2021

# AP Physics 2: Algebra-Based Free-Response Questions- ANSWERS

**Que-1** → $\Delta Q = \Delta U + \Delta W$

$\Delta W = P \cdot dV$

$PV = nRT$

**Que-2** $P = \rho g h$, $P = F/A$

$\rho = \frac{M}{V}$

**Que-3** $F = q(\vec{v} \times \vec{B})$, $e = -N\frac{d\phi}{dt}$

$P = e^2/R$

**Que-4** → $E = hf$, $E = mc^2$, $E = \frac{1}{2}mv^2$

# AP® PHYSICS 2 TABLE OF INFORMATION

| CONSTANTS AND CONVERSION FACTORS | |
|---|---|
| Proton mass, $m_p = 1.67 \times 10^{-27}$ kg | Electron charge magnitude, $e = 1.60 \times 10^{-19}$ C |
| Neutron mass, $m_n = 1.67 \times 10^{-27}$ kg | 1 electron volt, $1 \text{ eV} = 1.60 \times 10^{-19}$ J |
| Electron mass, $m_e = 9.11 \times 10^{-31}$ kg | Speed of light, $c = 3.00 \times 10^{8}$ m/s |
| Avogadro's number, $N_0 = 6.02 \times 10^{23}\ \text{mol}^{-1}$ | Universal gravitational constant, $G = 6.67 \times 10^{-11}\ \text{m}^3/\text{kg}\cdot\text{s}^2$ |
| Universal gas constant, $R = 8.31$ J/(mol•K) | Acceleration due to gravity at Earth's surface, $g = 9.8\ \text{m/s}^2$ |
| Boltzmann's constant, $k_B = 1.38 \times 10^{-23}$ J/K | |

| | |
|---|---|
| 1 unified atomic mass unit, | $1 \text{ u} = 1.66 \times 10^{-27} \text{ kg} = 931 \text{ MeV}/c^2$ |
| Planck's constant, | $h = 6.63 \times 10^{-34} \text{ J}\cdot\text{s} = 4.14 \times 10^{-15} \text{ eV}\cdot\text{s}$ |
| | $hc = 1.99 \times 10^{-25} \text{ J}\cdot\text{m} = 1.24 \times 10^{3} \text{ eV}\cdot\text{nm}$ |
| Vacuum permittivity, | $\varepsilon_0 = 8.85 \times 10^{-12}\ \text{C}^2/\text{N}\cdot\text{m}^2$ |
| Coulomb's law constant, | $k = 1/4\pi\varepsilon_0 = 9.0 \times 10^{9}\ \text{N}\cdot\text{m}^2/\text{C}^2$ |
| Vacuum permeability, | $\mu_0 = 4\pi \times 10^{-7}$ (T•m)/A |
| Magnetic constant, | $k' = \mu_0/4\pi = 1 \times 10^{-7}$ (T•m)/A |
| 1 atmosphere pressure, | $1 \text{ atm} = 1.0 \times 10^{5}\ \text{N/m}^2 = 1.0 \times 10^{5}$ Pa |

| UNIT SYMBOLS | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | meter, | m | mole, | mol | watt, | W | farad, | F |
| | kilogram, | kg | hertz, | Hz | coulomb, | C | tesla, | T |
| | second, | s | newton, | N | volt, | V | degree Celsius, | °C |
| | ampere, | A | pascal, | Pa | ohm, | Ω | electron volt, | eV |
| | kelvin, | K | joule, | J | henry, | H | | |

| PREFIXES | | |
|---|---|---|
| Factor | Prefix | Symbol |
| $10^{12}$ | tera | T |
| $10^{9}$ | giga | G |
| $10^{6}$ | mega | M |
| $10^{3}$ | kilo | k |
| $10^{-2}$ | centi | c |
| $10^{-3}$ | milli | m |
| $10^{-6}$ | micro | μ |
| $10^{-9}$ | nano | n |
| $10^{-12}$ | pico | p |

VALUES OF TRIGONOMETRIC FUNCTIONS FOR COMMON ANGLES

| $\theta$ | 0° | 30° | 37° | 45° | 53° | 60° | 90° |
|---|---|---|---|---|---|---|---|
| $\sin\theta$ | 0 | 1/2 | 3/5 | $\sqrt{2}/2$ | 4/5 | $\sqrt{3}/2$ | 1 |
| $\cos\theta$ | 1 | $\sqrt{3}/2$ | 4/5 | $\sqrt{2}/2$ | 3/5 | 1/2 | 0 |
| $\tan\theta$ | 0 | $\sqrt{3}/3$ | 3/4 | 1 | 4/3 | $\sqrt{3}$ | ∞ |

The following conventions are used in this exam.

