E&M Waves
Where to go from here
Final Review

Phys 122A Lecture 28

Gray Rybka

B is related to E

- Wave eqn for E_x:

$$\frac{\partial^2 E_x}{\partial z^2} = \frac{1}{c^2}\frac{\partial^2 E_x}{\partial t^2}$$

- Similar derivation gives B_y:

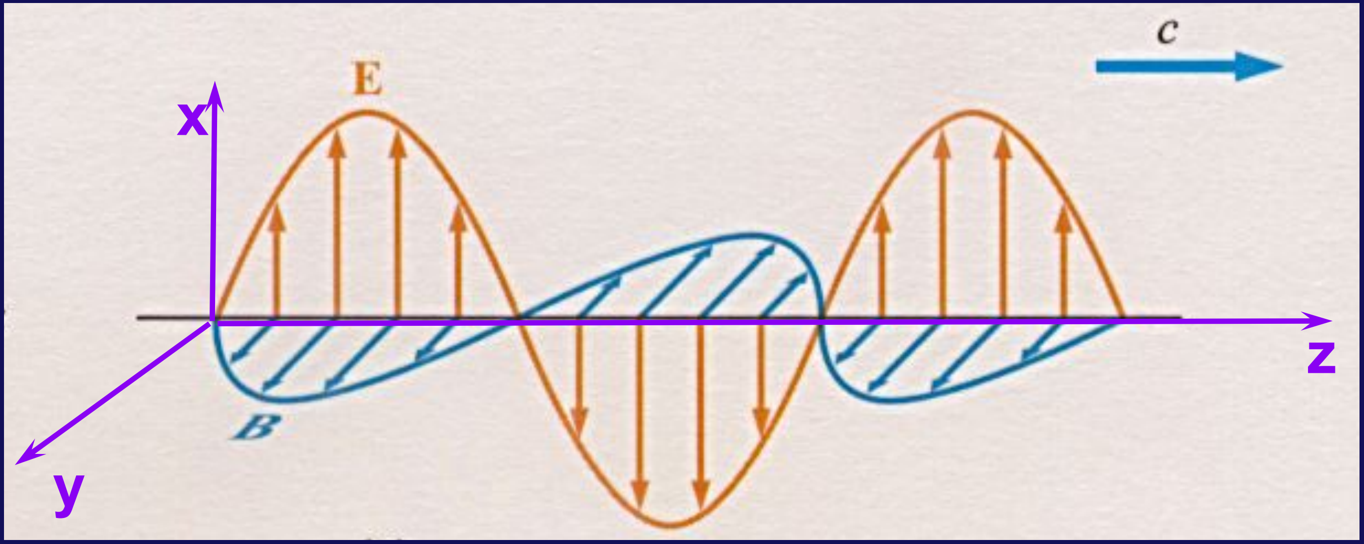
  (I will spare you the proof)

$$\frac{\partial^2 B_y}{\partial z^2} = \frac{1}{c^2}\frac{\partial^2 B_y}{\partial t^2}$$

- E_x and B_y are in phase

$$E_x = E_0 \sin(kz - \omega t)$$
$$B_y = B_0 \sin(kz - \omega t)$$

- And $B_0 = E_0 / c$ relates their magnitudes



Velocity of Electromagnetic Waves

- We derived the wave equation for E_x:

$$\frac{\partial^2 h}{\partial x^2} = \frac{1}{v^2}\frac{\partial^2 h}{\partial t^2}$$

wave eqn.

$$\boxed{\frac{\partial^2 E_x}{\partial z^2} = \mu_0 \varepsilon_0 \frac{\partial^2 E_x}{\partial t^2}}$$

- The velocity of EM waves in free space is embedded in the equation:

$$\boxed{v = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}}$$

- Using measured values for μ_0 & ε_0, we get:

$$v = 3.00 \times 10^8 \, m/s \equiv c$$

- This value is identical to the measured speed of light!
  - We identify light as an electromagnetic wave.

