Lectures: Physics 3306

Provides an introduction to a wide variety of topics in classical (pre-quantum) physics as a bridge to prepare students for subsequent upper-level courses in physics. The topics covered include thermodynamics, fluid mechanics, mechanical waves, optics, radiation, electromagnetic phenomena, atoms, and laboratory techniques. Prerequisites: C- or better in PHYS 1106; and in PHYS 1304 or PHYS 1308.

Saptaparna Bhattacharya

April 13th, 2026

Based on Simon Dalley's lectures taught in Spring 2025

Labs

Lectures

Schedule

No class

Month	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
January	19	20	21 ✅	22	23 ✅	24	25
	26 ❄️🌨️❄❄❄	27	28 ❄️🌨️❄❄❄	29	30 ✅	31	1
February	2 ✅	3	4 ✅	5	6 ✅	7	8
	9 ✅	10	11 HWB due ✅	12	13 ✅	14	15
	16 ✅	17	18 ✅	19	20 HWC due ✅	21	22
	23 Hegi Center ✅	24	25 HWD due ✅	26	27 ✅	28	1
March	2 ✅	3	4 HWE due	5	6 ✅	7	8
	9 ✅	10	11	12	13 Midterm	14	15
	16	17	18	19	20	21	22
	23 ✅	24	25	26	27 ✅	28	29
April	30 Lecture 11	31	1 HWF due	2	3	4	5

Labs

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Schedule

No class

Month	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
April	6 Midterm 2	7	8 HWG due	9	10 Lecture 15	11	12
	13 Lecture 16	14	15 HWH due	16	17 Lecture 17	18	19
	20 Lecture 18	21	22 HWI due	23	24 Lecture 19	25	26
May	27 Lecture 20	28	29 HWJ due	30	1 Lecture 21	2	3
	4 Lecture 22	5 Lecture 23	6	7	8	9	10

Halliday: 32.1 - 32.3

MAXWELL'S EQUATIONS: THE FOUNDATIONS OF ELECTROMAGNETISM

1. GAUSS'S LAW FOR ELECTRICITY

$$\oint \vec{E} \cdot d\vec{A} = \frac{Q_{enc}}{\varepsilon_0}$$

Relates electric flux through a **closed surface** to the enclosed electric charge.

2. GAUSS'S LAW FOR MAGNETISM

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

Magnetic field lines form closed loops; **no magnetic** monopoles exist.

3.FARADAY'S LAW OF INDUCTION

$$\oint \vec{E} \cdot d\vec{l} = -\frac{d\Phi_B}{dt}$$

A changing magnetic field induces a circulating electric field.

4. AMPÈRE'S LAW (with Maxwell's Addition)

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 \left(I_{enc} + \varepsilon_0 \frac{d\Phi_E}{dt} \right)$$

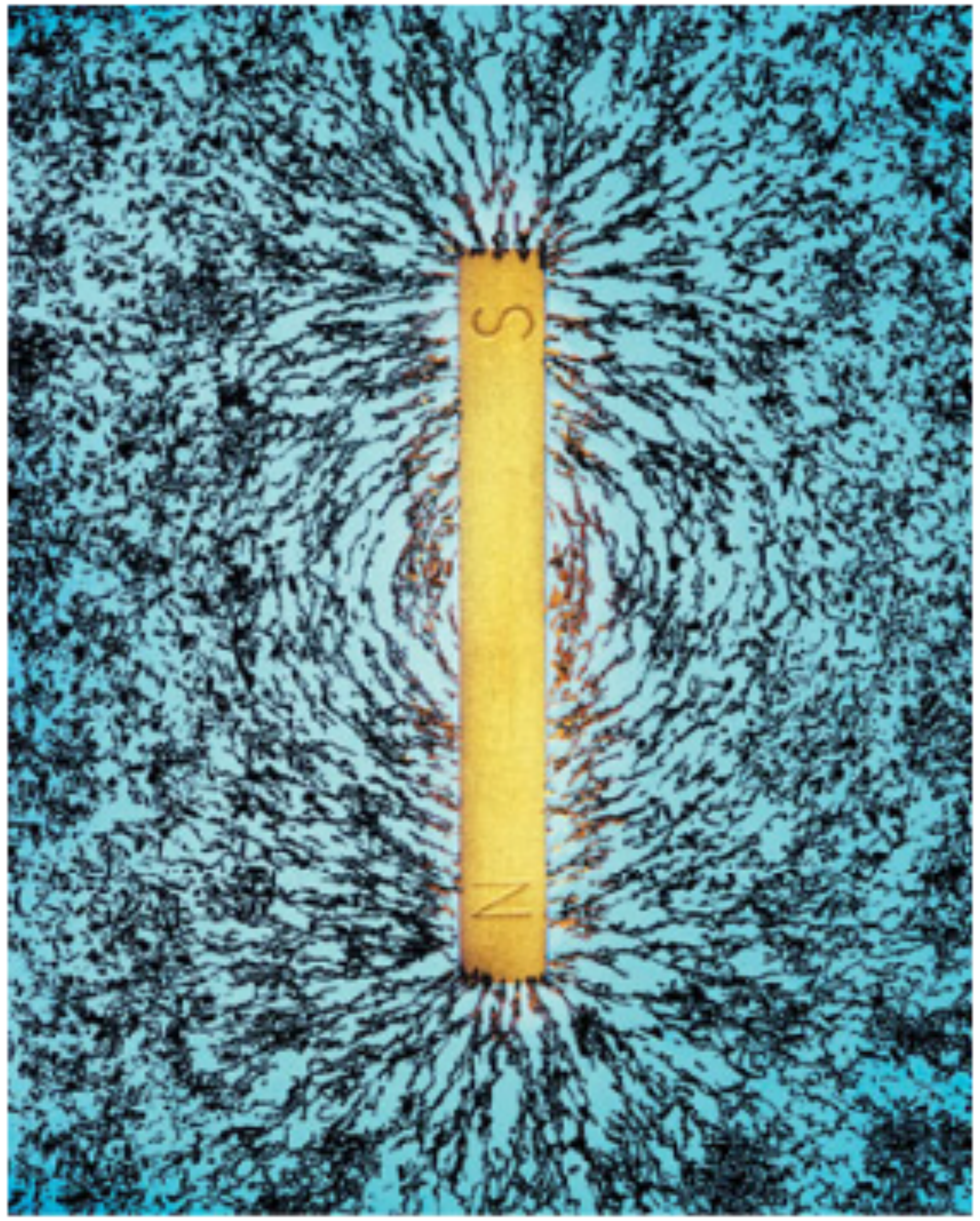
Magnetic fields are generated by electric currents AND changing electric fields.