I. The frame of reference of any problem is assumed to be inertial unless otherwise stated.
II. In all situations, positive work is defined as work done on a system.
III. The direction of current is conventional current: the direction in which positive charge would drift.
IV. Assume all batteries and meters are ideal unless otherwise stated.
V. Assume edge effects for the electric field of a parallel plate capacitor unless otherwise stated.
VI. For any isolated electrically charged object, the electric potential is defined as zero at infinite distance from the charged object

# AP® PHYSICS 2 EQUATIONS

## MECHANICS

$$v_x = v_{x0} + a_x t$$

$$x = x_0 + v_{x0} t + \frac{1}{2} a_x t^2$$

$$v_x^2 = v_{x0}^2 + 2a_x\left(x - x_0\right)$$

$$\vec{a} = \frac{\sum \vec{F}}{m} = \frac{\vec{F}_{net}}{m}$$

$$\left|\vec{F}_f\right| \le \mu\left|\vec{F}_n\right|$$

$$a_c = \frac{v^2}{r}$$

$$\vec{p} = m\vec{v}$$

$$\Delta\vec{p} = \vec{F}\,\Delta t$$

$$K = \frac{1}{2} m v^2$$

$$\Delta E = W = F_{\|} d = F d\cos\theta$$

$$P = \frac{\Delta E}{\Delta t}$$

$$\theta = \theta_0 + \omega_0 t + \frac{1}{2}\alpha t^2$$

$$\omega = \omega_0 + \alpha t$$

$$x = A\cos(\omega t) = A\cos(2\pi f t)$$

$$x_{cm} = \frac{\sum m_i x_i}{\sum m_i}$$

$$\vec{\alpha} = \frac{\sum \vec{\tau}}{I} = \frac{\vec{\tau}_{net}}{I}$$

$$\tau = r_{\perp} F = r F \sin\theta$$

$$L = I\omega$$

$$\Delta L = \tau\,\Delta t$$

$$K = \frac{1}{2} I\omega^2$$

$$\left|\vec{F}_s\right| = k\left|\vec{x}\right|$$

$$U_s = \frac{1}{2} k x^2$$

$$\Delta U_g = m g\,\Delta y$$

$$T = \frac{2\pi}{\omega} = \frac{1}{f}$$

$$T_s = 2\pi\sqrt{\frac{m}{k}}$$

$$T_p = 2\pi\sqrt{\frac{\ell}{g}}$$

$$\left|\vec{F}_g\right| = G\frac{m_1 m_2}{r^2}$$

$$\vec{g} = \frac{\vec{F}_g}{m}$$

$$U_G = -\frac{G m_1 m_2}{r}$$

- $a$ = acceleration
- $A$ = amplitude
- $d$ = distance
- $E$ = energy
- $F$ = force
- $f$ = frequency
- $I$ = rotational inertia
- $K$ = kinetic energy
- $k$ = spring constant
- $L$ = angular momentum
- $\ell$ = length
- $m$ = mass
- $P$ = power
- $p$ = momentum
- $r$ = radius or separation
- $T$ = period
- $t$ = time
- $U$ = potential energy
- $v$ = speed
- $W$ = work done on a system
- $x$ = position
- $y$ = height
- $\alpha$ = angular acceleration
- $\mu$ = coefficient of friction
- $\theta$ = angle
- $\tau$ = torque
- $\omega$ = angular speed

## ELECTRICITY AND MAGNETISM

$$\left|\vec{F}_E\right| = \frac{1}{4\pi\varepsilon_0}\frac{\left|q_1 q_2\right|}{r^2}$$