Important Consequences

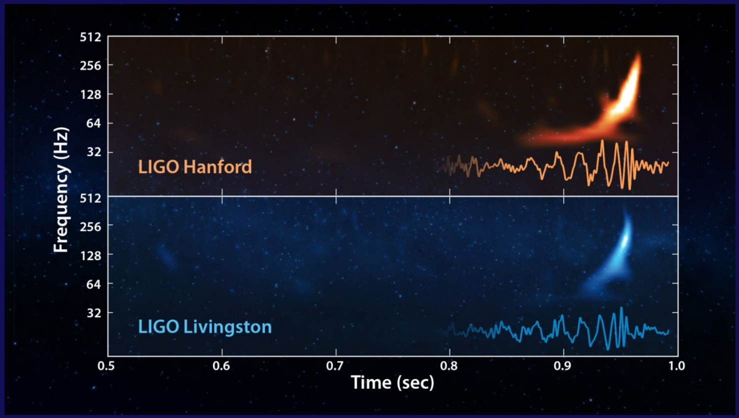
- Electric and magnetic fields can be self sustaining objects, waves, that propgate at the speed of light
- We can make these with properly designed LC circuits where changing currents make changing magnetic fields, making changing electric fields, etc…
- When these waves hit another LC circuit, they can induce current to flow
- We've invented radio. You can now rebuild cellphone technology if civilization collapses

Where do we go from here?

- You now know different epsilon materials have different speeds of light -> Optics
- The speed of a light wave is the same for observers moving relative to one another -> Special Relativity
- Electromagnetic waves carry finite amounts of energy, and sometimes electrons behave like waves -> Quantum Mechanics
- Are there any other forces besides gravity and E&M? -> Nuclear/High Energy Physics

Where do we go from here? -continued

- **If electric and magnetic fields can make waves, can there be waves in gravity fields?**
  - Yes, first observation was 4 months ago



Go look up “LIGO gravitatonal wave”

- **Congratulations, you finally have learned enough physics to get to the interesting parts**

End of Physics 122A

Thank you, you've been a great class

Commence Final Exam Review

What to expect on the final

- Maybe ¼ of problems relate to material covered since exam 3
  - LC circuits. Driven, damped LRC circuits. Displacement current
  - No waves
- All labs are fair game
- Multiple choice with a small amount of long answer
- 2 hours, starting at 8:30am in PAA118

- Q_1 has charge +Q
- Q_2 has charge +2Q
- They are separated by d.
- Charge q is a distance a away from Q_1

Is there a place – the value for a -- between Q_1 and Q_2 where the force on ANY charge (positive or negative) is zero?

$$\frac{\cancel{k}\cancel{Q}}{r^2} - \frac{\cancel{k}2\cancel{Q}}{(d-a)^2}$$

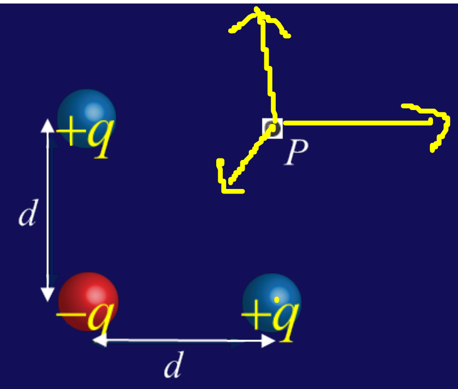
F_{Net} at a

$\vec{F} = q\vec{E}$

$$\hookrightarrow (d-a)^2 = 2a^2$$

$$d-a = \sqrt{2}a \ldots.$$

What is the direction of the electric field at point P, the unoccupied corner of the square?



[✓ A) ↗]

B) ↙

C) $E = 0$

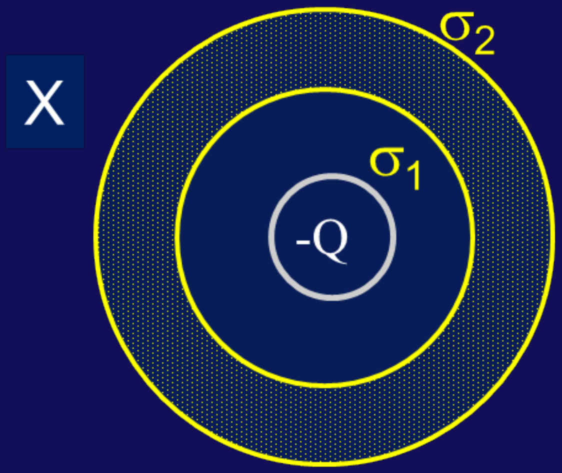
D) Need to know d

E) Need to know d & q

Clicker 2-5

A $Q = -3\ \mu C$ charge is surrounded by an uncharged conducting spherical shell (in yellow)

Compare the electric field at point X to the one you would find if the conducting shell was removed.