Before jumping in…

- Tell me what you know about electricity and magnetism
  - Faraday’s law
  - Ampere’s law
  - Capacitor
  - Inductor

Key concepts: Gauss’ Law

- Gauss’ law for magnetic fields is a formal way of saying that magnetic monopoles do not exist
  - Net magnetic flux Φ_B through any closed Gaussian surface is zero
  - $\Phi_B = \oint \overrightarrow{B} \cdot d\overrightarrow{A} = 0$
- Gauss’ law for electric fields:
  - $\Phi_E = \oint \overrightarrow{E} \cdot d\overrightarrow{A} = \dfrac{q_{\text{enc}}}{\epsilon_0}$
  - Gauss’ law for electric fields says that this integral (the net electric flux through the surface) is proportional to the net electric charge q_{enc} enclosed by the surface



Richard Megna/Fundamental Photographs

Figure 32-2 A bar magnet is a magnetic dipole. The iron filings suggest the magnetic field lines. (Colored light fills the background.)

Key concepts: Gauss' Law

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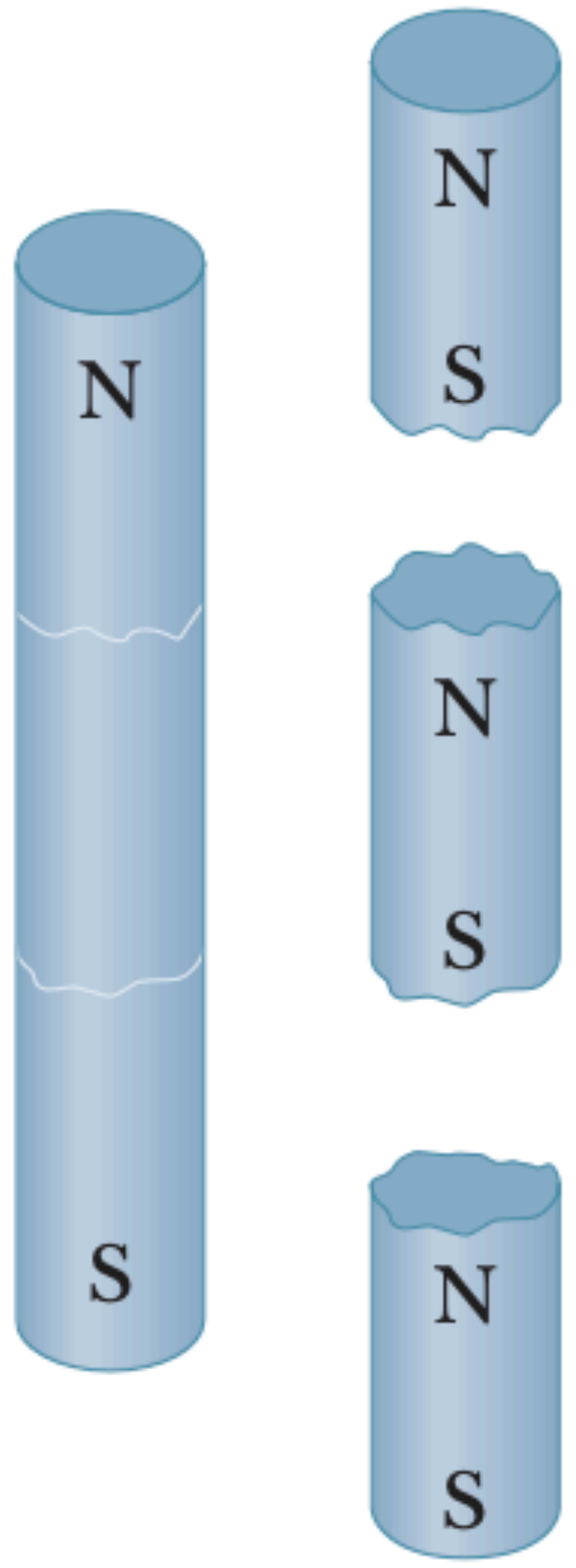

Figure 32-3 If you break a magnet, each fragment becomes a separate magnet, with its own north and south poles.

Key concepts: Gaussian surface

- **The Three Rules for Choosing a Surface**
  - To pull E out of the integral, your chosen imaginary surface must perfectly exploit the symmetry of the charge distribution. A valid Gaussian surface must satisfy these conditions:
    - **Symmetry Match:** The surface should mimic the shape of the electric field created by the charge distribution.
    - **Constant Field Magnitude:** The magnitude of the electric field (E) must be constant over the portions of the surface where the field lines pass through.
    - **Perpendicular or Parallel:** The electric field vectors must be either exactly perpendicular to the surface ($E \parallel dA$ so the dot product is $E \cdot dA$) or exactly parallel to the surface ($E \perp dA$, so the flux is zero).
- Standard Choices for Common Symmetries: Because of the strict rules above, there are really only three standard Gaussian surfaces used in introductory physics:
  - **Spherical Symmetry (Point charges, charged spheres, or spherical shells):**
    The Choice: A concentric Sphere.
    Why: The electric field points radially outward (or inward) in all directions. On the surface of a concentric sphere, the electric field is everywhere perpendicular to the surface and has the exact same magnitude at every point.
  - **Cylindrical Symmetry (Infinite line charges, charged wires, or long cylinders):**
    The Choice: A coaxial **Cylinder** (with flat end caps).
    Why: The field radiates straight outward from the line. On the curved part of the cylinder, the field is perpendicular to the surface and constant in magnitude. On the flat end caps, the field is parallel to the surface, meaning no field lines pass through them (flux is zero).
  - **Planar Symmetry (Infinite sheets of charge or large flat conducting plates):**
    The Choice: A **"Pillbox"** (a small cylinder or rectangular box that pierces through the sheet like a needle through fabric).
    Why: The field points straight away from the sheet on both sides. The flux only passes through the flat end caps of the pillbox (where E is constant and perpendicular to the surface). The flux through the sides of the pillbox is zero because the field is parallel to those sides.

The Maxwell equations are valid:

A.Always

B.If the charges are not accelerating

C.If the fields are static

D.If the currents are steady

E.If the fields are not in vacuum

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A. Always

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Maxwell's equations are the fundamental laws of classical electromagnetism and are universally valid within the classical regime. They do not require special conditions to hold true:

- **Accelerating charges (B):** Maxwell's equations perfectly describe accelerating charges; this is exactly how electromagnetic radiation (like light or radio waves) is generated.
- **Dynamic fields and currents (C & D):** The equations specifically account for changing fields and non-steady currents (most notably through Faraday's Law of Induction and the Maxwell-Ampère Law).
- **In a vacuum (E):** They are entirely valid in a vacuum, which is how we understand that electromagnetic waves can travel through empty space.

