CollegeBoard

AP® Physics 2

Practice Exam and Notes

Effective Fall 2014

About the College Board®

The College Board is a mission-driven not-for-profit organization that connects students to college success and opportunity. Founded in 1900, the College Board was created to expand access to higher education. Today, the membership association is made up of over 6,000 of the world's leading educational institutions and is dedicated to promoting excellence and equity in education. Each year, the College Board helps more than seven million students prepare for a successful transition to college through programs and services in college readiness and college success — including the SAT® and the Advanced Placement Program®. The organization also serves the education community through research and advocacy on behalf of students, educators, and schools.

For further information visit **www.collegeboard.org**.

AP Equity and Access Policy

The College Board strongly encourages educators to make equitable access a guiding principle for their AP programs by giving all willing and academically prepared students the opportunity to participate in AP. We encourage the elimination of barriers that restrict access to AP for students from ethnic, racial and socioeconomic groups that have been traditionally underserved. Schools should make every effort to ensure their AP classes reflect the diversity of their student population. The College Board also believes that all students should have access to academically challenging course work before they enroll in AP classes, which can prepare them for AP success. It is only through a commitment to equitable preparation and access that true equity and excellence can be achieved.

Important Note

This Practice Exam is provided by the College Board for AP Exam preparation. Teachers are permitted to download the materials and make copies to use with their students in a classroom setting only. To maintain the security of this exam, teachers should collect all materials after their administration and keep them in a secure location.

Exams may **not** be posted on school or personal websites, nor electronically redistributed for any reason. Further distribution of these materials outside of the secure College Board site disadvantages teachers who rely on uncirculated questions for classroom testing. Any additional distribution is in violation of the College Board's copyright policies and may result in the termination of Practice Exam access for your school as well as the removal of access to other online services such as the AP Teacher Community and Online Score Reports.

Contents

Introduction

Beginning in 2014-15, AP Physics 2: Algebra-Based will focus on the big ideas typically included in the second semester of an algebra-based, introductory college-level physics sequence.* The course covers electricity and magnetism, thermal physics, fluids, optics, and modern physics. The revised exam will include a reduced number of multiple-choice and free-response questions, and will include a new experimental-design question that demonstrates understanding of the science practices.

Part I of this publication is the AP Physics 2 Practice Exam. This will mirror the look and feel of an actual AP Exam, including instructions and sample questions. However, these exam items have never been administered in an operational exam, and, therefore, statistical analysis is **not** available. The purpose of this section is to provide educators with sample exam questions that accurately reflect the composition/design of the revised exam and to offer these questions in a way that gives teachers the opportunity to test their students in an exam situation that closely resembles the actual exam administration.

Part II is the Notes on the AP Physics 2 Practice Exam. This section offers detailed explanations of how each question in the practice exam links back to the AP Physics 1: Algebra-based and AP Physics 2: Algebra-based curriculum framework (Notes) in order to provide a clear link between curriculum and assessment. It also explains why the correct answer is the correct choice and why the other answers are incorrect (Rationales).

How AP Courses and Exams Are Developed

AP courses and exams are designed by committees of college faculty and AP teachers who ensure that each AP course and exam reflects and assesses college-level expectations. These committees define the scope and expectations of the course, articulating through a curriculum framework what students should know and be able to do upon completion of the AP course. Their work is informed by data collected from a range of colleges and universities to ensure that AP course work reflects current scholarship and advances in the discipline.

These same committees are also responsible for designing and approving exam specifications and exam questions that clearly connect to the curriculum framework. The AP Exam development process is a multi-year endeavor; all AP Exams undergo extensive review, revision, piloting, and analysis to ensure that questions are high quality and fair and that the questions comprise an appropriate range of difficulty.

Throughout AP course and exam development, the College Board gathers feedback from secondary and post-secondary educators. This feedback is carefully considered to ensure that AP courses and exams provide students with a college-level learning experience and the opportunity to demonstrate their qualifications for advanced placement and college credit upon college entrance.

*The AP Program has replaced AP Physics B with two new courses: AP Physics 1 and AP Physics 2. Resources for AP Physics 1 will be available separately.

Course Development

Each committee first articulates its discipline's high-level goals and then identifies the course's specific learning objectives. This approach is consistent with "backward design," the practice of developing curricula, instruction, and assessments with the end goal in mind. The learning objectives describe what students should know and be able to do, thereby providing clear instructional goals as well as targets of measurement for the exam.

Exam Development

Exam development begins with the committee making decisions about the overall nature of the exam. How long will it be? How many multiple-choice questions? How many free-response questions? How much time will be devoted to each section? How will the course content and skills be distributed across each section of the exam? Answers to these questions become part of the exam specifications.

With the exam specifications set, test developers design questions that conform to these specifications. The committee reviews every exam question for alignment with the curriculum framework, content accuracy, and a number of other criteria that ensure the integrity of the exam.

Exam questions are then piloted in AP classrooms to determine their statistical properties. Questions that have been approved by the committee and piloted successfully are included in an exam. When an exam is assembled, the committee conducts a final review of the exam to ensure overall conformity with the specifications.