(a) $E_{shell} < E_{NoShell}$

(b) $E_{shell} = E_{NoShell}$

(c) $E_{shell} > E_{NoShell}$

Clicker 5-1

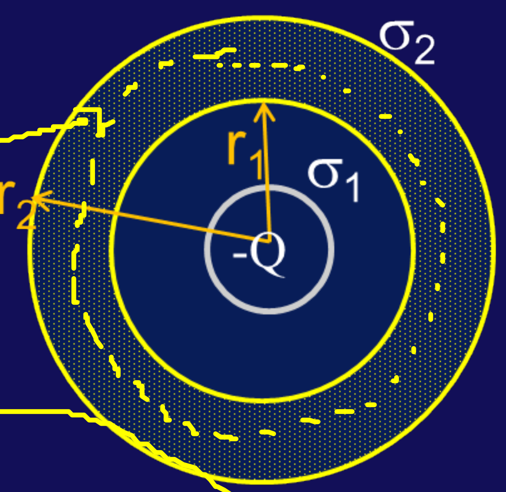
Clicker 5-2

A $Q = -3\ \mu C$ charge is surrounded by an uncharged conducting spherical shell (in yellow)

What is the value of the surface charge density σ_1 on the inner surface of the conducting shell?

w/wo ◎ , E?

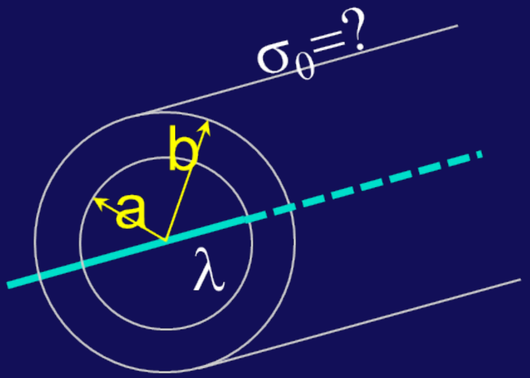
E = 0



(a) $\sigma_1 = -Q$ (b) $\sigma_1 = +Q$ (c) $\sigma_1 = 0$ (d) $\sigma_1 = \frac{-Q}{4\pi r_1^2}$ (e) $\sigma_1 = \frac{+Q}{4\pi r_1^2}$

A line charge λ C/m is placed along the axis of an uncharged conducting cylinder of inner radius $r_i = a$, and outer radius $r_o = b$ as shown.

What is the value of the charge density **σ_o (C/m²)** on the outer surface of the cylinder?



(a) $\sigma_o = -\dfrac{\lambda}{2\pi b}$ (b) $\sigma_o = 0$ (c) $\sigma_o = +\dfrac{\lambda}{2\pi b}$

Clicker 5-3

$$E = \frac{\lambda}{2\pi\varepsilon_0 r}$$

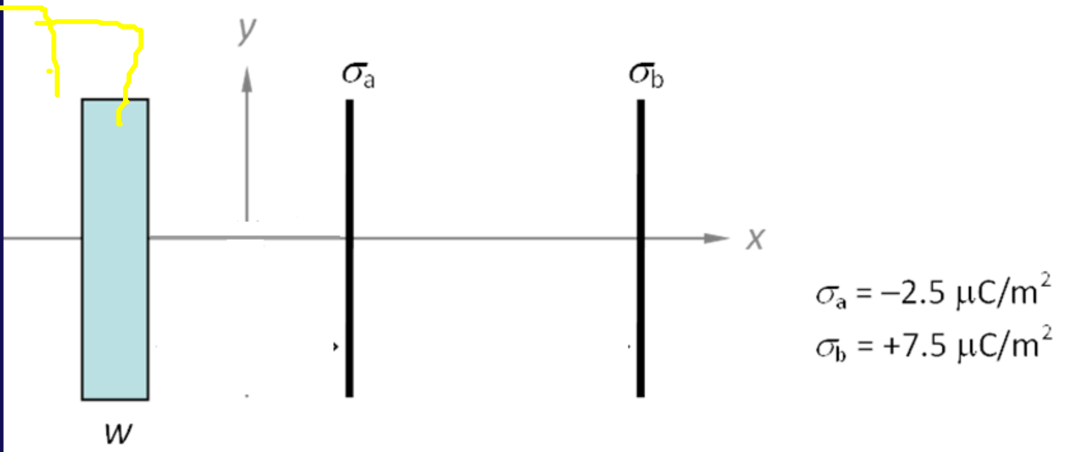
$$\sigma_{out} = \frac{\lambda}{2\pi b}$$

Clicker 6-5

The two thin plates are made of insulating material and carry uniformly-distributed surface charge densities of σ_a and σ_b respectively. The thick metal plate has width w, and is uncharged.