Key concepts: Faraday’s Law

- Changing magnetic flux induces an electric field:
  - Faraday’s law of induction:
    - $\oint \overrightarrow{E} \cdot d\vec{s} = -\frac{d\Phi_B}{dt}$
    - $\overrightarrow{E}$ = electric field induced along a closed loop by the changing magnetic flux Φ_B encircled by that loop
- Symmetry is powerful:
  - Can induction occur in the opposite sense; that is, can a changing electric flux induce a magnetic field
  - Yes!
- Maxwell’s law of induction:
  - $\oint \overrightarrow{B} \cdot d\vec{s} = \mu_0 \epsilon_0 \frac{d\Phi_E}{dt}$

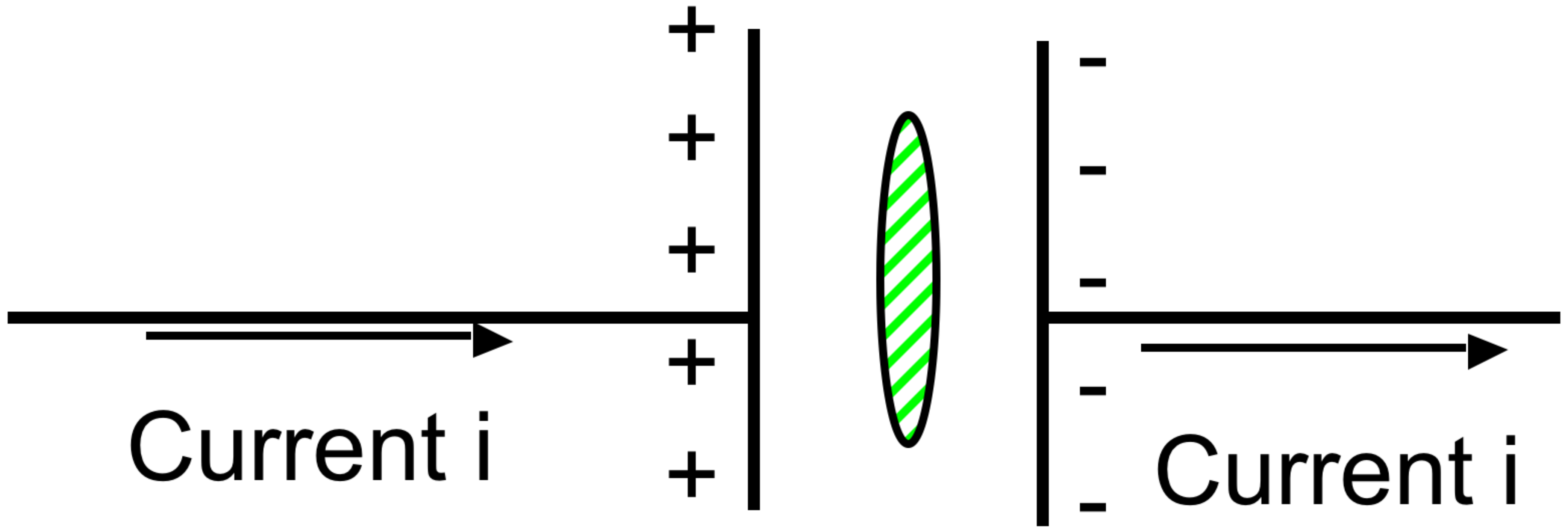
A capacitor is charging. (Neglect “edge effects”)

Is there electric flux Φ_E through the green hatched area shown?

A) YES

B) NO

C) I’m not really so sure



A capacitor is charging. (Neglect "edge effects")

Is there electric flux Φ_E through the green hatched area shown?

A) YES

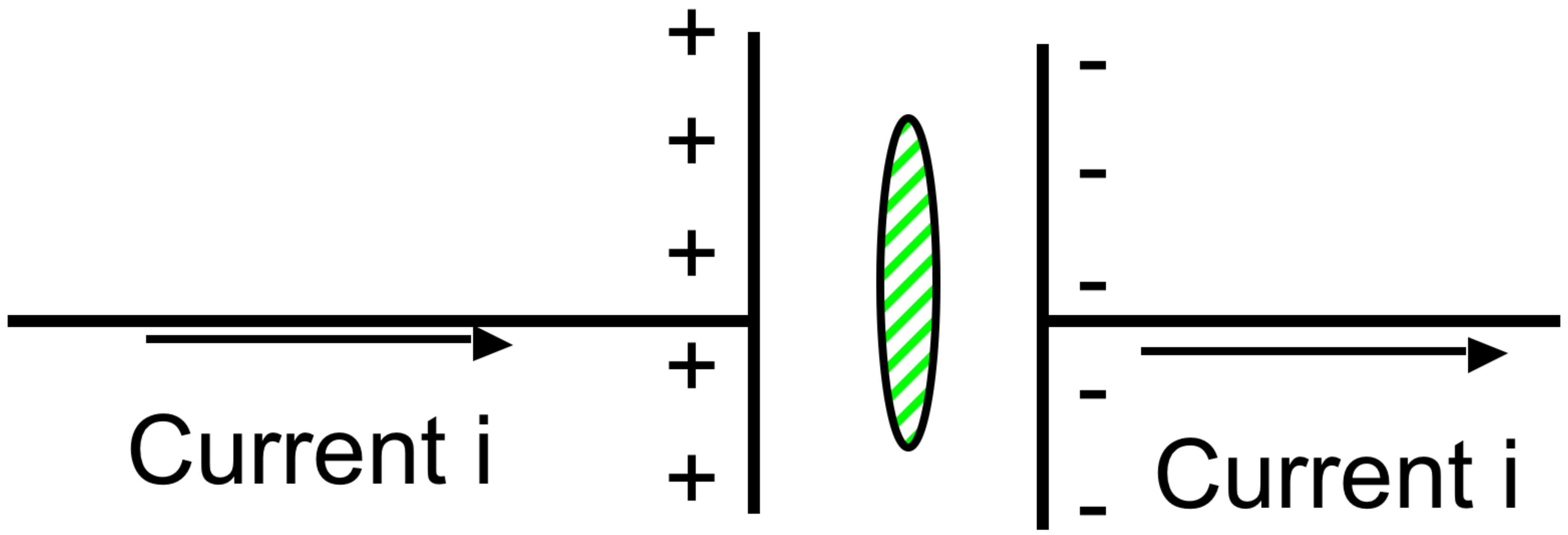
B) NO

C) I'm not really so sure

- **Electric Field:** As the capacitor charges, positive charge accumulates on one plate and negative charge on the other. This creates an electric field ($\vec{E}$) between the plates that points uniformly from the positive plate to the negative plate.
- **Electric Flux:** Electric flux (Φ_E) measures the amount of electric field passing through a given area. Mathematically, it is the dot product of the electric field vector and the area vector:

$$\Phi_E = \vec{E} \cdot \vec{A}$$

Because the electric field lines pierce directly through the surface area between the plates, there is a non-zero electric flux.