How AP Exams Are Scored

The exam scoring process, like the course and exam development process, relies on the expertise of both AP teachers and college faculty. While multiple-choice questions are scored by machine, the free-response questions are scored by thousands of college faculty and expert AP teachers at the annual AP Reading. AP Exam Readers are thoroughly trained, and their work is monitored throughout the Reading for fairness and consistency. In each subject, a highly respected college faculty member fills the role of Chief Reader, who, with the help of AP Readers in leadership positions, maintains the accuracy of the scoring standards. Scores on the free-response questions are weighted and combined with the results of the computer-scored multiple-choice questions, and this raw score is summed to give a composite AP score of 5, 4, 3, 2, or 1.

The score-setting process is both precise and labor intensive, involving numerous psychometric analyses of the results of a specific AP Exam in a specific year and of the particular group of students who took that exam. Additionally, to ensure alignment with college-level standards, part of the score-setting process involves comparing the performance of AP students with the performance of students enrolled in comparable courses in colleges throughout the United States. In general, the AP composite score points are set so that the lowest raw score needed to earn an AP score of 5 is equivalent to the average score among college students earning grades of A in the college course. Similarly, AP Exam scores of 4 are equivalent to college grades of A–, B+, and B. AP Exam scores of 3 are equivalent to college grades of B–, C+, and C.

Using and Interpreting AP Scores

The extensive work done by college faculty and AP teachers in the development of the course and the exam and throughout the scoring process ensures that AP Exam scores accurately represent students' achievement in the equivalent college course. While colleges and universities are responsible for setting their own credit and placement policies, AP scores signify how qualified students are to receive college credit and placement:

AP Score	Qualification
5	Extremely well qualified
4	Well qualified
3	Qualified
2	Possibly qualified
1	No recommendation

Additional Resources

Visit apcentral.collegeboard.org for more information about the AP Program.

Practice Exam

Exam Content and Format

The AP Physics 2 Exam is approximately 3 hours in length. There are two sections:

- Section I is 90 minutes in length and consists of 50 multiple-choice questions accounting for 50 percent of the final score.
- Section II is 90 minutes in length and consists of 4 free-response questions accounting for 50 percent of the final score.

Administering the Practice Exam

This section contains instructions for administering the AP Physics 2 Practice Exam. You may wish to use these instructions to create an exam situation that resembles an actual administration. If so, read the indented, boldface directions to the students; all other instructions are for administering the exam and need not be read aloud. Before beginning testing, have all exam materials ready for distribution. These include test booklets, answer sheets, the AP Physics 2 Table of Information and Equations list, and calculators.

SECTION I: Multiple-Choice Questions

When you are ready to begin Section I, say:

> **Section I is the multiple-choice portion of the exam. Mark all of your responses on your answer sheet, one response per question. If you need to erase, do so carefully and completely. Your score on the multiple-choice section will be based solely on the number of questions answered correctly. You may use a scientific/graphing calculator and Physics 2 Table of Information and Equations list during this ENTIRE section. Are there any questions?**
>
> **You have 90 minutes for this section. Open your Section I booklet and begin.**

Note Start Time here______. Note Stop Time here______. Check that students are marking their answers in pencil on their answer sheets, and that they are not looking at their Section II booklets. After 90 minutes, say:

> **Stop working. I will now collect your Section I booklet.**

There is a 10-minute break between Sections I and II. When all Section I materials have been collected and accounted for and you are ready for the break, say:

> **Please listen carefully to these instructions before we take a 10-minute break. Leave your Section II packet on your desk during the break. Are there any questions?**

You may begin your break. Testing will resume at _______.

SECTION II: Free-Response Questions

After the break, say:

> **You have 90 minutes to answer the questions in this section. You are responsible for pacing yourself, and may proceed freely from one question to the next. Write your answers in the space provided for each part of a question. If you need more paper during the exam, raise your hand. At the top of each extra piece of paper you use, be sure to write your name and the number and part of the question you are working on. You may use a scientific/graphing calculator and Physics 2 Table of Information and Equations list during this ENTIRE section. Are there any questions?**
>
> **You have 90 minutes for this section. Open your Section II booklet and begin.**

Note Start Time here______. Note Stop Time here______. Check that students are writing their answers in their exam booklets. After 80 minutes, say:

> **There are 10 minutes remaining.**

After 10 minutes, say:

> **Stop working and close your exam booklet. Put your exam booklet on your desk, face up. Remain in your seat, without talking, while the exam materials are collected.**

If any students used extra paper for the free-response section, have those students staple the extra sheet/s to the first page corresponding to that question in their exam booklets. Collect a Section II booklet from each student and check that each student wrote answers on the lined pages corresponding to each question.

Then say:

> **You are now dismissed.**

Name:________________________________

AP® Physics 2
Student Answer Sheet
for Multiple-Choice Section

No.	Answer
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	
16	
17	
18	
19	
20	
21	
22	
23	
24	
25	
26	
27	
28	
29	
30	

No.	Answer
31	
32	
33	
34	
35	
36	
37	
38	
39	
40	
41	
42	
43	
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45	

46		
47		
48		
49		
50		

AP® Physics 2 Practice Exam

SECTION I: Multiple Choice

DO NOT OPEN THIS BOOKLET UNTIL YOU ARE TOLD TO DO SO.