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

$$\left|\vec{E}\right| = \frac{1}{4\pi\varepsilon_0}\frac{|q|}{r^2}$$

$$\Delta U_E = q\Delta V$$

$$V = \frac{1}{4\pi\varepsilon_0}\frac{q}{r}$$

$$\left|\vec{E}\right| = \left|\frac{\Delta V}{\Delta r}\right|$$

$$\Delta V = \frac{Q}{C}$$

$$C = \kappa\varepsilon_0\frac{A}{d}$$

$$E = \frac{Q}{\varepsilon_0 A}$$

$$U_C = \frac{1}{2} Q\Delta V = \frac{1}{2} C(\Delta V)^2$$

$$I = \frac{\Delta Q}{\Delta t}$$

$$R = \frac{\rho\ell}{A}$$

$$P = I\,\Delta V$$

$$I = \frac{\Delta V}{R}$$

$$R_s = \sum_i R_i$$

$$\frac{1}{R_p} = \sum_i \frac{1}{R_i}$$

$$C_p = \sum_i C_i$$

$$\frac{1}{C_s} = \sum_i \frac{1}{C_i}$$

$$B = \frac{\mu_0}{2\pi}\frac{I}{r}$$

- $A$ = area
- $B$ = magnetic field
- $C$ = capacitance
- $d$ = distance
- $E$ = electric field
- $\mathcal{E}$ = emf
- $F$ = force
- $I$ = current
- $\ell$ = length
- $P$ = power
- $Q$ = charge
- $q$ = point charge
- $R$ = resistance
- $r$ = separation
- $t$ = time
- $U$ = potential (stored) energy
- $V$ = electric potential
- $v$ = speed
- $\kappa$ = dielectric constant
- $\rho$ = resistivity
- $\theta$ = angle
- $\Phi$ = flux

$$\vec{F}_M = q\vec{v}\times\vec{B}$$

$$\left|\vec{F}_M\right| = |q\vec{v}||\sin\theta|\left|\vec{B}\right|$$

$$\vec{F}_M = I\vec{\ell}\times\vec{B}$$

$$\left|\vec{F}_M\right| = \left|I\vec{\ell}\right||\sin\theta|\left|\vec{B}\right|$$

$$\Phi_B = \vec{B}\bullet\vec{A}$$

$$\Phi_B = \left|\vec{B}\right|\cos\theta\left|\vec{A}\right|$$

$$\mathcal{E} = -\frac{\Delta\Phi_B}{\Delta t}$$

$$\mathcal{E} = B\ell v$$

# AP® PHYSICS 2 EQUATIONS

## FLUID MECHANICS AND THERMAL PHYSICS

$$\rho = \frac{m}{V}$$

$$P = \frac{F}{A}$$

$$P = P_0 + \rho g h$$

$$F_b = \rho V g$$

$$A_1 v_1 = A_2 v_2$$

$$P_1 + \rho g y_1 + \frac{1}{2}\rho v_1^2 = P_2 + \rho g y_2 + \frac{1}{2}\rho v_2^2$$

$$\frac{Q}{\Delta t} = \frac{kA\,\Delta T}{L}$$

$$PV = nRT = Nk_BT$$

$$K = \frac{3}{2}k_BT$$

$$W = -P\,\Delta V$$

$$\Delta U = Q + W$$

$A$ = area
$F$ = force
$h$ = depth
$k$ = thermal conductivity
$K$ = kinetic energy
$L$ = thickness
$m$ = mass
$n$ = number of moles
$N$ = number of molecules
$P$ = pressure
$Q$ = energy transferred to a system by heating
$T$ = temperature
$t$ = time
$U$ = internal energy
$V$ = volume
$v$ = speed
$W$ = work done on a system
$y$ = height
$\rho$ = density

## MODERN PHYSICS

$$E = hf$$

$$K_{max} = hf - \phi$$

$$\lambda = \frac{h}{p}$$

$$E = mc^2$$

$E$ = energy
$f$ = frequency
$K$ = kinetic energy
$m$ = mass
$p$ = momentum
$\lambda$ = wavelength
$\phi$ = work function

## WAVES AND OPTICS

$$\lambda = \frac{v}{f}$$

$$n = \frac{c}{v}$$

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

$$\frac{1}{s_i} + \frac{1}{s_o} = \frac{1}{f}$$

$$|M| = \left|\frac{h_i}{h_o}\right| = \left|\frac{s_i}{s_o}\right|$$

$$\Delta L = m\lambda$$

$$d\sin\theta = m\lambda$$

$d$ = separation
$f$ = frequency or focal length
$h$ = height
$L$ = distance
$M$ = magnification
$m$ = an integer
$n$ = index of refraction
$s$ = distance
$v$ = speed
$\lambda$ = wavelength
$\theta$ = angle