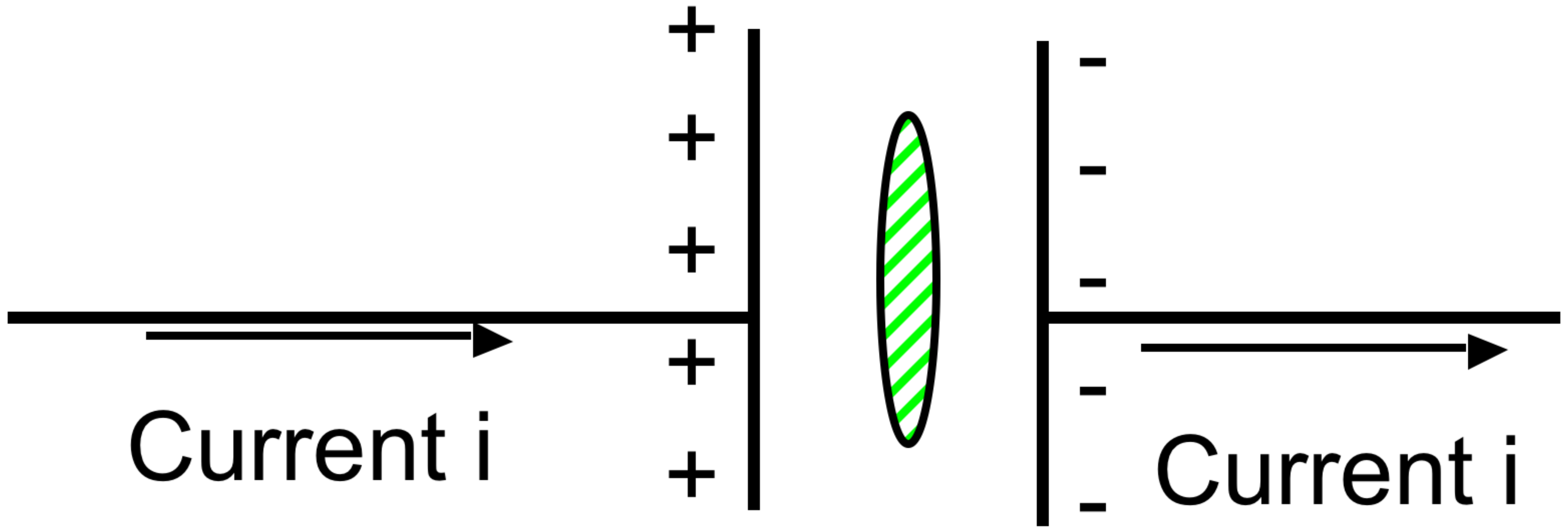
A capacitor is charging. (Neglect “edge effects”)

Is the electric flux Φ_E through the green hatched area shown changing with time?

A) YES

B) NO

C) I’m not really so sure



A capacitor is charging. (Neglect "edge effects")

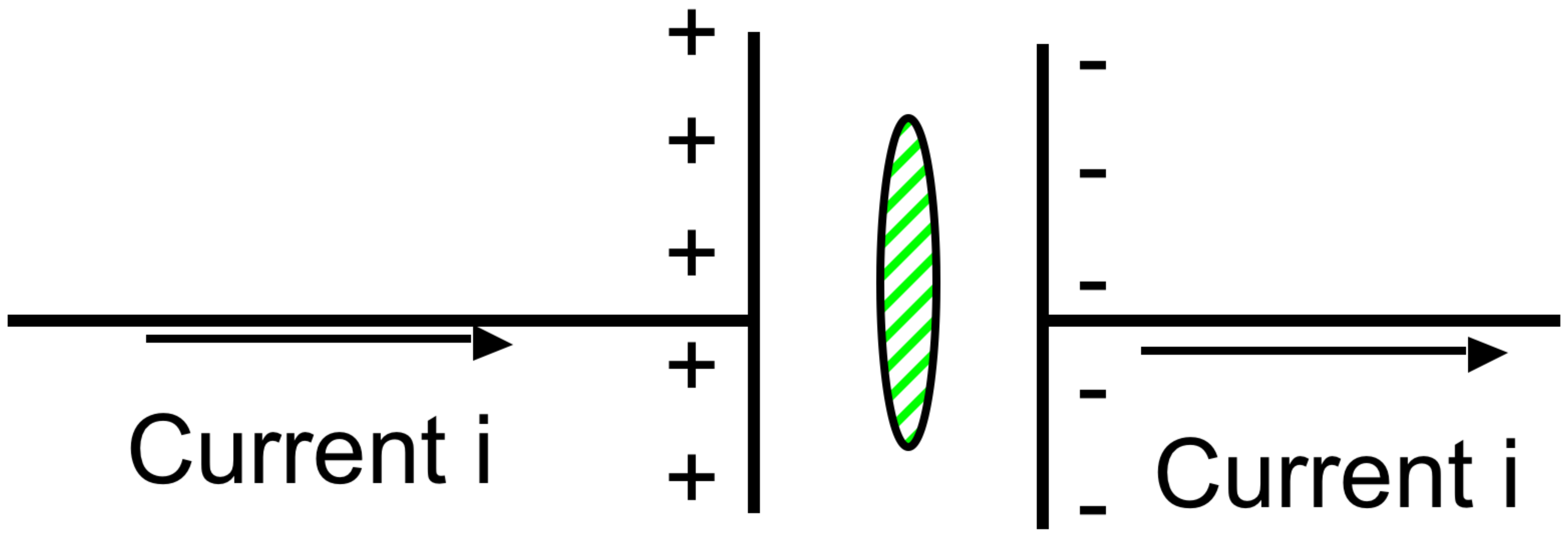
Is the electric flux Φ_E through the green hatched area shown changing with time?

A) YES

B) NO

C) I'm not really so sure

- **Charge Accumulation:** Because the capacitor is actively *charging*, the total charge Q on the plates is increasing over time.
- **Electric Field Strength:** The electric field E between the plates is directly proportional to the charge on the plates ($E = \frac{Q}{\epsilon_0 A}$). Since Q is increasing, the strength of the electric field E is also increasing.
- **Changing Flux:** Because the electric field E is getting stronger as time goes on, the electric flux ($\Phi_E = E \cdot A$) through the static area must also be increasing with time.



Key concepts: Ampere’s Law

- Ampere’s law:
  - $\oint \vec{B} \cdot d\vec{s} = \mu_0 i_{\text{enc}}$

Figure 32-6 A uniform magnetic field $\vec{B}$ in a circular region. The field, directed into the page, is increasing in magnitude. The electric field $\vec{E}$ induced by the changing magnetic field is shown at four points on a circle concentric with the circular region. Compare this situation with that of Fig. 32-5*b*.

The induced $\vec{E}$ direction here is opposite the induced $\vec{B}$ direction in the preceding figure.