At a Glance

Total Time
90 minutes
Number of Questions
50
Percent of Total Score
50%
Writing Instrument
Pencil required
Electronic Device
Calculator allowed

Instructions

Section I of this exam contains 50 multiple-choice questions. Pages containing equations and other information are also printed in this booklet. Calculators, rulers, and straightedges may be used in this section.

Indicate all of your answers to the multiple-choice questions on the answer sheet. No credit will be given for anything written in this exam booklet, but you may use the booklet for notes or scratch work.

For questions 1 through 45, select the single best answer choice for each question. After you have decided which of the choices is best, fill in the appropriate letter in the corresponding space on the answer sheet.

For questions 46 through 50, select the two best answer choices for each question. After you have decided which two of the choices are best, enter both letters in the corresponding space on the answer sheet.

Use your time effectively, working as quickly as you can without losing accuracy. Do not spend too much time on any one question. Go on to other questions and come back to the ones you have not answered if you have time. It is not expected that everyone will know the answers to all of the multiple-choice questions.

Your total score on Section I is based only on the number of questions answered correctly. Points are not deducted for incorrect answers or unanswered questions.

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, $N_0 = 6.02 \times 10^{23}$ mol^{-1}	Universal gravitational constant, $G = 6.67 \times 10^{-11}$ m^3/kg•s^2
Universal gas constant, $R = 8.31$ J/(mol•K)	Acceleration due to gravity at Earth's surface, $g = 9.8$ m/s^2
Boltzmann's constant, $k_B = 1.38 \times 10^{-23}$ J/K	

1 unified atomic mass unit,	$1 \text{ u} = 1.66 \times 10^{-27}$ kg $= 931$ MeV$/c^2$
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,	$\varepsilon_0 = 8.85 \times 10^{-12}$ C^2/N•m^2
Coulomb's law constant,	$k = 1/4\pi\varepsilon_0 = 9.0 \times 10^9$ N•m^2/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,	$1 \text{ atm} = 1.0 \times 10^5$ 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

θ	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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$L = I\omega$$

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

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

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

a = acceleration
d = distance
E = energy
F = force
f = frequency
h = height
I = rotational inertia
K = kinetic energy
k = spring constant
L = angular momentum
ℓ = 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
α = angular acceleration
μ = coefficient of friction
θ = angle
τ = torque
ω = 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

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

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

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

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

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

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

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

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

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

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

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

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

$$P = I \Delta V$$

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

$$R_s = \sum_i R_i$$

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

$$C_p = \sum_i C_i$$

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

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

A = area
B = magnetic field
C = capacitance
d = distance
E = electric field
$\mathcal{E}$ = emf
F = force
I = current
ℓ = length
P = power
Q = charge
q = point charge
R = resistance
r = separation
t = time
U = potential (stored) energy
V = electric potential
v = speed
ρ = resistivity
θ = angle
Φ = flux

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

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

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

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

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

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

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

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

AP® PHYSICS 2 EQUATIONS

FLUID MECHANICS AND THERMAL PHYSICS

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

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

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

$$F_b = \rho V g$$

$$A_1 v_1 = A_2 v_2$$

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

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

$$PV = nRT = Nk_B T$$

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

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

$$\Delta U = Q + W$$

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
ρ = 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
λ = wavelength
ϕ = 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
λ = wavelength
θ = angle

GEOMETRY AND TRIGONOMETRY

Rectangle
$A = bh$

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

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

Rectangular solid
$V = \ell wh$

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

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

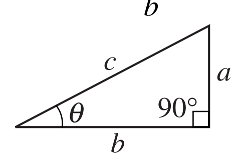
A = area
C = circumference
V = volume
S = surface area
b = base
h = height
ℓ = length
w = width
r = radius

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

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

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

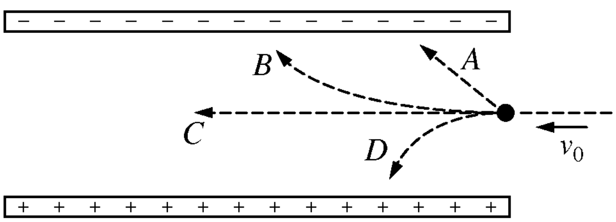
$\tan\theta = \frac{a}{b}$



PHYSICS 2
Section I
50 Questions
Time—90 minutes

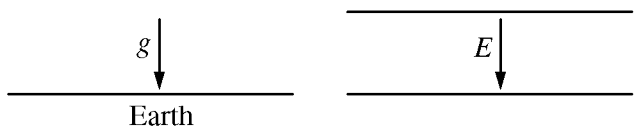
Note: To simplify calculations, you may use $g = 10 \text{ m/s}^2$ in all problems.

Directions: Each of the questions or incomplete statements below is followed by four suggested answers or completions. Select the one that is best in each case and then enter the appropriate letter in the corresponding space on the answer sheet.



1. A proton is traveling to the left when it enters the space between two oppositely charged parallel plates, as shown above. Which of the four labeled paths will the proton take?

