

2024



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# AP<sup>®</sup> Physics 2: Algebra-Based

## Free-Response Questions

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AP<sup>®</sup> 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, $N_0 = 6.02 \times 10^{23}$ mol <sup>-1</sup>                                  | Universal gravitational constant, $G = 6.67 \times 10^{-11}$ m <sup>3</sup> /kg·s <sup>2</sup> |
| Universal gas constant, $R = 8.31$ J/(mol·K)                                                      | Acceleration due to gravity at Earth's surface, $g = 9.8$ m/s <sup>2</sup>                     |
| Boltzmann's constant, $k_B = 1.38 \times 10^{-23}$ J/K                                            |                                                                                                |
| 1 unified atomic mass unit,                                                                       | $1 \text{ u} = 1.66 \times 10^{-27}$ kg = 931 MeV/c <sup>2</sup>                               |
| Planck's constant,                                                                                | $h = 6.63 \times 10^{-34}$ J·s = $4.14 \times 10^{-15}$ eV·s                                   |
|                                                                                                   | $hc = 1.99 \times 10^{-25}$ J·m = $1.24 \times 10^3$ eV·nm                                     |
| Vacuum permittivity,                                                                              | $\epsilon_0 = 8.85 \times 10^{-12}$ C <sup>2</sup> /N·m <sup>2</sup>                           |
| Coulomb's law constant, $k = 1/4\pi\epsilon_0 = 9.0 \times 10^9$ N·m <sup>2</sup> /C <sup>2</sup> |                                                                                                |
| 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,                                                                            | $1 \text{ atm} = 1.0 \times 10^5$ N/m <sup>2</sup> = $1.0 \times 10^5$ Pa                      |

| UNIT<br>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.

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AP<sup>®</sup> PHYSICS 2 EQUATIONS