Key concepts: Ampere's Law

- Combining Maxwell's law of induction and Ampere's law:
  - $\oint \overrightarrow{B} \cdot d\vec{s} = \mu_0 \epsilon_0 \frac{d\Phi_E}{dt} + \mu_0 i_{\text{enc}}$
  - When there is a current but no change in electric flux (such as with a wire carrying a constant current), the first term is zero
  - When there is a change in electric flux but no current (such as inside or outside the gap of a charging capacitor), the second term on the right side is zero

Key concepts: Displacement current

- Combining Maxwell's law of induction and Ampere's law:
  - $\oint \overrightarrow{B} \cdot d\vec{s} = \mu_0 \epsilon_0 \frac{d\Phi_E}{dt} + \mu_0 i_{\text{enc}}$
- The first term on the right hand side:
  - $\mu_0 \epsilon_0 \frac{d\Phi_E}{dt}$ must have the dimensions of current
  - This term is called "displacement current"
    - Misnomer, nothing is being displaced
    - Associated with a changing field ($\overrightarrow{E}$)
    - Charge q on the plates at any time is related to the magnitude E of the field between the plates at that time and the plate area A
      - $q = \epsilon_0 A E$
      - $\frac{dq}{dt} = i = \epsilon_0 A \frac{dE}{dt}$

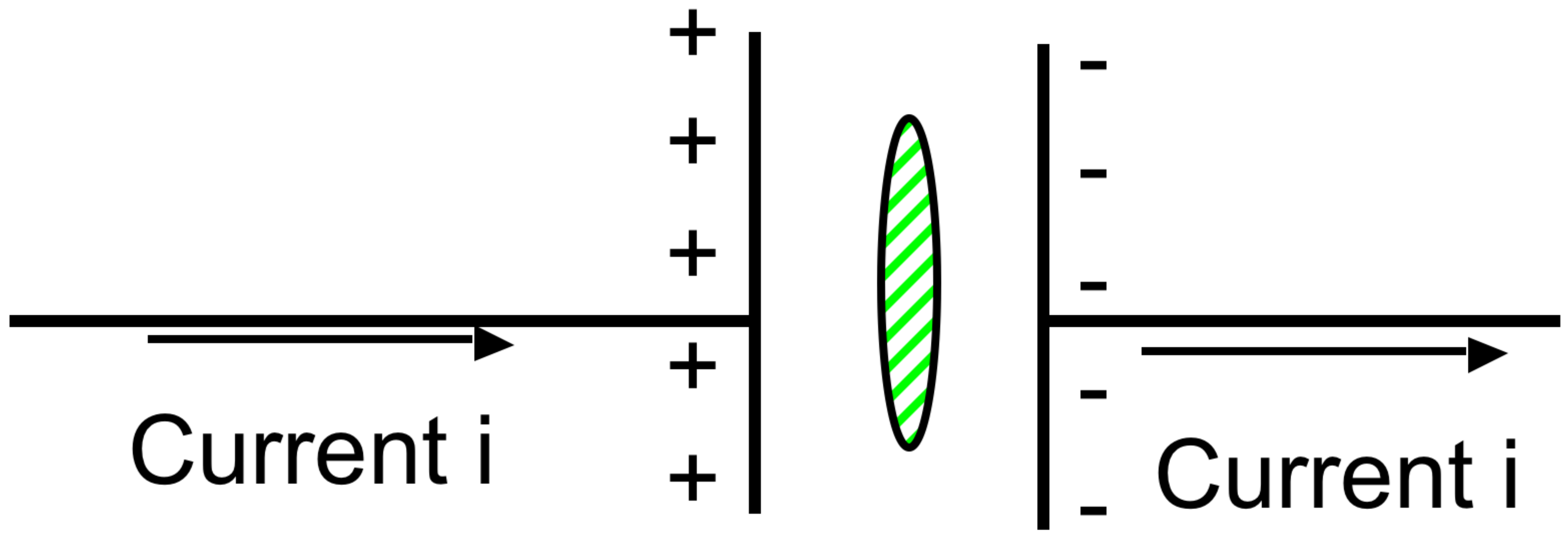
A capacitor is charging. (Neglect “edge effects”)

Is there magnetic field between the plates of the capacitor?

A) YES

B) NO

C) I’m not really so sure



A capacitor is charging. (Neglect “edge effects”)

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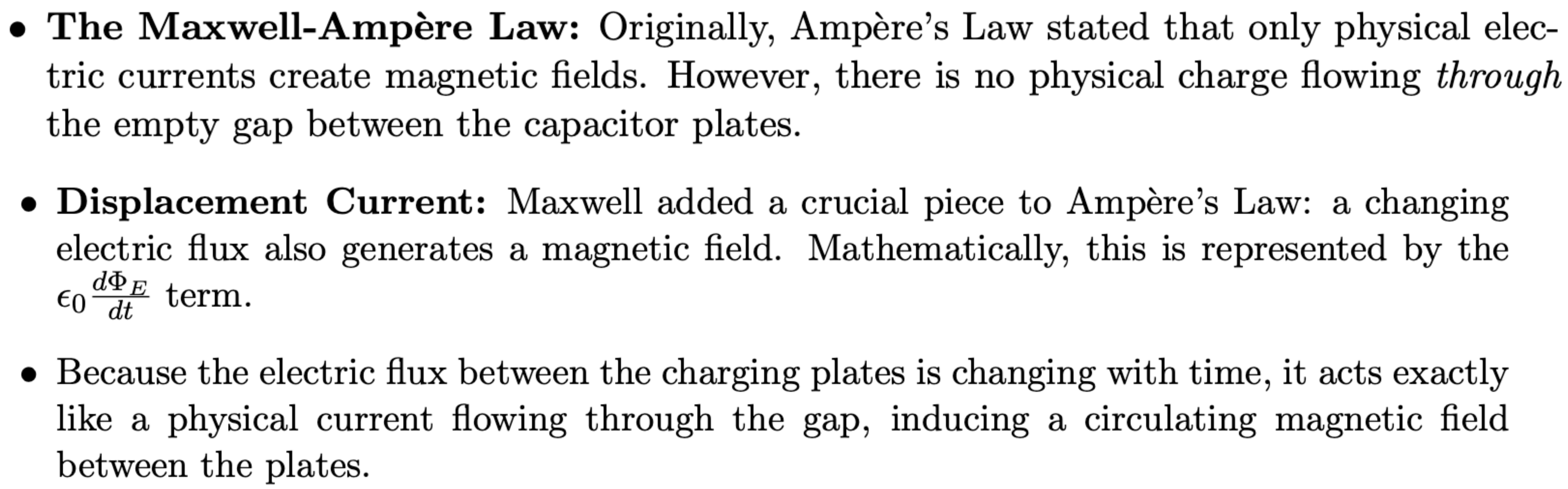
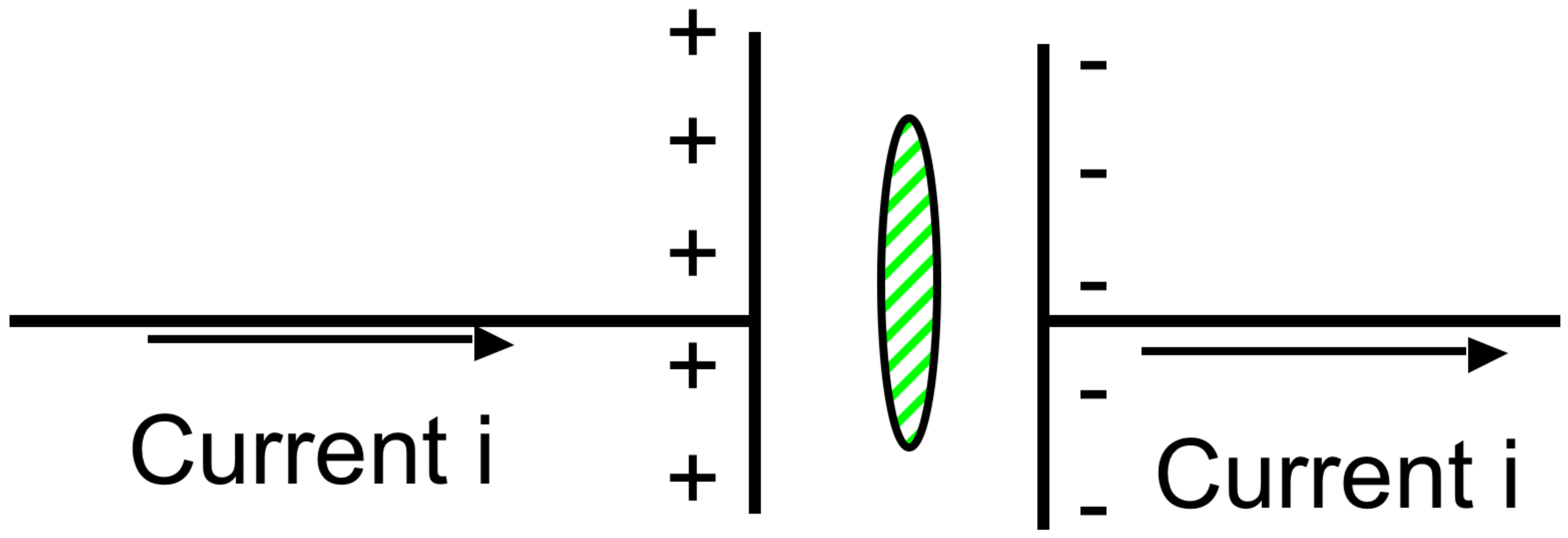