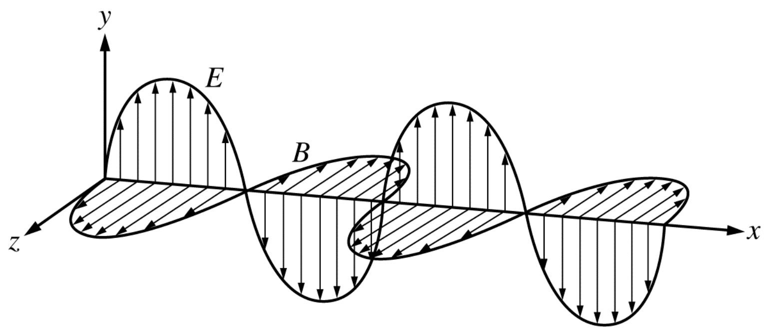
(A) *A*
(B) *B*
(C) *C*
(D) *D*



2. The figures above represent two fields. The figure on the left represents the uniform gravitational field very near Earth's surface. The figure on the right represents the uniform electric field E near the center of the region between very large parallel plates. Which of the following describes the shape of the isolines of potential for the gravitational field and the electric field in these regions?

(A) Isolines are straight, vertical lines for both the gravitational and electric fields.
(B) Isolines are straight, horizontal lines for both the gravitational and electric fields.
(C) Gravitational isolines are straight, while electric isolines are curved.
(D) Gravitational isolines are curved, while electric isolines are straight.

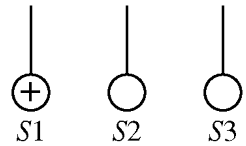
GO ON TO THE NEXT PAGE.



3. The figure above shows a model of an electromagnetic wave, where E is the electric field and B is the magnetic field. In what direction is the energy of the wave transmitted?

(A) Along the x-axis only
(B) Along the y-axis only
(C) Along the z-axis only
(D) In a direction that is at a nonzero angle to each of the axes

GO ON TO THE NEXT PAGE.



4. Three identical conducting spheres, $S1$, $S2$, and $S3$, are supported by insulating thread, as shown above. Initially, sphere $S1$ has a net positive charge and the other two spheres are uncharged. Spheres $S1$ and $S2$ are brought into contact and then separated. Next, spheres $S2$ and $S3$ are brought into contact and then separated. Which of the following shows the signs of the final net charges on the spheres?

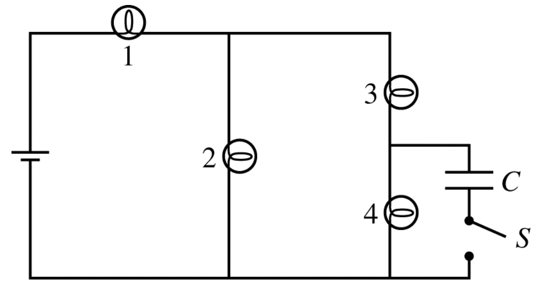
   (A) ⊕ ⊕ ⊕

   (B) ⊕ ○ ○

   (C) ○ ○ ⊕

   (D) ○ ⊕ ⊕

Questions 5-7 refer to the following material.



The circuit shown above contains four identical lightbulbs with constant resistance, a capacitor C, which is initially uncharged, and a switch S. The switch is initially open.

5. Which of the following correctly ranks the potential differences ΔV_1, ΔV_2, ΔV_3, and ΔV_4 across the bulbs while the switch is open?

   (A) $\Delta V_1 = \Delta V_2 = \Delta V_3 = \Delta V_4$
   (B) $\Delta V_1 > \Delta V_2 = \Delta V_3 = \Delta V_4$
   (C) $\Delta V_1 > \Delta V_2 > \Delta V_3 = \Delta V_4$
   (D) $\Delta V_1 > \Delta V_2 > \Delta V_3 > \Delta V_4$

6. Immediately after the switch is closed, the current in bulb 1 is I_a. What is the current in bulb 2 at that time?

   (A) I_a
   (B) $2I_a/3$
   (C) $I_a/2$
   (D) $I_a/3$

7. After the switch has been closed a long time, how does the brightness of bulb 4 compare with its brightness before the switch was closed?

   (A) Bulb 4 is much dimmer and is only barely lit.
   (B) Bulb 4 is slightly dimmer.
   (C) Bulb 4 is the same brightness.
   (D) Bulb 4 is slightly brighter.

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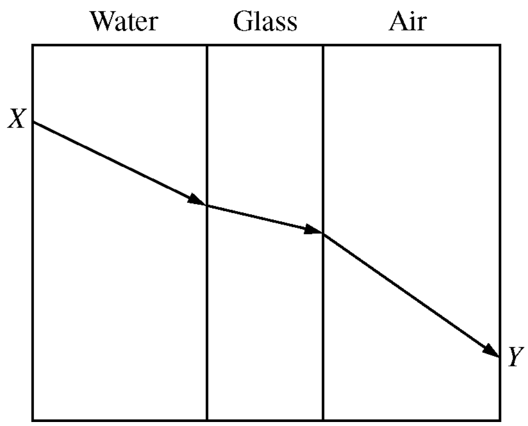
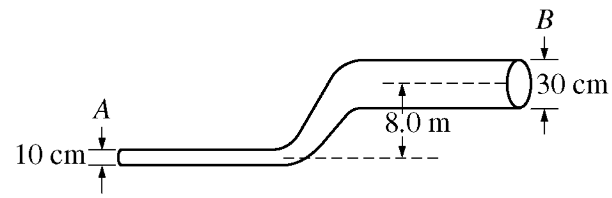


8. A light ray enters a layer of water at point *X*, passes through a layer of glass, and exits through a layer of air at point *Y*, as shown in the figure above. Where would the ray exit the layer of air if the glass was replaced with a material of higher index of refraction?