## MECHANICS

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

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

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

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

$$|\vec{F}_f| \leq \mu |\vec{F}_n|$$

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

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

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

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

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

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

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

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

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

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

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

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

$$L = I \omega$$

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

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

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

$$a = \text{acceleration}$$

$$A = \text{amplitude}$$

$$d = \text{distance}$$

$$E = \text{energy}$$

$$F = \text{force}$$

$$f = \text{frequency}$$

$$I = \text{rotational inertia}$$

$$K = \text{kinetic energy}$$

$$k = \text{spring constant}$$

$$L = \text{angular momentum}$$

$$\ell = \text{length}$$

$$m = \text{mass}$$

$$P = \text{power}$$

$$p = \text{momentum}$$

$$r = \text{radius or separation}$$

$$T = \text{period}$$

$$t = \text{time}$$

$$U = \text{potential energy}$$

$$v = \text{speed}$$

$$W = \text{work done on a system}$$

$$x = \text{position}$$

$$y = \text{height}$$

$$\alpha = \text{angular acceleration}$$

$$\mu = \text{coefficient of friction}$$

$$\theta = \text{angle}$$

$$\tau = \text{torque}$$

$$\omega = \text{angular speed}$$

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

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

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

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

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

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

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

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

## ELECTRICITY AND MAGNETISM

$$|\vec{F}_E| = \frac{1}{4\pi\epsilon_0} \frac{|q_1 q_2|}{r^2}$$

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

$$|\vec{E}| = \frac{1}{4\pi\epsilon_0} \frac{|q|}{r^2}$$

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

$$V = \frac{1}{4\pi\epsilon_0} \frac{q}{r}$$

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

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

$$C = \kappa \epsilon_0 \frac{A}{d}$$

$$E = \frac{Q}{\epsilon_0 A}$$

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

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

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

$$P = I \Delta V$$

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

$$R_s = \sum_i R_i$$

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

$$C_p = \sum_i C_i$$

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

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

$$A = \text{area}$$

$$B = \text{magnetic field}$$

$$C = \text{capacitance}$$

$$d = \text{distance}$$

$$E = \text{electric field}$$

$$\mathcal{E} = \text{emf}$$

$$F = \text{force}$$

$$I = \text{current}$$

$$\ell = \text{length}$$

$$P = \text{power}$$

$$Q = \text{charge}$$

$$q = \text{point charge}$$

$$R = \text{resistance}$$

$$r = \text{separation}$$

$$t = \text{time}$$

$$U = \text{potential (stored) energy}$$

$$V = \text{electric potential}$$

$$v = \text{speed}$$

$$\kappa = \text{dielectric constant}$$

$$\rho = \text{resistivity}$$

$$\theta = \text{angle}$$

$$\Phi = \text{flux}$$

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

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

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

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

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

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

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

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

AP<sup>®</sup> PHYSICS 2 EQUATIONS

## FLUID MECHANICS AND THERMAL PHYSICS

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

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

$$P = P_0 + \rho gh$$

$$F_b = \rho Vg$$

$$A_1 v_1 = A_2 v_2$$

$$P_1 + \rho gy_1 + \frac{1}{2} \rho v_1^2 = P_2 + \rho gy_2 + \frac{1}{2} \rho v_2^2$$

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

$$PV = nRT = Nk_B T$$

$$K = \frac{3}{2} k_B T$$

$$W = -P \Delta V$$

$$\Delta U = Q + W$$

$A$  = 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

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

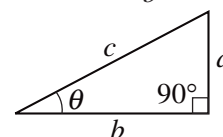
$A$  = area  
 $C$  = circumference  
 $V$  = volume  
 $S$  = surface area  
 $b$  = base  
 $h$  = height  
 $\ell$  = length  
 $w$  = width  
 $r$  = radius

Rectangular solid  
 $V = \ell wh$

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

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

Right triangle  
 $c^2 = a^2 + b^2$   
 $\sin \theta = \frac{a}{c}$   
 $\cos \theta = \frac{b}{c}$   
 $\tan \theta = \frac{a}{b}$



## 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

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)

In each trial of a photoelectric experiment, a scientist uses a device to shine light of a single frequency on two different metals, 1 and 2. The device can emit light with frequency  $f_A$ ,  $f_B$ , or  $f_C$ . Each frequency of light is used to test both metals.

The scientist determines the minimum de Broglie wavelength  $\lambda_e$  of the electrons ejected from the metal in each trial of the experiment. The following table summarizes the results of the experiment. For each trial, the scientist analyzes only the electrons with the minimum de Broglie wavelength.

| Trial | Frequency of Light | Metal Tested | $\lambda_e$ ( $\times 10^{-10}$ m) |
|-------|--------------------|--------------|------------------------------------|
| 1     | $f_A$              | Metal 1      | 6.9                                |
| 2     | $f_A$              | Metal 2      | 9.4                                |
| 3     | $f_B$              | Metal 1      | No electrons ejected               |
| 4     | $f_B$              | Metal 2      | No electrons ejected               |
| 5     | $f_C$              | Metal 1      | 5.3                                |
| 6     | $f_C$              | Metal 2      | 6.3                                |

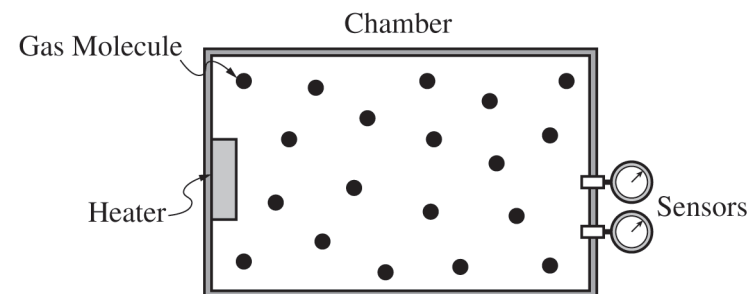
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Continue your response to **QUESTION 1** on this page.

- (a) In a coherent, paragraph-length response, **indicate** which frequency,  $f_A$ ,  $f_B$ , or  $f_C$ , is greatest and which frequency is least. **Justify** your answer using physics principles.
- (b) **Calculate** the maximum kinetic energy of the electrons ejected from Metal 1 in Trial 1. Assume that the momentum  $p$  of an ejected electron can be described by the classical definition  $p = mv$ .
- (c) **Indicate** whether the work function of Metal 1 is greater than, less than, or equal to the work function of Metal 2. **Justify** your answer by referring to the table of results.

**GO ON TO THE NEXT PAGE.**

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



Note: Figure not drawn to scale.