- **The Maxwell-Ampère Law:** Originally, Ampère’s Law stated that only physical electric currents create magnetic fields. However, there is no physical charge flowing *through* the empty gap between the capacitor plates.
- **Displacement Current:** Maxwell added a crucial piece to Ampère’s Law: a changing electric flux also generates a magnetic field. Mathematically, this is represented by the $\epsilon_0 \frac{d\Phi_E}{dt}$ term.
- Because the electric flux between the charging plates is changing with time, it acts exactly like a physical current flowing through the gap, inducing a circulating magnetic field between the plates.



The capacitor is now fully charged.

Is there magnetic field between the plates of the capacitor?

A) YES

B) NO

C) I’m not really so sure

The capacitor is now fully charged.

Is there magnetic field between the plates of the capacitor?

A) YES

B) NO

C) I’m not really so sure

Correct Answer: B) NO

Explanation: When a capacitor reaches a fully charged state, the physical dynamics change significantly:

- **Current Stops:** The physical current i flowing into the capacitor drops to zero.
- **Static Electric Field:** The amount of charge on the plates reaches its maximum and becomes constant. Consequently, the electric field between the plates is also constant and is no longer changing over time.
- **Zero Displacement Current:** Because the electric field is steady, its rate of change with respect to time is zero ($\frac{d\Phi_E}{dt} = 0$).

We can see this mathematically using the complete Ampère-Maxwell Law:

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 I_{enc} + \mu_0 \epsilon_0 \frac{d\Phi_E}{dt}$$

Between the plates, there is no physical current ($I_{enc} = 0$), and because the capacitor is fully charged, the electric flux is no longer changing ($\frac{d\Phi_E}{dt} = 0$). With both terms on the right side equaling zero, no magnetic field is generated.

How does the flux (whether electric or magnetic) across the open surface bounded by the same loop depend upon the surface chosen?

A) The flux is larger for the larger area

B) The flux is larger for the smaller area

C) The flux is the same

D) It depends on the shape

How does the flux (whether electric or magnetic) across the open surface bounded by the same loop depend upon the surface chosen?

C) The flux is the same

Explanation: Here is the best way to visualize why this is true:

1. **The Butterfly Net Analogy:** Imagine the closed boundary loop as the solid rim of a butterfly net, and the vector field (electric or magnetic) as wind blowing through it. The flux is essentially the amount of "wind" passing through the net.
2. **Conservation of Field Lines:** Whether your netting is completely flat and stretched tight across the rim (the left image), or deep and cone-shaped (the right image), every single bit of wind that passes through the rim *must* also pass through the netting to exit.
3. **No Hidden Sources:** Assuming there are no charges (for electric fields) or magnetic monopoles magically floating in the space between the flat surface and the curved surface, field lines cannot start or stop in that gap. Therefore, any field line that enters through the flat boundary area must exit through the curved surface.

Because every field line that goes through one surface must go through the other, the total flux through any surface bounded by that exact same loop is identical.

A) The flux is larger for the larger area

B) The flux is larger for the smaller area

C) The flux is the same

D) It depends on the shape

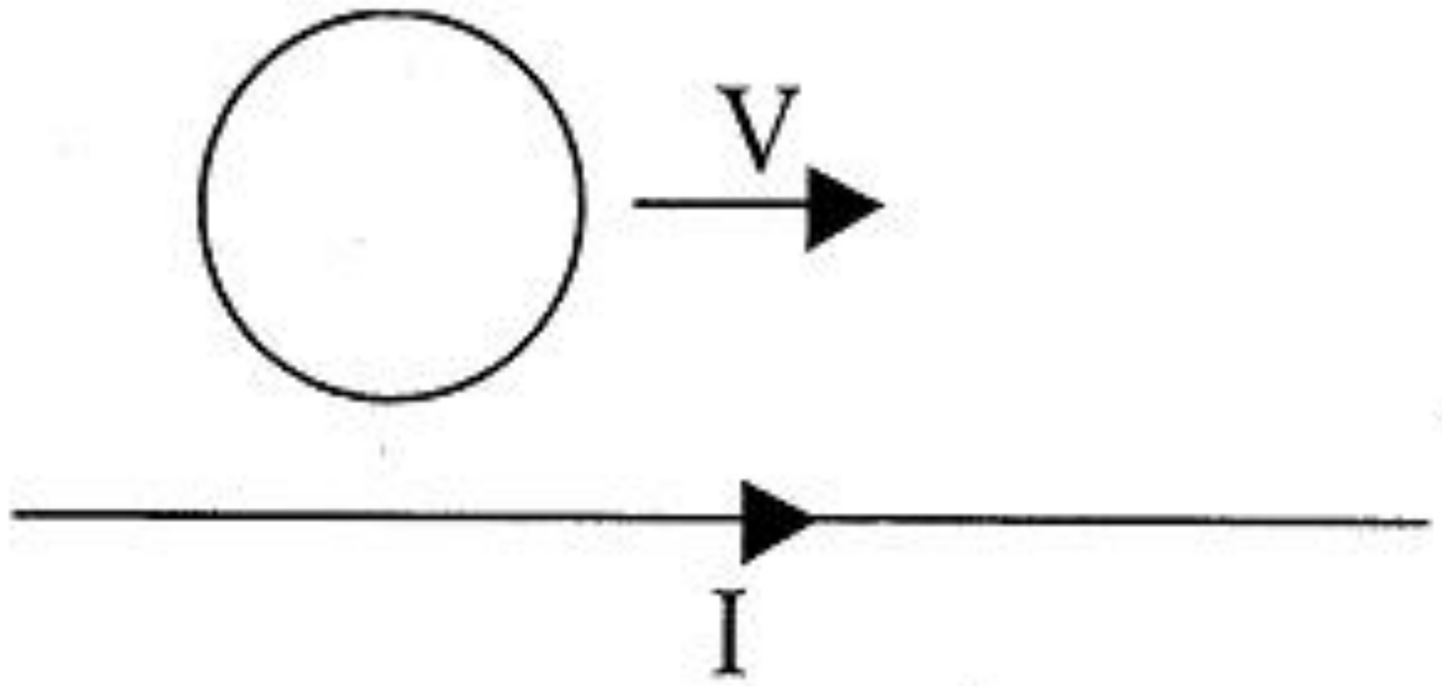
A circular loop of wire is moving at constant speed parallel to a long wire with current I. They are both in the plane of the page.