(A) At a point above point *Y*
(B) At a point below point *Y*
(C) At point *Y*
(D) The location cannot be determined without knowing how much higher the index of refraction of the new material is.

9. Which of the following indicates the object distance s_o for which a spherical concave mirror of focal length *f* produces an upright image?

(A) $s_o < f$
(B) $s_o = f$
(C) $2f > s_o > f$
(D) $s_o > 2f$



Note: Figure not drawn to scale.

10. Water is flowing with a speed of $9.0\ \text{m/s}$ through a pipe of diameter 10 cm. The pipe widens to 30 cm as it goes up an 8.0 m step, as shown in the figure above. If the pressure at point *A* is $2.0 \times 10^5\ \text{Pa}$, what is the pressure at point *B* ? (The density of water is $1.0 \times 10^3\ \text{kg/m}^3$.)

(A) $1.2 \times 10^5\ \text{Pa}$
(B) $1.6 \times 10^5\ \text{Pa}$
(C) $2.4 \times 10^5\ \text{Pa}$
(D) $3.2 \times 10^5\ \text{Pa}$

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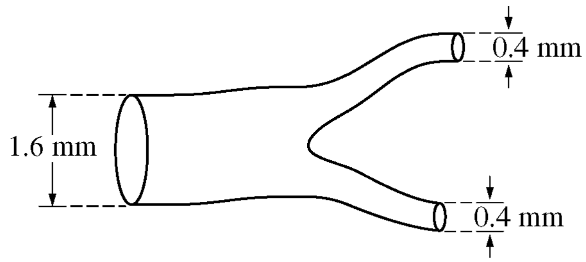


11. The figure above represents a portion of a blood vessel with circular cross sections. The segment on the left has diameter 1.6 mm, and each of the segments on the right has diameter 0.4 mm. Assume the blood can be treated as an ideal fluid. If blood enters the segment on the left with speed v, at what speed does the blood leave the segments on the right?

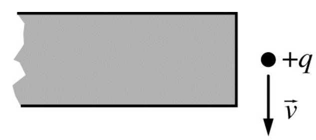
(A) $2v$
(B) $4v$
(C) $8v$
(D) $16v$

12. A slab of metal and a slab of wood are placed in a classroom and allowed to sit undisturbed for a long time. A student then places one hand on the metal and the other hand on the wood. Which of the following describes the student's perception of the temperatures of the slabs and their actual temperatures?

(A) The metal slab feels colder to the student because it is at a lower temperature.
(B) The metal slab feels colder to the student because it conducts thermal energy away from the student's hand faster, but the slabs have the same temperature.
(C) The metal slab feels warmer to the student because it conducts thermal energy to the student's hand faster, but the slabs have the same temperature.
(D) Both slabs feel the same to the student because they are at the same temperature.

13. When one end of a cold metal spoon is placed upright in a cup of hot cocoa, the other end eventually gets warmer. On the scale of the molecules of the spoon, which of the following is the primary explanation of this phenomenon?

(A) Higher-energy molecules will, on average, rise to the top.
(B) The hot molecules produce thermal radiation that is then absorbed by the colder molecules.
(C) Higher-energy molecules hit lower-energy molecules and, on average, tend to reduce the difference in temperature between the ends of the spoon.
(D) Thermal energy is a fluid that flows from high concentration (hot areas) to low concentration (cold areas).



14. An object with charge $+q$ passes to the right of one pole of a magnet and at a particular instant is moving with a velocity $\vec{v}$ toward the bottom of the page, as shown in the figure above. The force exerted on the object by the magnet at that instant is directed into the page. What is the direction of the force exerted on the magnet by the object?

(A) Out of the page
(B) Toward the right
(C) Toward the top of the page
(D) No direction; the force is zero.

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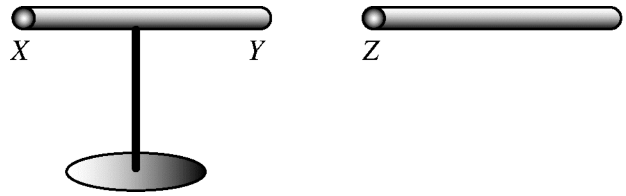
Wire	1	2	3	4	5
Current (A)	0.5	1.0	2.0	2.5	3.0

15. A student was given five wires of the same length and diameter. The student connected the wires to the same battery one by one and measured the current through each wire. The table above shows the data collected. Which of the following can be concluded from the data?

(A) The wires are ohmic.
(B) The wires are made of different materials.
(C) The resistance of the wires depends on their size and shape.
(D) The battery has internal resistance.