What is the sign of the surface charge density σ_{LHS} on the left-hand side of the thick metal plate?

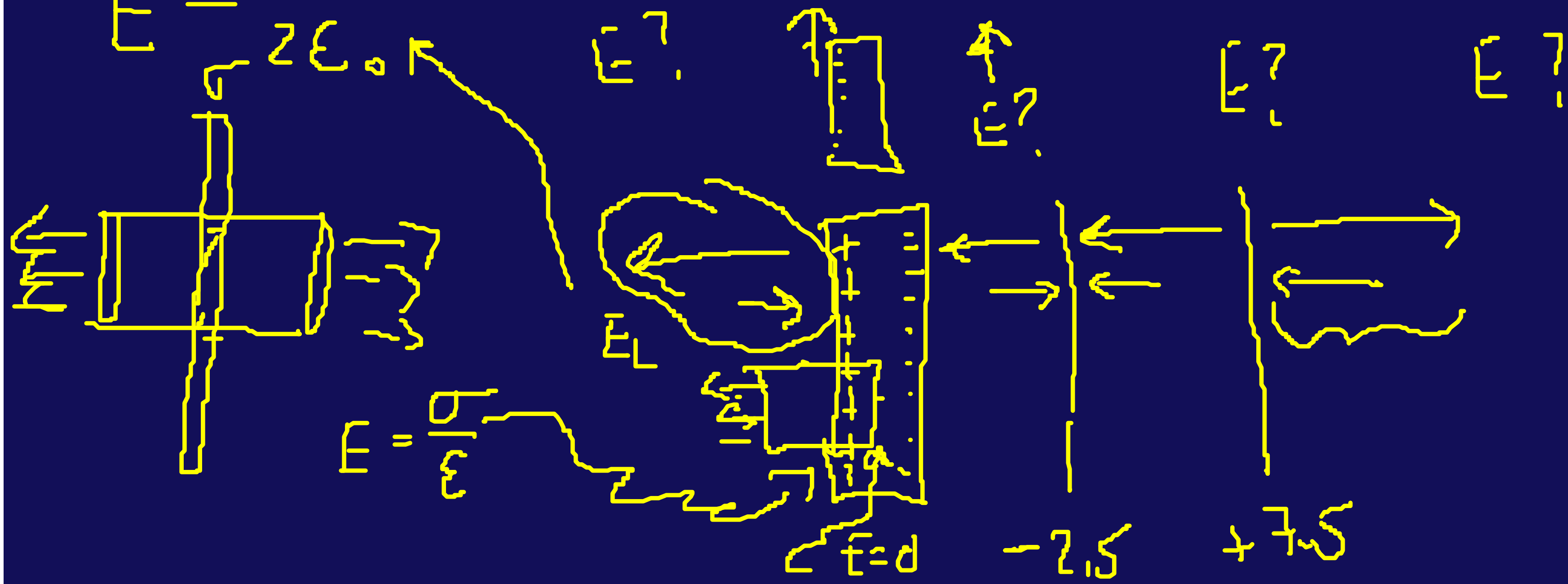
- A. $\sigma_{LHS} < 0$
- B. $\sigma_{LHS} = 0$
- C. $\sigma_{LHS} > 0$