The induced current in the loop is:

A. Zero

B. Clockwise

C. Counter clockwise



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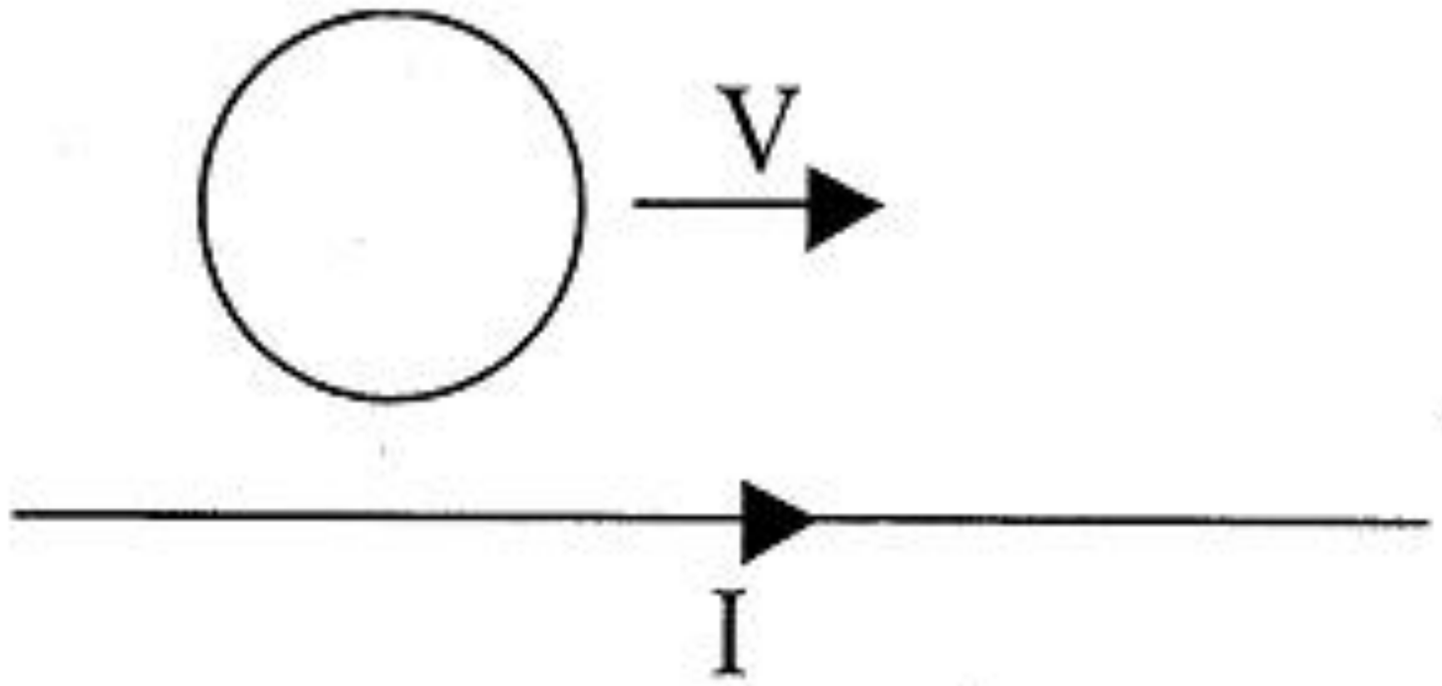


This problem requires applying Faraday's Law of Induction, which states that an electromotive force (EMF)—and thus an induced current—is only generated when the magnetic flux through a loop **changes** over time ($\mathcal{E} = -\frac{d\Phi_B}{dt}$).

Here is the step-by-step breakdown:

1. **The Magnetic Field:** The straight wire carrying current I to the right creates a magnetic field. Using the right-hand rule, we know this magnetic field points *out of the page* in the region above the wire where the loop is located. The strength of this magnetic field depends entirely on the distance from the wire (it gets weaker the further away you get).

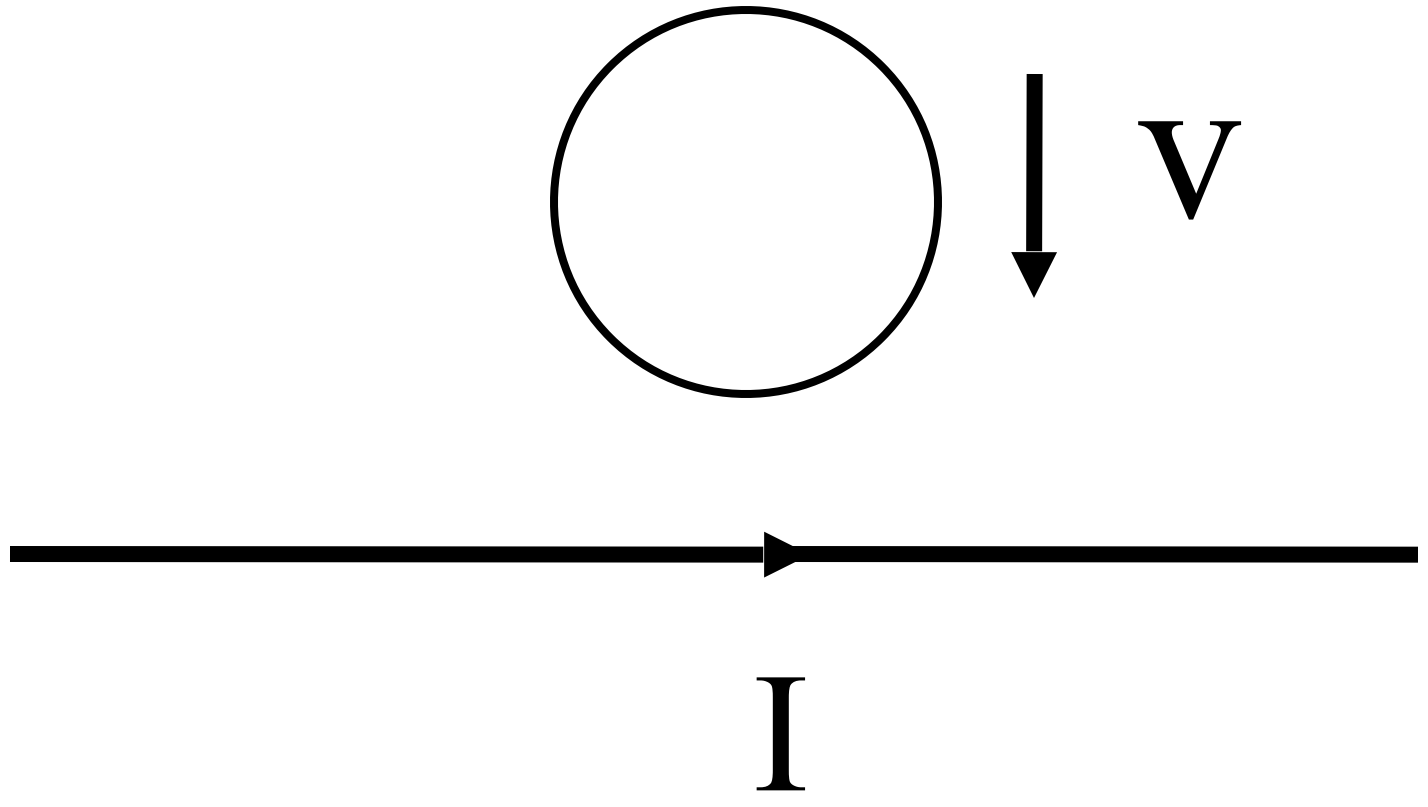
2. **Constant Distance:** The circular loop is moving with velocity v strictly *parallel* to the straight wire. Because it is moving parallel, its vertical distance from the current-carrying wire never changes.