16. In the figure above, the initially uncharged insulating rod on the left is free to rotate on an insulating stand. End X is then rubbed with a piece of fur. End Z of a second insulating rod is also rubbed with fur and then brought near the first rod. As the second rod is moved around, it is found that end Y of the first rod is attracted to end Z, and end X is repelled. Which of the following correctly describes the signs of the charges on ends X and Y, if any?

	End X	End Y
(A)	Opposite Z's charge	Same as Z's charge
(B)	Opposite Z's charge	No net charge
(C)	Same as Z's charge	Opposite Z's charge
(D)	Same as Z's charge	No net charge

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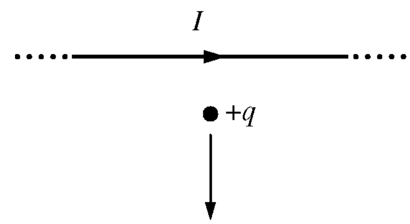
17. A student has a positively charged insulating rod and two initially uncharged conducting spheres, A and B, with insulated handles. Which of the following ordered sequences of actions could the student use to produce a net positive charge on sphere A ?

(A) Bring the rod near the right side of A. Touch B to the left side of A. Remove B and then remove the rod.
(B) Bring the rod near the right side of A. Touch B to the left side of A. Remove the rod and then remove B.
(C) Bring the rod near the right side of B. Touch A to the left side of B. Remove B and then remove the rod.
(D) Bring the rod near the right side of B. Touch A to the left side of B. Remove the rod and then remove B.



18. The figure above shows a long conducting wire that lies in the plane of the page and carries an electric current I toward the right. At the instant shown, a positive point charge $+q$ is in the plane of the page and moving toward the bottom of the page. What is the direction of the magnetic force on the point charge at that instant?

(A) Into the page
(B) Out of the page
(C) Toward the right
(D) Toward the left

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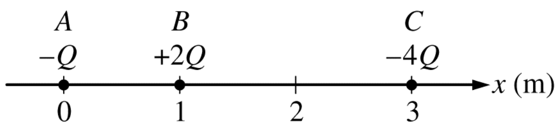
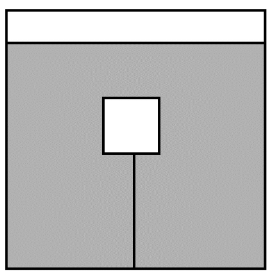


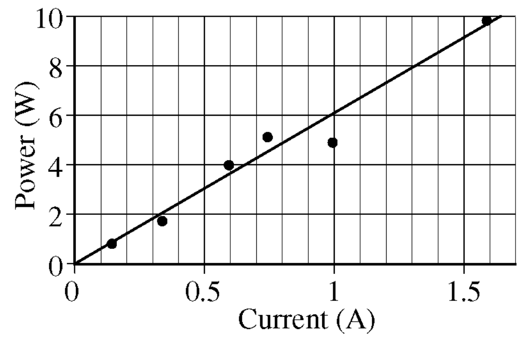
19. The figure above shows three point charges located on an x-axis. Which of the following ranks the magnitude of the net electric force, F, on each point charge due to the other charges?

(A) $F_A = F_C > F_B$
(B) $F_B > F_C = F_A$
(C) $F_A = F_B > F_C$
(D) $F_A > F_C > F_B$



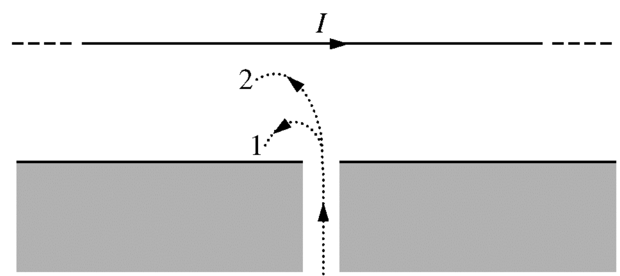
20. A block is submerged in a container of liquid and held under the surface of the liquid by a string connected to the bottom of the container, as shown in the figure above. The tension in the string is not zero. How does the buoyant force F_B exerted by the liquid on the block compare to the block's weight w ?

(A) $F_B < w$
(B) $F_B = w$
(C) $F_B > w$
(D) Either $F_B < w$ or $F_B > w$, depending on the density of the liquid.



21. A variable resistor is connected to a battery of unknown potential difference. The power dissipated by the resistor and the current through the resistor are measured. The figure above shows a graph of the data and a best-fit line for the data. The potential difference provided by the battery is most nearly

(A) 0.3 V
(B) 3.0 V
(C) 5.0 V
(D) 6.0 V



Note: Figure not drawn to scale.

22. A scientist is studying the radioactive decay of an element and wants to determine the sign of some of the particles emitted. The scientist lets a beam of the particles, all with the same speed, pass through an opening in a shield and enter the field created by a wire carrying a constant current. Paths 1 and 2 represent the observed paths of the particles. Based on the paths, which of the following could be the types of particles?