Figure 1

2. (12 points, suggested time 25 minutes)

In Experiment 1, shown in Figure 1, a sample of an ideal gas is contained in an insulated, sealed chamber with thin, rigid walls. The chamber contains a heater and sensors that measure the temperature and pressure of the gas. A student is asked to design an experiment to determine the number  $N$  of molecules of the gas contained in the chamber.

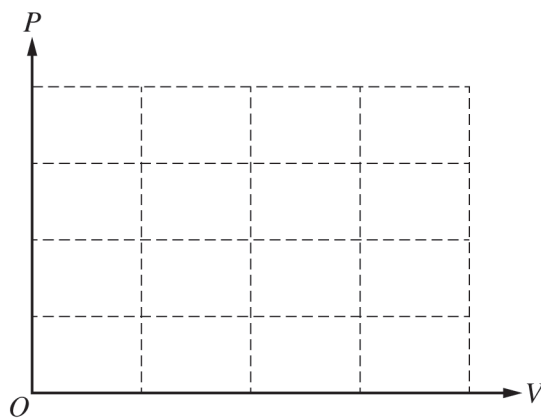
- (a) **Describe** a procedure for collecting data that would allow the student to determine an experimental value for  $N$ . Provide enough detail so that a student could replicate the experiment, including any steps necessary to reduce experimental uncertainty.

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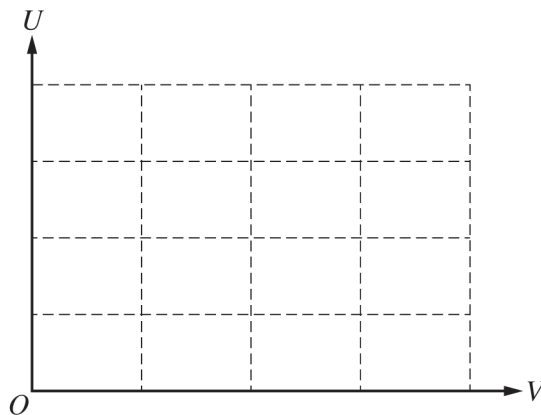
Continue your response to **QUESTION 2** on this page.

(b)

- i. On the following axes, **sketch** a curve or line to represent the expected relationship between the pressure  $P$  and the volume  $V$  of the gas while the heater is on. **Draw** an arrow on the curve or line to represent the direction of the resulting thermal process.



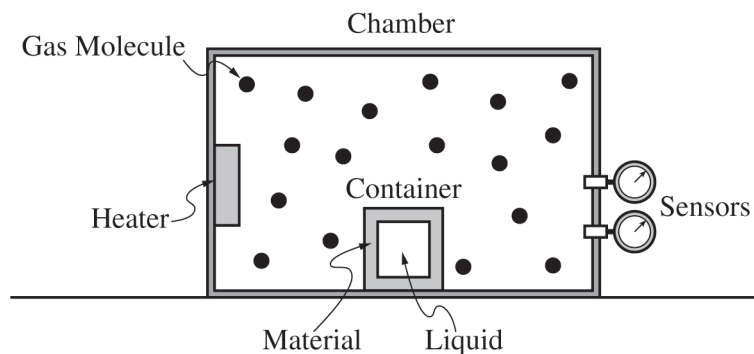
- ii. On the following axes, **sketch** a curve or line to represent the expected relationship between the internal energy  $U$  and the volume  $V$  of the gas while the heater is on. **Draw** an arrow on the curve or line to represent the direction of the resulting thermal process.



- iii. Briefly **justify** why the curve or line drawn in part (b)(ii) has the shape that you sketched.

**GO ON TO THE NEXT PAGE.**

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



Note: Figure not drawn to scale.

Figure 2

In Experiment 2, shown in Figure 2, a liquid-filled container that is completely wrapped with a material of uniform thickness 0.01 m is inside the sealed chamber that is filled with an ideal gas. The material has a total area of  $0.06 \text{ m}^2$  in contact with the gas. The heater is turned on. As the temperature  $T_G$  of the gas increases, the following data for the temperature  $T_L$  of the liquid and the rate  $\frac{Q}{\Delta t}$  of energy transfer are collected.

|  | $T_G$ (K) | $T_L$ (K) | $\frac{Q}{\Delta t} \left( \frac{\text{J}}{\text{s}} \right)$ |  |
|--|-----------|-----------|---------------------------------------------------------------|--|
|  | 295       | 295       | 0.0                                                           |  |
|  | 371       | 303       | 26.3                                                          |  |
|  | 425       | 308       | 43.1                                                          |  |
|  | 475       | 313       | 60.0                                                          |  |
|  | 528       | 323       | 75.0                                                          |  |

- (c) The student is asked to determine an experimental value of the thermal conductivity  $k$  of the material used to wrap the container inside the sealed chamber.