## GEOMETRY AND TRIGONOMETRY

Rectangle
$A = bh$

Triangle
$A = \frac{1}{2}bh$

Circle
$A = \pi r^2$
$C = 2\pi r$

Rectangular solid
$V = \ell w h$

Cylinder
$V = \pi r^2 \ell$
$S = 2\pi r \ell + 2\pi r^2$

Sphere
$V = \frac{4}{3}\pi r^3$
$S = 4\pi r^2$

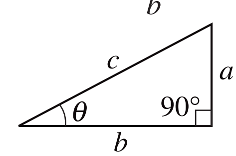
$A$ = area
$C$ = circumference
$V$ = volume
$S$ = surface area
$b$ = base
$h$ = height
$\ell$ = length
$w$ = width
$r$ = radius

Right triangle
$c^2 = a^2 + b^2$

$\sin\theta = \frac{a}{c}$

$\cos\theta = \frac{b}{c}$

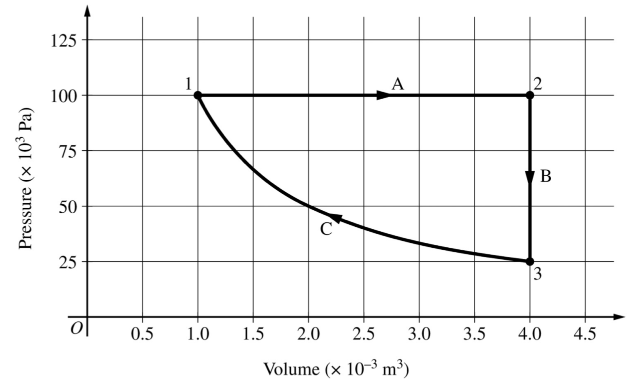
$\tan\theta = \frac{a}{b}$



## Begin your response to QUESTION 1 on this page.

## PHYSICS 2 SECTION II Time—1 hour and 30 minutes 4 Questions

**Directions: Questions 1 and 4 are short free-response questions that require about 20 minutes each to answer and are worth 10 points each. Questions 2 and 3 are long free-response questions that require about 25 minutes each to answer and are worth 12 points each. Show your work for each part in the space provided after that part.**




**1. (10 points, suggested time 20 minutes)**

A sample of ideal gas is taken through the thermodynamic cycle shown above. Process C is isothermal.

(a) Consider the portion of the cycle that takes the gas from state 1 to state 3 by processes A and B. Calculate the magnitude of the following and indicate the sign of any nonzero quantities.

The net change in internal energy $\Delta U$ of the gas → since final and initial tem perature is same hence $\Delta U = 0$

The net work W done on the gas $w = -PdV = -100 \times 10^3 (3 \times 10^{-3}) = -300\ J$

The net energy Q transferred to the gas by heating $\Delta Q = \Delta U + \Delta W$ ($\Delta U \to 0$)

$= 300\ J$

**(b) Consider isothermal process C.**

i. Compare the magnitude and sign of the work W done on the gas in process C to the magnitude and sign of the work in the portion of the cycle in part (a). Support your answer using features of the graph.

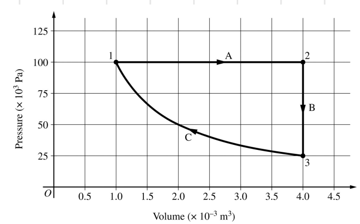
$W_a \big|_{\text{process a}} > W_c \big|_{\text{process c}}$

(More area of PV graph) in process (a)
(+ve) because volume increases

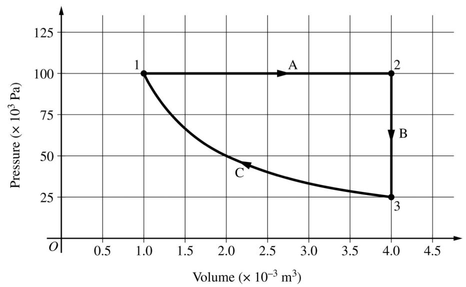
Less PV (Area) of graph
(−ve) because volume decreases

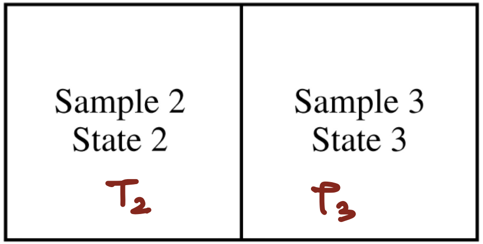
ii. Explain how the microscopic behavior of the gas particles and changes in the size of the container affect interactions on the microscopic level and produce the observed pressure difference between the beginning and end of process C.

process (C) → Temperature remains constant
speed of the molecule and force of collision remains same.
→ Volume decreases, $d = \frac{m}{V}$
hence density increases, colloid more frequently → more net force of collision on the wall.