3. **Constant Flux:** Since the distance from the wire isn't changing, the magnetic field strength penetrating the loop remains completely constant. The area of the loop is also constant. Therefore, the total magnetic flux (Φ_B) through the loop is not changing.

4. **No Induction:** Because there is no *change* in magnetic flux ($\frac{d\Phi_B}{dt} = 0$), there is no induced EMF. Consequently, no induced current flows through the loop.

A circular loop of wire is moving at constant speed toward a long wire with current I. They are both in the plane of the page.

The induced current in the loop is:

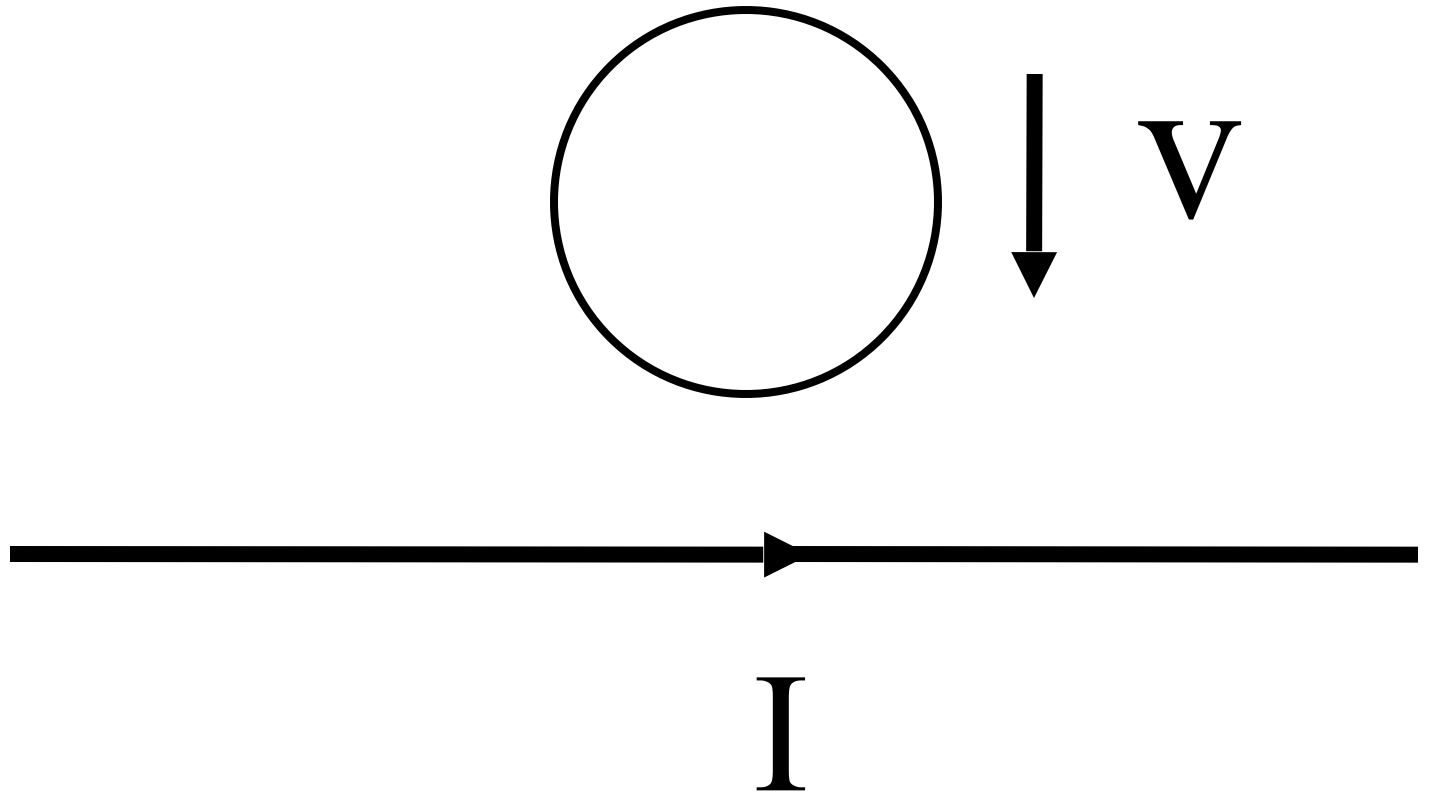


A. Zero

B. Clockwise

C. Counter clockwise

A circular loop of wire is moving at constant speed toward a long wire with current I.
They are both in the plane of the page.
The induced current in the loop is:



A. Zero

B. Clockwise

C. Counter clockwise

Explanation:
This problem requires applying Faraday's Law of Induction and Lenz's Law. Here is the step-by-step breakdown:

1. **The Original Magnetic Field:** The straight wire carries current I to the right. Using the right-hand grip rule, the magnetic field created by this wire points *out of the page* in the region above it where the loop is located.

2. **Changing Flux:** The strength of a magnetic field around a wire increases as you get closer to the wire ($B \propto 1/r$). Because the loop is moving *toward* the wire, the outward magnetic field penetrating the loop is constantly getting stronger. Therefore, the outward magnetic flux (Φ_B) through the loop is *increasing.*

3. **Lenz's Law:** Nature opposes a change in flux. To counteract the increasing outward flux, the loop will induce a current that creates its own magnetic field pointing in the opposite direction—*into the page.*

4. **Direction of Current:** Point your right thumb *into the page* (the direction of the induced magnetic field). Your fingers naturally curl in a **clockwise** direction, which dictates the path of the induced current.