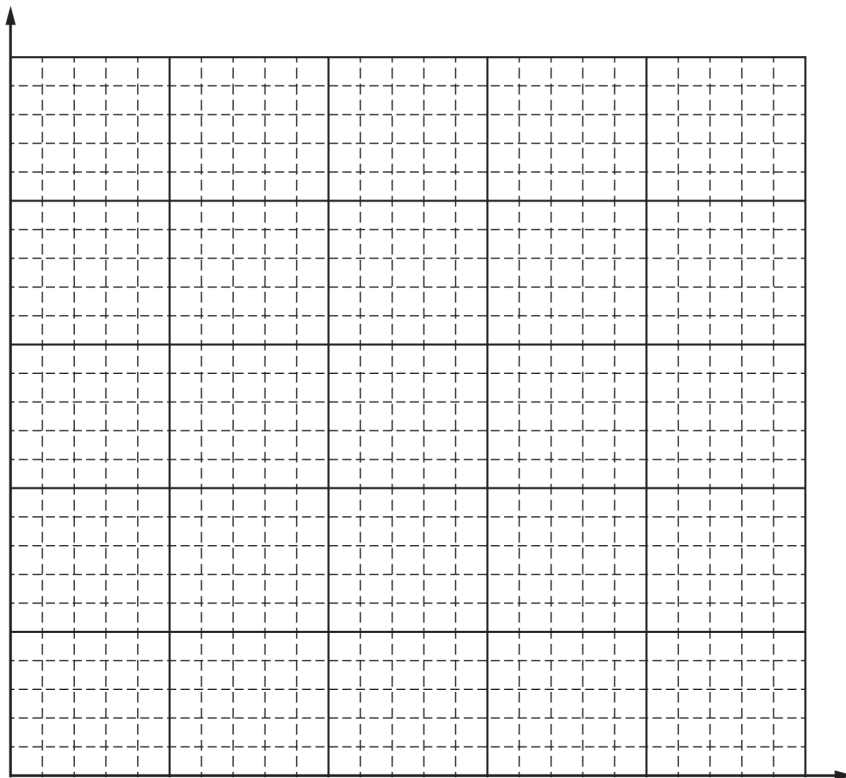
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Continue your response to **QUESTION 2** on this page.

- i. **Indicate** what measured and/or calculated quantities could be graphed to yield a straight line that could be used to calculate an experimental value for the thermal conductivity  $k$  of the material. Use the blank columns in the table to list any calculated quantities you graph in addition to the data provided.

Vertical Axis: \_\_\_\_\_ Horizontal Axis: \_\_\_\_\_

- ii. **Plot** the data points for the quantities indicated in part (c)(i) on the graph provided. Clearly scale and **label** all axes, including units, as appropriate.



- iii. **Draw** the best-fit line for the data graphed in part (c)(ii).

- (d) Using the best-fit line, **calculate** an experimental value for  $k$ .

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Begin your response to **QUESTION 3** on this page.

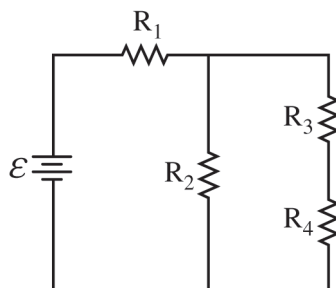


Figure 1

3. (12 points, suggested time 25 minutes)

A circuit consists of an ideal battery of emf  $\mathcal{E}$  and four identical resistors  $R_1$ ,  $R_2$ ,  $R_3$ , and  $R_4$ , each of resistance  $R$ , as shown in Figure 1.

