Problem 1 (20 points). If \( Q = 25 \mu C \), \( q = 10 \mu C \), and \( L = 40 \text{ cm} \) in the figure, what is the magnitude and the direction of the electrostatic force on \( q \)?

\[ F = F_{13} + F_{15} + F_{33} \]

\[ F_{13} = \frac{kQq_1q_3}{r^2} \]

\[ F_{15} = \frac{kQq_1q_5}{r^2} \]

\[ F_{33} = \frac{kq_3q_3}{L} \]

\[ Q = 25 \mu C \quad q = 10 \mu C \]

\[ \sin = \frac{x}{h} \]

\[ \cos = \frac{y}{h} \]

\[ h = \frac{x}{\sin} \]

\[ h = \frac{y}{\cos} \]

\[ F_{13} = \frac{kQq_1q_3}{L} \]

\[ F_{15} = \frac{kQq_1q_5}{L} \]

\[ F_{33} = \frac{kq_3q_3}{L} \]

\[ F = \text{repulsion} \quad -Q + q = \text{attract} \]

\[ F_{13} = \frac{kQq_1q_3}{L} \cdot \sin(45) \]

\[ F_{15} = \frac{kQq_1q_5}{L} \cdot \sin(45) \]

\[ F_{33} = \frac{kq_3q_3}{L} \cdot \sin(45) \]

\[ y: \frac{kQq_1q_3}{L^2} y + \frac{kQq_1q_5}{L^2} y = 0 \]

\[ x: \left( \frac{kQq_1q_3}{L^2} \sin(45) \right) x = \left( 8.99 \times 10^9 \right) \left( 25 \times 10^{-6} \right) \left( 10 \times 10^{-6} \right) \sin(45) \cdot 2 \left( 0.4 \right)^2 \]

\[ 19.87 \text{ N} \]

\[ \text{only in } +x \text{ direction} \]
Problem 2 (20 points). At what rate is thermal energy being generated in the 2R-resistor when E (or e) = 12 V and R = 3.0 Ω?

\[ \frac{1}{R_{\text{th}}} = \frac{1}{2R} + \frac{1}{2R} = \frac{1}{5} + \frac{1}{5} \quad \text{so} \quad R_{\text{th}} = 3 \]

For series:
\[ R_{\text{total}} = \left( R + \frac{1}{\frac{1}{2R} + \frac{1}{2R}} \right) = 3 + 3 = 6 \text{.} \]

\[ V = I \cdot R \]
\[ V = 12 = 2 \cdot (1) \quad \text{watts} \]
\[ I = 2 \text{ A} \quad \text{for system} \]
\[ I_{\text{total}} = I_1 + I_2 \]
\[ II_1 = \frac{I_{\text{total}}}{2} + \frac{1}{2} \]
\[ P = I^2 \cdot R = (1)^2 \cdot (6) = 6 \text{ W in } 2R \text{ resistor} \]

For 2R:
\[ R = \frac{2E}{I} = \frac{240}{2} = 120 \text{ ohms} \]
\[ R_{\text{max}} = 2 \times 3 = \text{ (ewe/s) } \]
\[ \frac{\text{W}}{\text{At}} \]
Problem 3 (40 points). What is the magnitude and direction of the current in the 20-Ω resistor?

\[ I_1 = I_2 + I_3 \checkmark \]

\[ 10 - 10I_1 - 20I_2 = 0 \checkmark \]
\[ 15 - 20I_2 + 10I_3 = 0 \checkmark \]

\[ I_1 = \frac{10 - 20I_2}{10} \]

\[ I_3 = \frac{-15 + 20I_2}{10} \checkmark \]

\[ 1 - 2I_2 = I_2 + \left( \frac{-3}{2} + 2I_2 \right) \]
\[ 1 + \frac{3}{2} = I_2 + 2I_2 + 2I_2 \]
\[ 2.5 = 5I_2 \]
\[ I_2 = \frac{1}{2} \]

0.5 A downward = \( I_2 \) (in 20-Ω R)
Problem 4 (50 points). A conducting rectangular loop of mass $M$, resistance $R$, and dimensions $a \times b$ is allowed to fall from rest through a uniform magnetic field which is perpendicular to the plane of the loop. The loop accelerates until it reaches a terminal speed (before the upper end enters the magnetic field). If $a = 2.0 \text{ m}$, $B = 6.0 \text{ T}$, $R = 40 \Omega$, and $M = 0.60 \text{ kg}$, what is the terminal speed?