$\sigma_a = -2.5\ \mu C/m^2$

$\sigma_b = +7.5\ \mu C/m^2$

$E = \frac{\sigma}{2\varepsilon_0}$

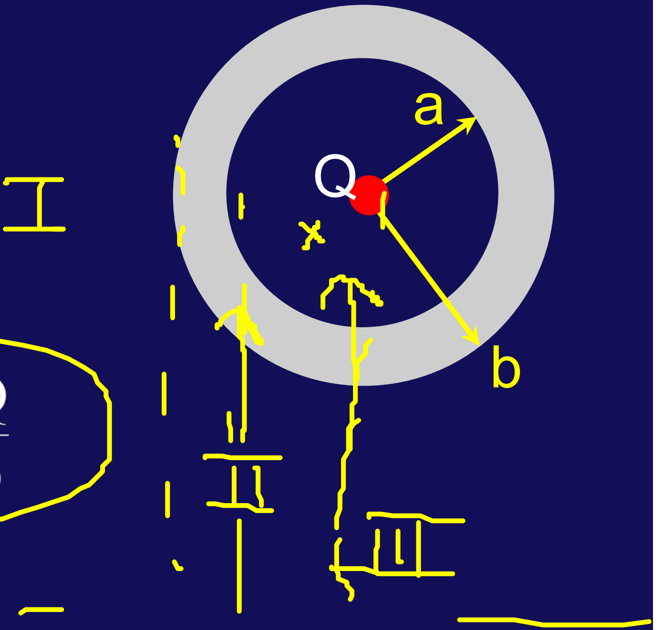


$E = \frac{\sigma}{\varepsilon}$

- **Tips to *Prepare* for Final Exam:**
  - Review Clicker Questions and previous Exam Questions
  - Try to resolve the blank Practice or Real Exams
    - » I’ve posted just about everything
    - » Look at PostLabs
    - » Look at Tutorials
- **How to *TAKE* the exam next week (110 min)**
  - Read questions carefully.
  - Then re-read them. Underline or circle the key facts
  - Take a breath. Don’t succumb to immediate “impulse” thought.
    - » Does it make sense?
    - » Does it obey the key physics laws?

A point charge Q is fixed at the center of an uncharged conducting spherical shell of inner radius a and outer radius b.

- What is the value of the potential V_a at the inner surface of the spherical shell?



(a) $V_a = 0$ (b) $V_a = \frac{1}{4\pi\varepsilon_0}\frac{Q}{a}$ (c) $V_a = \frac{1}{4\pi\varepsilon_0}\frac{Q}{b}$

Clicker 8-1

$V_a = \int_{\infty}^{a} \vec{E}\cdot d\vec{l} = \int_{\infty}^{b} \frac{kQ}{r^2}\,dr \cancel{+ \int_{b}^{a} \vec{E}\cdot d\vec{l}} + \int_{a}^{x} \frac{kQ}{r^2}\,dr$

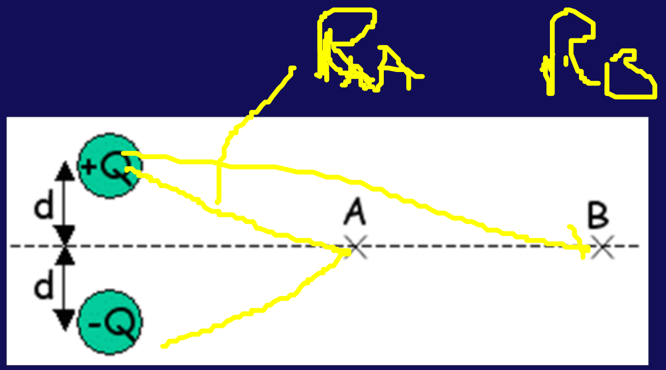
0

$\frac{kQ}{b} + 0$

$\frac{kQ}{b} - \frac{kQ}{x}$

Clicker 9-3

An electric dipole with charge magnitude Q and separation 2d is shown. Compare V_A, the electric potential at point A, with V_B, the electric potential at point B.