	Path 1 Particle	Path 2 Particle
(A)	Electron	Alpha
(B)	Alpha	Electron
(C)	Positron	Alpha
(D)	Alpha	Positron

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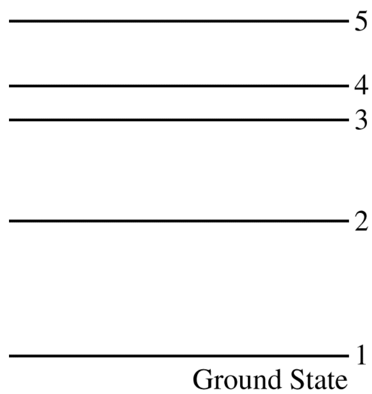
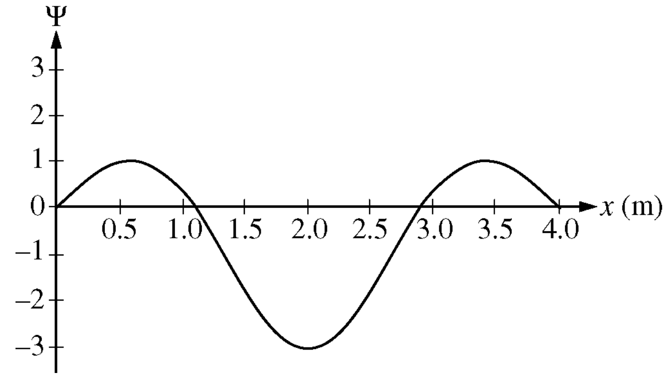


23. The energy states for an electron in a hypothetical atom are represented above. A cold sample of gas of such atoms is illuminated by a brief flash of light with a continuous spectrum. The atoms are then observed to emit light with discrete wavelengths. Which of the following transitions produces the longest wavelength light?

(A) 5 to 4
(B) 4 to 3
(C) 3 to 2
(D) 2 to 1

24. A nucleus of $^{238}_{92}\text{U}$ undergoes a series of decays in which it emits eight $^{4}_{2}\text{He}$ nuclei and some β^- particles to produce the nucleus $^{206}_{82}\text{Pb}$. How many β^- particles are emitted in the process?

(A) 10
(B) 8
(C) 6
(D) 5



25. The graph above shows the wave function $\Psi(x)$ of a particle moving in the region $0 < x < 4$ m. At which of the following positions is the probability of finding the particle greatest?

(A) 0.7 m
(B) 2.0 m
(C) 2.5 m
(D) 4.0 m

$$\text{n} + {}^{235}_{92}\text{U} \rightarrow {}^{141}_{56}\text{Ba} + {}^{92}_{36}\text{Kr} + 3\text{n}$$

26. Which of the following expressions, where m represents the mass of a particle, equals the energy released in the nuclear reaction represented above?

(A) $(m_{\text{Ba}} + m_{\text{Kr}} + m_{\text{U}} - 3m_{\text{n}})c^2$
(B) $(m_{\text{Ba}} + m_{\text{Kr}} - m_{\text{U}} - 2m_{\text{n}})c^2$
(C) $(m_{\text{U}} - m_{\text{Ba}} - m_{\text{Kr}} - 3m_{\text{n}})c^2$
(D) $(m_{\text{U}} - m_{\text{Ba}} - m_{\text{Kr}} - 2m_{\text{n}})c^2$

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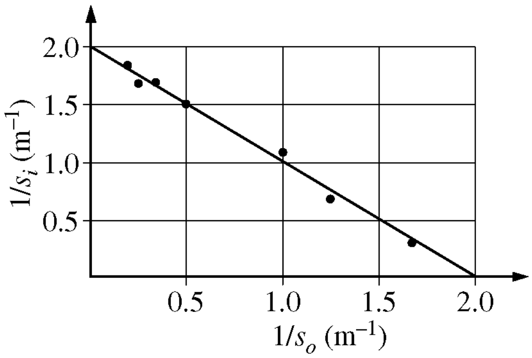
Questions 27-28 refer to the following material.



A group of students collected data using a lens. They varied the distance s_o of an object from the lens and measured the image distance s_i. The figure above is their graph of the inverse of the image distance as a function of the inverse of the object distance.

27. The focal length of the lens is approximately

(A) 0.5 m
(B) 1.0 m
(C) 2.0 m
(D) 4.0 m

28. What is the magnitude of the image's magnification when the object is placed 2 m from the lens?

(A) $1/3$
(B) 1
(C) 3
(D) The magnification is undefined because the image is an infinite distance from the lens.

29. A partially evacuated vertical cylindrical container is covered by a circular lid that makes an airtight seal. The pressure in the room surrounding the container is 1.01×10^5 N/m^2, and the pressure inside the container is 0.41×10^5 N/m^2. The lid has radius 0.20 m and weight 200 N. The minimum upward applied force required to lift the lid is most nearly

(A) 7.5×10^3 N
(B) 7.7×10^3 N
(C) 1.3×10^4 N
(D) 1.8×10^4 N

30. A sealed container of air has been sitting on a table in a dark room for a very long time. The room is always kept at a constant temperature. Which of the following best describes what will happen to the speeds and the average kinetic energy of the molecules of the air in the container as the container continues to sit on the table?

(A) Each molecule will continue to move at constant speed, keeping the average kinetic energy of the molecules constant.
(B) Some molecules will speed up and others will slow down, keeping the average kinetic energy of the molecules constant.
(C) The molecules will gradually slow down, decreasing their average kinetic energy.
(D) The molecules will gradually speed up, increasing their average kinetic energy.

