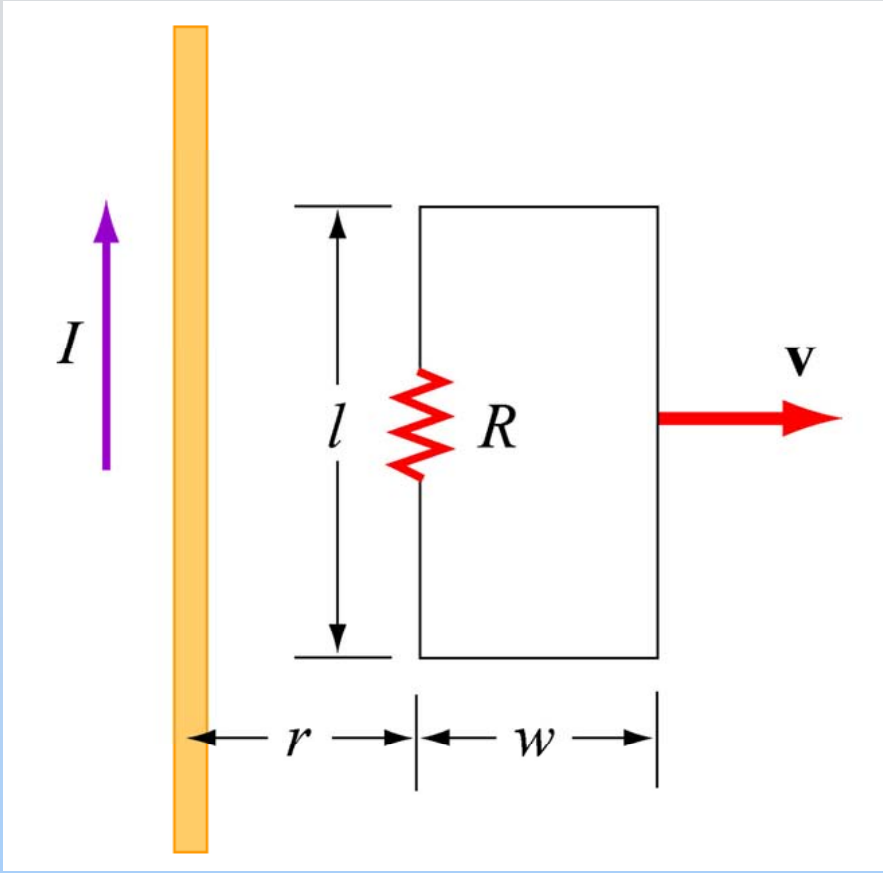
1) Write an expression for current $I(t)$ assuming the loop is vertical at time $t = 0$.
2) How much work from generator per revolution?
3) To make it twice as hard to turn, what do you do to *R*?



Concept Question Question:
Wrap-Up
Faraday's Law

Concept Question: Circuit

A circuit in the form of a rectangular piece of wire is pulled away from a long wire carrying current *I* in the direction shown in the sketch. The induced current in the rectangular circuit is



1. Clockwise
2. Counterclockwise
3. Neither, the current is zero

8.02SC Physics II: Electricity and Magnetism

Fall 2010