(a) For parts (a)(i) and (a)(ii), express your answers in terms of numerical values,  $\mathcal{E}$ , and  $R$  only.

i. **Derive** an expression for the current  $I_1$  in Resistor  $R_1$ .

ii. **Derive** an expression for the current  $I_3$  in Resistor  $R_3$ .

**GO ON TO THE NEXT PAGE.**

Continue your response to **QUESTION 3** on this page.

(b) The partially completed bar chart in Figure 2 shows a bar that represents the absolute value  $|\Delta V|$  of the potential difference across the ideal battery.

- In Figure 2, **draw** a bar to represent  $|\Delta V|$  across each resistor, relative to the emf  $\mathcal{E}$  of the ideal battery.
- The height of each bar should be proportional to the value of  $|\Delta V|$  represented by that bar. If  $|\Delta V|$  is zero, write a “0” in that column.

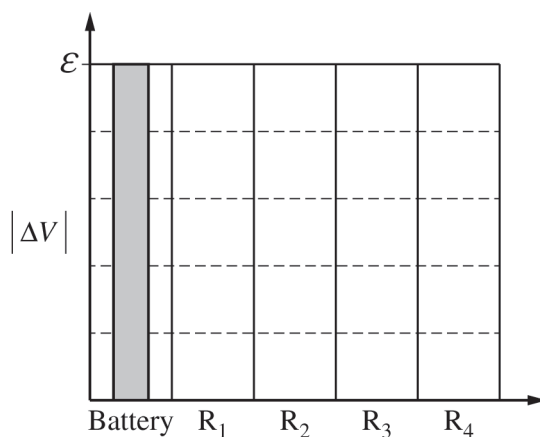


Figure 2

A student claims that the rate at which energy is dissipated (power) by the circuit can be expressed

as  $P = \frac{3\mathcal{E}^2}{5R}$ .

(c) **State** whether the expression for  $P$  is correct or incorrect. **Justify** your answer by referring to the derivations from part (a) or the bar chart from part (b).

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Continue your response to **QUESTION 3** on this page.

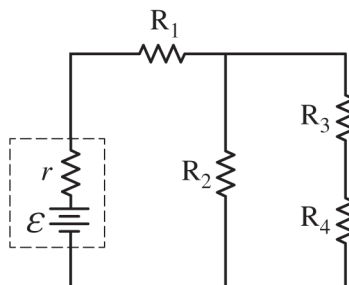


Figure 3

When the ideal battery is connected in the original circuit, the rate at which energy is dissipated by Resistor  $R_1$  is  $P_{\text{original}}$ . The ideal battery is now replaced with a nonideal battery of emf  $\mathcal{E}$  and internal resistance  $r$  to form the new circuit shown in Figure 3. The rate at which energy is dissipated by Resistor  $R_1$  in the new circuit is  $P_{\text{new}}$ .

(d) **Indicate** whether  $P_{\text{new}}$  is greater than, less than, or equal to  $P_{\text{original}}$ .

\_\_\_\_\_  $P_{\text{new}} > P_{\text{original}}$       \_\_\_\_\_  $P_{\text{new}} < P_{\text{original}}$       \_\_\_\_\_  $P_{\text{new}} = P_{\text{original}}$

Briefly **justify** your answer.

**GO ON TO THE NEXT PAGE.**

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

4. (10 points, suggested time 20 minutes)

Two particles, 1 and 2, have different mass and charge as described by the following.

- Particle 1 has mass  $M$  and negative charge  $-Q$ .
- Particle 2 has mass  $\frac{M}{2}$  and positive charge  $+2Q$ .

In separate trials, a device is used to accelerate each particle in the  $-y$ -direction from rest through a potential difference of absolute value  $|\Delta V|$ . The polarity of the potential difference can be adjusted so that a particle with either positive charge or negative charge can be accelerated in the  $-y$ -direction by the device. Gravitational effects are negligible.

After moving through the potential difference, particles 1 and 2 exit the device with kinetic energies  $K_1$  and  $K_2$ , respectively.

(a) **Calculate** the ratio  $\frac{K_2}{K_1}$ .