(a) $V_A < V_B$

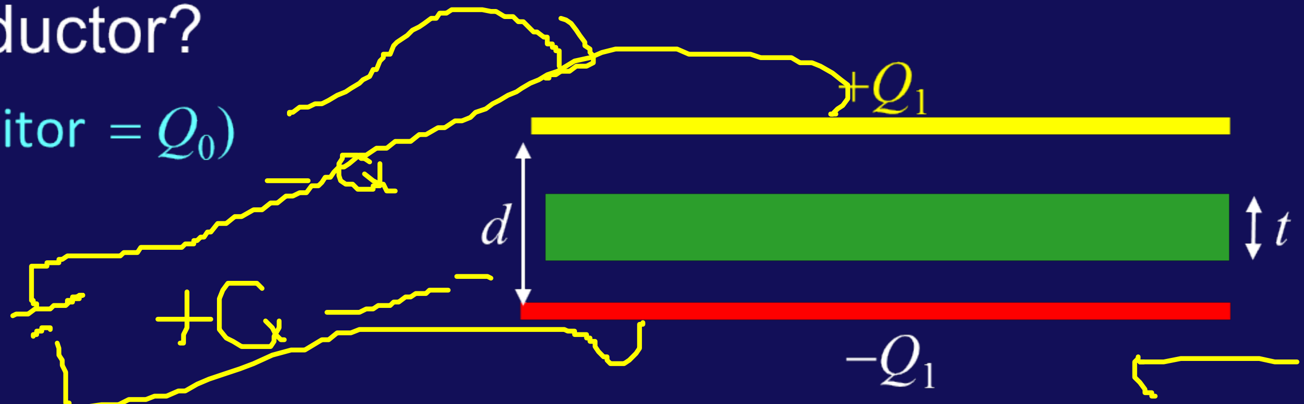
(b) $V_A = V_B$

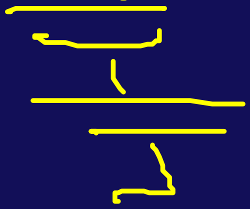
(c) $V_A > V_B$

$$V_A = \frac{kQ}{\underset{B}{R_A}} + \frac{k(-Q)}{\underset{B}{R_A}} = 0$$

What is the total charge induced on the bottom surface of the conductor?

(Initial charge on capacitor $= Q_0$)



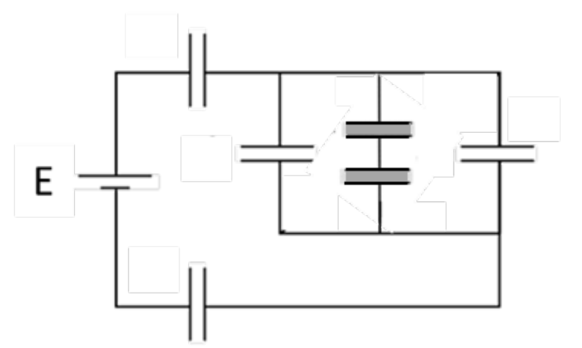


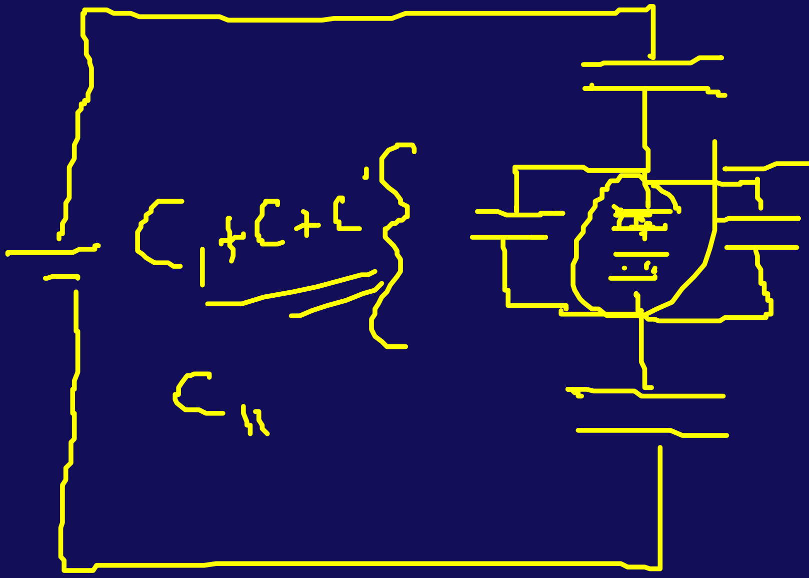
A) $+Q_0$
B) $-Q_0$
C) 0
D) Positive but the magnitude is unknown
E) Negative but the magnitude is unknown

Clicker 10-3

The six capacitors in the circuit are geometrically identical, but the two SHADED ones are filled with a material of dielectric constant *k* = 1.5, while the other capacitors are filled with vacuum. If the vacuum filled capacitors have capacitance of 2 μF, what is the equivalent capacitance of this entire network?