(Hint: get the current for which the acceleration of the loop is zero)

\[ a = 0 \text{ at terminal speed} \]

\[ \text{Induced } E \text{ due to } B! \]

\[ E = \frac{B \cdot l \cdot v}{R} \]

\[ F_B = I \cdot l \cdot B = F_g = m \cdot g \]

\[ -\frac{B \cdot l \cdot v \cdot l \cdot B}{R} = -m \cdot g \quad \text{when } a = 0 \text{ forces should equal} \]

\[ \frac{B^2 \cdot l^2 \cdot v}{R} = m \cdot g \]

\[ \frac{v^2 \cdot (2)^2 \cdot v}{40} = \frac{(0.60 \text{ kg})(9.81 \text{ m/s}^2)}{40} \]

\[ v = 1.04 \text{ m/s} \]
Problem 5 (10 points). A light ray strikes a hexagonal ice crystal floating in the air perpendicular to one face, as shown below. The hexagonal faces of the crystal are perpendicular to the plane of the page. All the rays shown are in the plane of the page, and \( n_{\text{ice}} = 1.30 \). Which outgoing ray is correct when the incoming ray strikes the crystal face on the left head on? (Reason your answer)

\[
\begin{align*}
\eta_{\text{air}} &= 1.0 \\
\eta_{\text{ice}} &= 1.30 \\
n_{\text{ice}} \sin \theta_1 &= n_{\text{air}} \sin \theta_2 \\
1.0 \cdot \sin \theta &= 1.33 \sin \theta_2 \\
\sin^{-1} (\theta) &= 0 \\
\rightarrow \text{no change since hit } \bot
\end{align*}
\]
Problem 6 (40 points): An object is put in front of a converging lens and a concave mirror as shown. The lens has a focal length of 10 cm and the mirror has a focal length of 10 cm. The separation between the lens and the mirror is 45 cm. The object is at 15 cm in front of the lens.

a) Draw a ray diagram to find the image after the lens and the image after one reflection, as well. Indicate whether the images are real or virtual.

After lens: real

After mirror: real

b) What's the magnification of the first image?

\[
M = \frac{-q}{p} = \frac{-15}{10} = -1.5
\]

\[
\frac{1}{f} + \frac{1}{q} = \frac{1}{p}
\]

\[
\frac{1}{15} + \frac{1}{10} = \frac{1}{q} \Rightarrow q = 30 \text{ cm}
\]

\[
M = \frac{-30}{15} = -2
\]
c) Use lens equation to find the location (w.r.t the mirror) of the second image

\[ \frac{1}{p_1} + \frac{1}{q_1} = \frac{1}{f} \]

\[ p_1 = 15 \text{ cm} \quad q_1 = 30 \text{ cm} \quad f = 10 \text{ cm} \]

\[ \frac{1}{15} + \frac{1}{30} = \frac{1}{10} \]

\[ q = 30 \text{ cm} \]

30 cm in front of mirror!

d) What's the total magnification of the second image w.r.t. the object?

\[ M_2 = \frac{-q}{p} = \frac{-30}{15} = -2 \]

\[ M_1 \cdot M_2 = -2 \cdot -2 = +4 \]

4 times larger than object (\( \times \) upright compared to object)
Problem 7 (20 points). As shown in the figure, a light beam of $\lambda=500\text{nm}$ is incident at a near normal angle on a thin oil film floating on water.

\[ n_1 = 1 \]
\[ n_2 = 1.5 \]
\[ n_3 = 1.3 \]

\[ \frac{n}{n} \]

\[ 3 \]
\[ 4 \]

\[ \text{oil} \]
\[ \text{water} \]

\[ \Delta \phi_{34} = \frac{2\pi}{\lambda} \cdot 2t = \frac{2\pi}{\lambda} \cdot 2 \cdot \frac{m+1}{2} \pi \]

\[ t = 4\text{nm} \times \frac{\lambda}{4\text{nm}} = 8.38 \times 10^{-8} \text{m} \]

\[ t = \frac{\lambda}{4\text{nm}} \]

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a) Find the minimum thickness of the oil film such that rays 3 and 4 cancel each other.

\[ 2nt = (m + \frac{1}{2}) \lambda \]

\[ t = \frac{\lambda}{4nm} = \frac{500 \times 10^{-9}}{4(1.5)} = 8.38 \times 10^{-8} \text{m} \]

b) Find the values of the first two thicknesses of the oil film for which constructive interference is observed for rays 3 and 4.

\[ 2nt = m\lambda \]

\[ t = \frac{m\lambda}{2n} \]

For $m=1$: \[ t = \frac{500\text{nm}}{2(1.5)} = 1.67 \times 10^{-7} \text{m} \]

For $m=2$: \[ t = \frac{500\text{nm} \cdot 2}{2(1.5)} = 3.33 \times 10^{-7} \text{m} \]