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

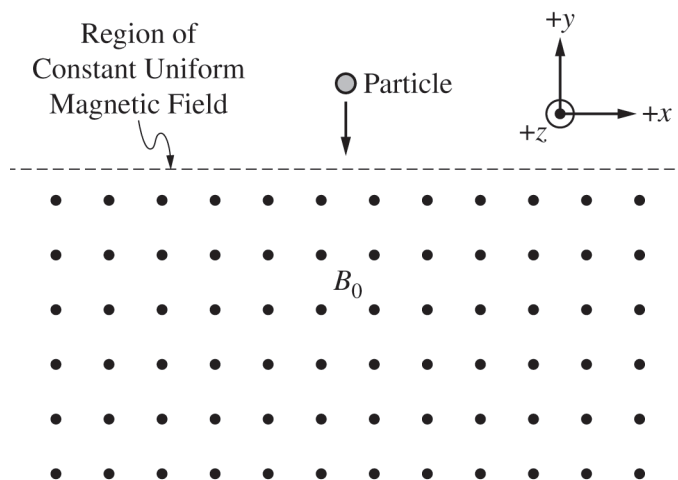


Figure 1

After exiting the device, the particles enter a large region of constant uniform magnetic field of magnitude  $B_0$  that is directed in the  $+z$ -direction (out of the page), as shown in Figure 1. Each particle is moving in the  $-y$ -direction when entering the region, and each particle is moving in the  $+y$ -direction when exiting the region.

(b)

i. **Determine** an expression for the speed of Particle 2 in the region. Express your answer in terms of  $M$ ,  $K_2$ , and physical constants, as appropriate.

ii. **Derive** an expression for the horizontal distance  $\Delta x$  between the locations where Particle 2 enters and leaves the region. Express your answer in terms of  $M$ ,  $Q$ ,  $K_2$ ,  $B_0$ , and physical constants, as appropriate.

**GO ON TO THE NEXT PAGE.**

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

- (c) On the following diagram in Figure 2, **sketch** and clearly **label** the paths of both particles 1 and 2 in the region.

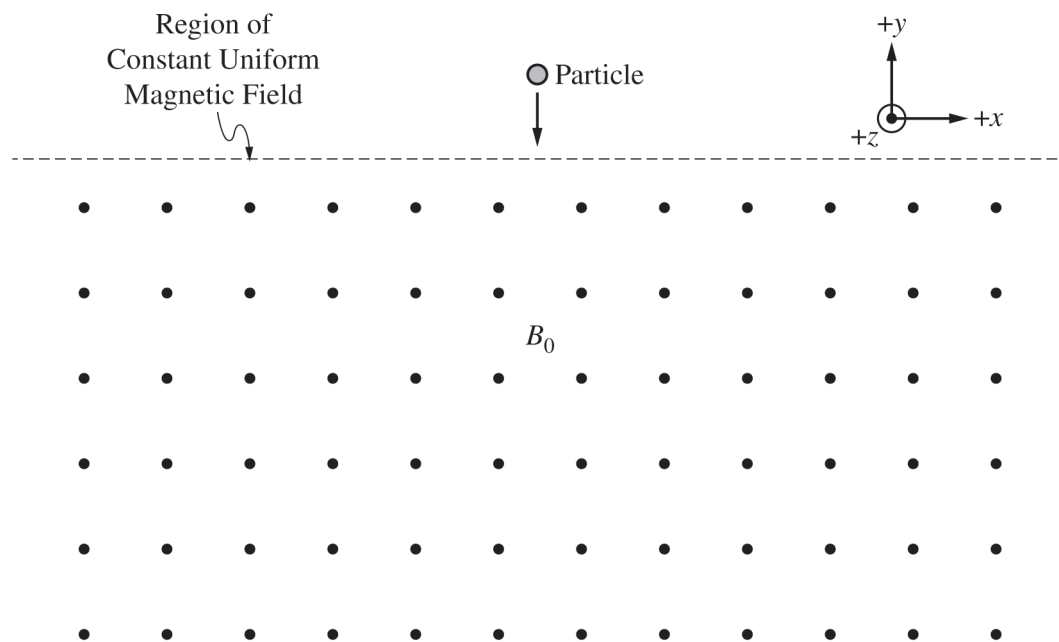


Figure 2

- (d) A uniform electric field is added to the region such that Particle 1 of negative charge  $-Q$  travels with constant speed in a straight line through the region. **Determine** the direction of the electric field.

**GO ON TO THE NEXT PAGE.**

**STOP**

**END OF EXAM**