- *A.* $C_{eq} = 14.0\ \mu F$
- *B.* $C_{eq} = 12.0\ \mu F$
- *C.* $C_{eq} = 4.86\ \mu F$
- *D.* $C_{eq} = 0.85\ \mu F$
- *E.* $C_{eq} = 0.50\ \mu F$





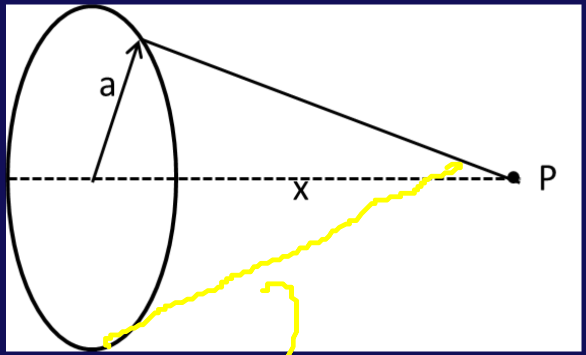
$C_1 + C + C'$

$C_{\|}$

$$\frac{1}{kC'} + \frac{1}{kC'} = \frac{1}{kC_{eq}}$$

$$\frac{1}{C_{\|}} + \frac{1}{C} + \frac{1}{C} = \frac{1}{C_{eq}} \ldots$$

A ring of radius a = 5 cm is in the *yz* plane with its center at the origin. The ring carries a uniform charge of 10 nC. The electric potential at *x* = 12 cm is approximately? (assume V = 0 at infinity)



A. 217 V
B. 543 V
C. 692 V
D. 809 V
E. 963 V

$$\frac{kQ}{r}$$

r

$$r = \sqrt{x^2+a^2}$$

A rectangular wire loop with resistance *R* lies in the *x*-*y* plane. The shaded region has a constant, uniform magnetic field that points in the +*z* direction. The wire loop is pulled at constant velocity *v* in the +*x* direction. (Quantities of interest are listed near the figure.)

What is the direction of the current induced in the wire loop at the instant shown?

A. Clockwise

B. Counter-clockwise

How much power is being used to pull the loop at speed v at the instant shown?