(c) Consider two samples of the gas, each with the same number of gas particles. Sample 2 is in state 2 shown in the graph, and sample 3 is in state 3 shown in the graph. The samples are put into thermal contact, as shown above. Indicate the direction, if any, of energy transfer between the samples. Support your answer using macroscopic thermodynamic principles.

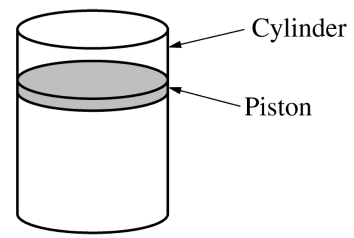



$T_2 > T_3$

energy goes from hot to cold, so energy will transfer from sample ② to sample ①

Begin your response to QUESTION 2 on this page.




**2. (12 points, suggested time 25 minutes)**

A group of students design an experiment to investigate the relationship between the density and pressure of a sample of gas at a constant temperature. The gas may or may not be ideal. They will create a graph of density as a function of pressure. They have the following materials and equipment.

A sample of the gas of known mass $M_g$ in a sealed, clear, cylindrical container, as shown above, with a movable piston of known mass $m_p$

A collection of objects each of known mass $m_o$

A meterstick

(a)

i. Describe the measurements the students should take and a procedure they could use to collect the data needed to create the graph. Specifically indicate how the students could keep the temperature constant. Include enough detail that another student could follow the procedure and obtain similar data.

→ place the container in an ice bath so that temperature will remain constant.

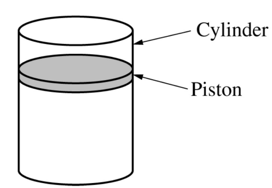
→ For eight different object of known mass

→ Add each object on piston and measure the height of the piston for each object.

ii. Determine an expression for the absolute pressure of the gas in terms of measured quantities, given quantities, and physical constants, as appropriate. Define any symbols used that are not already defined.

$$P_{TOTAL} = P_{ATM} + \frac{(m_p + N m_o) g}{A}$$

$$= P_{ATM} + \frac{(m_p + N m_o) g}{\pi r^2}$$



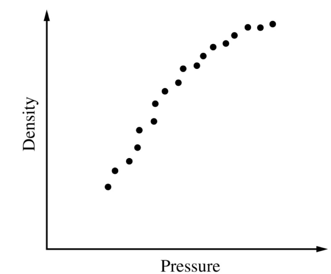

N = number of object, $r$ = radius of the piston.

Continue your response to QUESTION 2 on this page.



iii. Determine an expression for the density of the gas in terms of measured quantities, given quantities, and physical constants, as appropriate. Define any symbols used that are not already defined.

$$\rho = \frac{Mg}{V} = \frac{Mg}{(\pi r^2)(h)}$$




iv. The graph above represents the students' data. Does the data indicate that the gas is ideal? Describe the application of physics principles in an analysis of the graph that can be used to arrive at your answer.

As per Ideal gas equation $PV = nRT$, since temperature is constant hence $P \propto 1/V$, since $d = m/V$, $V = \frac{m}{d}$

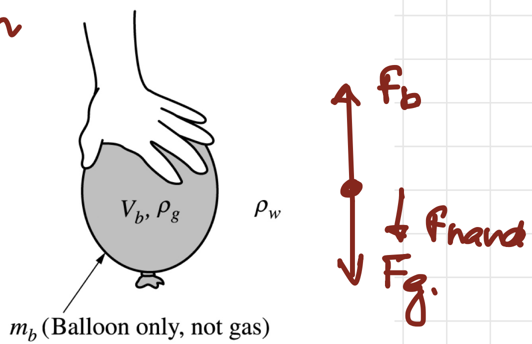
$P \propto \frac{d}{m}$    m - constant    $P \propto d$ → Linear, the graph does not show linear hence NON IDEAL

**Continue your response to QUESTION 2 on this page.**

Another group of students propose that the relationship between density and pressure could also be obtained by filling a balloon with the gas and submerging it to increasing depths in a deep pool of water.

(b) Why could submerging the balloon to increasing depths be useful for determining the relationship between the density and pressure of the gas?

Pressure of water increases with depth, which would decrease the volume & $d = \frac{m}{V}$ then density increases, because of pressure difference, this allows volume and density to be varied and graphed.

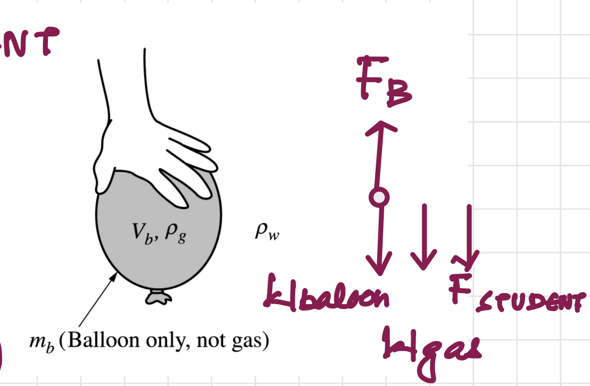


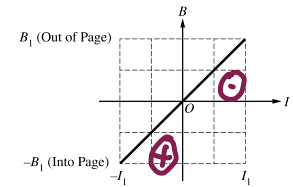
(c) The balloon is kept underwater in the deep pool by a student pushing down on the balloon, as shown above. Let Vb represent the volume of the inflated balloon, mb represent the mass of just the balloon (not including the mass of the gas), rg represent the density of the gas in the balloon, and rw represent the density of the water. Derive an expression for the force the student must exert to hold the balloon at rest under the water, in terms of the quantities given in this part and physical constants, as appropriate.

$$F_B = W_{baloon} + W_{gas} + F_{STUDENT}$$

$$F_{STUDENT} = F_B - W_{baloon} - W_{gas}$$

$$= \rho_w V_b g - (\rho_g V_b g + m_b g)$$

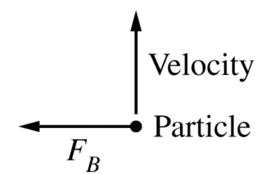





Graph 1

**3. (12 points, suggested time 25 minutes)**

An electromagnet produces a magnetic field that is uniform in a certain region and zero outside that region. The graph above represents the field as a function of the current in the electromagnet, with positive field directed out of the page and negative field directed into the page.

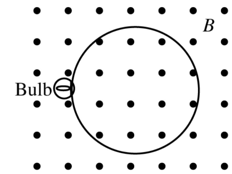


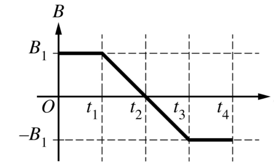

(a) The current in the electromagnet is set at $0.5I_1$. When a charged particle in the region moves toward the top of the page, the force exerted on it by the field is $F_B$ toward the left, as shown above. What changes to the current in the electromagnet could make the magnitude of the force exerted on the particle equal to $2F_B$ and the direction of the force to the right? Support your answer using physics principles.

$F = q(\vec{v} \times \vec{B})$

$B \propto I$

current must change the direction and double in magnitude Hence B-becomes double, fm-double, Reverse the direction reverses the direction of magnetic field then force. (By fleming left hand rule)

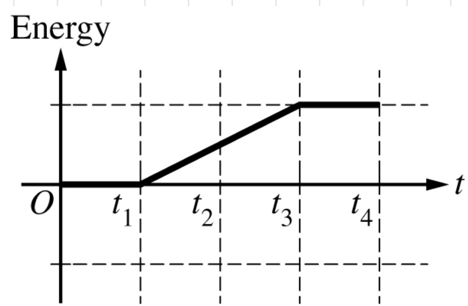



Graph 2

A circuit is made by connecting an ohmic lightbulb of resistance R and a circular loop of area A made of a wire with negligible resistance. The circuit is placed with the plane of the loop perpendicular to the field of the electromagnet, as shown above on the left. The magnetic field changes as a function of time, as shown in Graph 2. The bulb dissipates energy during the interval $t_1 < t < t_3$ Graph 3 below shows the cumulative energy dissipated by the bulb (the total energy dissipated since t = 0) as a function of time.

(b) The original bulb is replaced by a new ohmic lightbulb with a greater resistance, but everything else stays the same. How would the cumulative energy graph for the new bulb be different, if at all, from Graph 3 above? Support your answer using physics principles.




Graph 3

slope of the graph $= \frac{E}{t}$ = Power

Induced emf is same for both the cases and Power $= V^2/R$ , Power $\propto 1/R$

second case bulb is having more resistance Hence less Power is dissipiated as $P \propto 1/R$.