A. 0.6×10^{-8} W

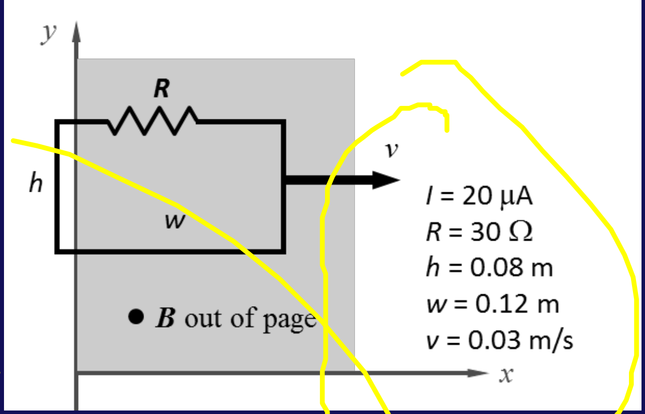
B. 1.2×10^{-8} W

C. 2.4×10^{-8} W

D. 0.6×10^{-5} W

E. 1.2×10^{-5} W

$P = I^2 R$



$I = 20\ \mu A$
$R = 30\ \Omega$
$h = 0.08$ m
$w = 0.12$ m
$v = 0.03$ m/s

$P = Fv = ILB$

L

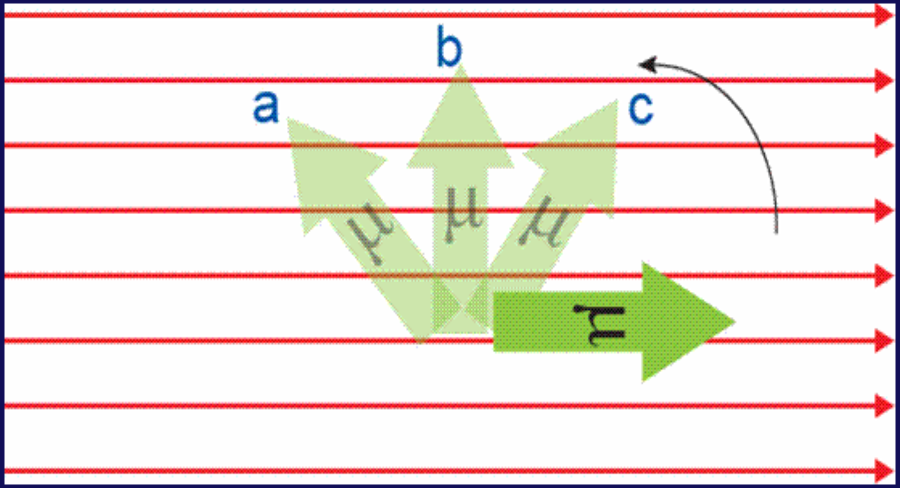
$= \frac{L^2 B^2 v^2}{r}$

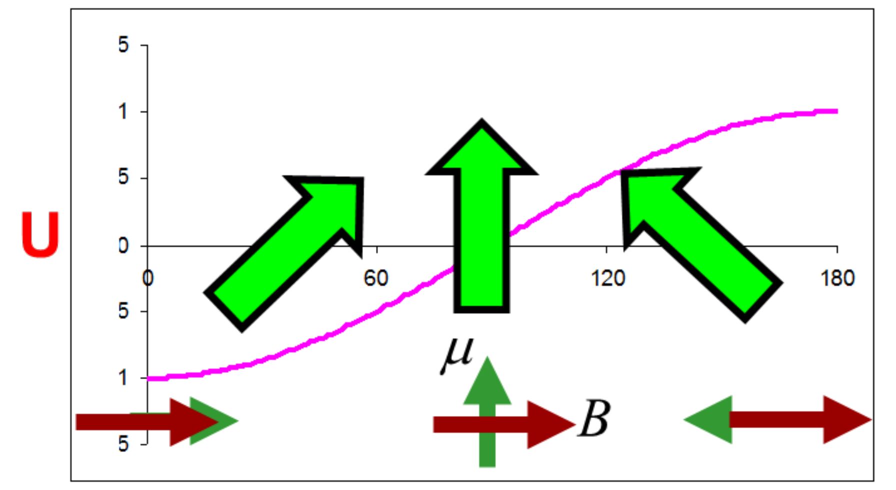
In order to rotate a horizontal magnetic dipole to the three positions shown, which one requires the most work done by the magnetic field?

A. A

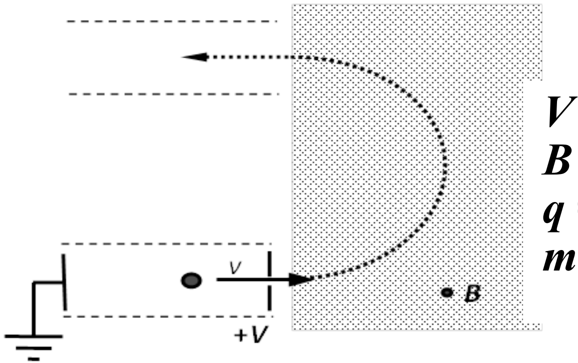
B. B

C. C





An electron of mass *m* and charge *q* is put in a track and accelerated to the right (in the plane of the paper) from rest through a potential difference *V*. The electron then enters a region containing a uniform magnetic field (direction of *B* is out of the page). The electron makes a 180º turn in the field to enter a track that is parallel to its initial trajectory



$V = 500$ V
$B = 0.1$ T out of page
$q = -1.6 \times 10^{-19}$ C
$m = 9.1 \times 10^{-31}$ kg

When the electron is in the magnetic field region, its speed

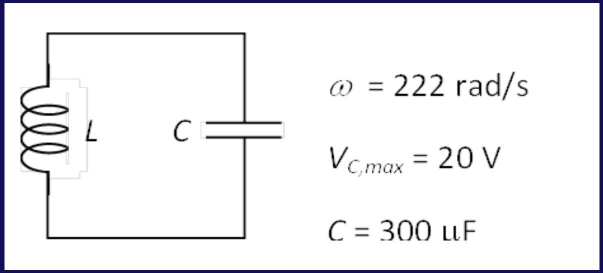
A. increases.
B. decreases.
C. remains constant.

What is the radius of curvature of the electron in the magnetic field region?

A. 5.3×10^{-4} m
B. 7.4×10^{-4} m
C. 10.7×10^{-4} m
D. 21.4×10^{-4} m
E. 42.8×10^{-4} m

An ideal (i.e., resistance-free), undriven LC circuit oscillates at a frequency ω = 222 radians/sec, has a maximum voltage across the capacitor of $V_{C,max}$ = 20 V, and has a capacitance of C = 300 μF

What is the maximum value, dI/dt_{max}, of the current's time derivative?



A. dI/dt_{max} = 50 A/s
B. dI/dt_{max} = 122 A/s
C. dI/dt_{max} = 296 A/s
D. dI/dt_{max} = 6.21 10^3 A/s
E. dI/dt_{max} = 4.86 10^3 A/s

Which of the following graphs best represents the power *P* which is lost to heat in this ideal LC circuit, as a function of time?