(c) The new lightbulb is removed and replaced by the original lightbulb. The magnetic field now changes from $2B_1$ to $-2B_1$ during the same interval $t_1 < t < t_3$. A new cumulative energy graph is created for this situation. How would the new graph be different, if at all, from Graph 3 ? Support your answer using physics principles.

$$e = -\frac{d\phi}{dt} = -\frac{A\,dB}{dt} = -\frac{A(B_f - B_i)}{dt}$$

$e \propto \Delta B$, since magnetic field change to larger value in the same time, and $P \propto (e)^2$ so P is larger, Power of slope of energy vs time is larger.

(d) A student derives the following expression for the cumulative energy dissipated by the original bulb during the interval $t_1 < t < t_3$ and with the original change in magnetic field shown in Graph 2.

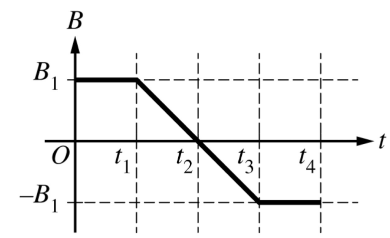
$$\text{Energy} = \frac{A^2 B_1 R}{4(t_3 - t_1)}$$

Whether or not the equation is correct, does the functional dependence of cumulative energy on the elapsed time $(t_3 - t_1)$ make physical sense? Support your answer using physics principles.

$$e = -\frac{d\phi}{dt} = -A\frac{(B_f - B_i)}{(t_3 - t_1)}$$

$$= -\frac{A(-B_1 - B_1)}{(t_3 - t_1)}$$

$$= +\frac{2AB_1}{(t_3 - t_1)}$$




Graph 2



$$\text{Energy} = (\text{Power})(t_3 - t_1) = \frac{e^2}{R}(t_3 - t_1)$$

$$= \frac{4A^2B_1^2 (t_3 - t_1)}{(t_3 - t_1)^2 (R)} = \frac{4A^2B_1^2}{R(t_3 - t_1)}$$

$$E \propto \frac{1}{(t_3 - t_1)}$$

this is functional dependence on time.

expression given in the question is not matching with our answer

Hence - NO

Begin your response to QUESTION 4 on this page.

4. (10 points, suggested time 20 minutes)
Light and matter can be modeled as waves or as particles. Some phenomena can be explained using the wave model, and others can be explained using the particle model.
(a) Calculate the speed, in m/s, of an electron that has a wavelength of 5.0 nm.

$$\lambda = \frac{h}{m v} \Rightarrow v = \frac{h}{\lambda m}$$

$$v = \frac{6.6 \times 10^{-34}}{5.0 \times 10^{-9} \times 9.1 \times 10^{-31}}$$

$$= 1.5 \times 10^{5} \text{ m/sec}$$

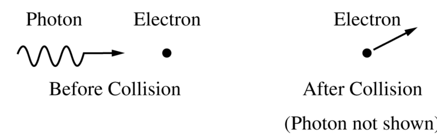
(b) The electron is moving with the speed calculated in part (a) when it collides with a positron that is at rest. A positron is a particle identical to an electron except that its charge is positive. The two particles annihilate each other, producing photons. Calculate the total energy of the photons.

$$E_{TOTAL} = 2mc^2 + \frac{1}{2}mv^2$$

$$= 2(9.1\times10^{-31})(3\times10^{8})^2 + \frac{1}{2}(9.1\times10^{-31})(1.5\times10^{5})^2$$

$$= 1.6\times10^{-13}\ J$$

**Continue your response to QUESTION 4 on this page.**




(c) A photon approaches an electron at rest, as shown above on the left, and collides elastically with the electron. After the collision, the electron moves toward the top of the page and to the right, as shown above on the right, at a known speed and angle. In a coherent, paragraph-length response, indicate a possible direction for the photon that exists after the collision and its frequency compared to that of the original photon. Describe the application of physics principles that can be used to determine the direction of motion and frequency of the photon that exists after the collision.



Apply conservation of linear momentum.

Initial momentum = final momentum
↓
because of photon = momentum of both the particle
in y direction will get cancelled
only momentum exists in x direction

FOR ENERGY

Initial energy of photon $E = h\nu$ since some part of the energy goes to electron hence energy of photon decreases hence $\nu$ decreases.

**STOP**

**END OF EXAM**