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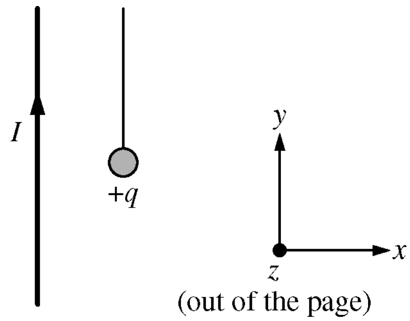

31. The figure above shows a long, straight wire that has a steady current I in the $+y$-direction. A small object with charge $+q$ hangs from a thread near the wire. A student wants to investigate the magnetic force on the object due to the current but is not able to observe or measure changes in the tension in the string. Of the following actions that the student can take, which will allow the student to observe a reaction of the object due to the magnetic force on it?

(A) Holding the object motionless
(B) Moving the object in a circle that is centered on the wire and in the x-z plane
(C) Moving the object in the $-x$-direction
(D) Moving the object in the $+y$-direction

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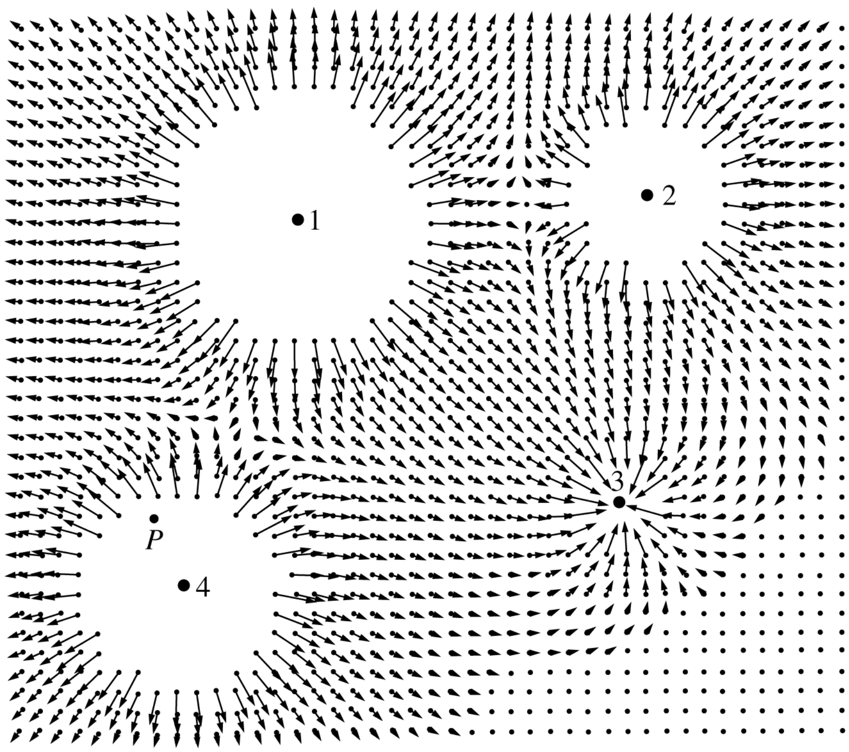
Questions 32-33 refer to the following material.



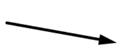
The figure above shows the electric field in a region surrounding four charged particles, labeled 1, 2, 3, and 4, that are held in place. (Vectors with very large magnitude are not shown.)

32. A small positive test charge is held at point *P*. Which of the following is closest to the direction of the force exerted on the test charge?

(A) 

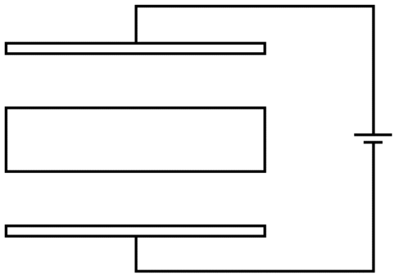
(B) 

(C) 

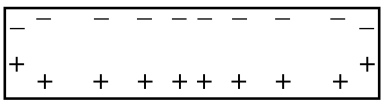
(D) 

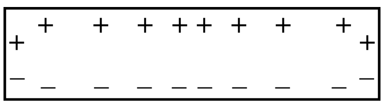
33. Which of the following indicates the particles with charges of the greatest and the least magnitude?

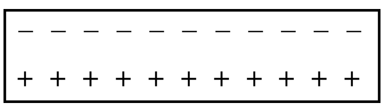
	Greatest	Least
(A)	4	2
(B)	3	1
(C)	2	4
(D)	1	3

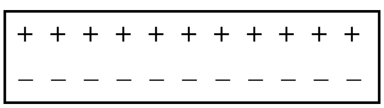


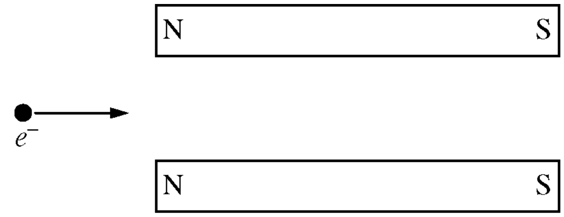
34. A parallel-plate capacitor is connected to a battery. A thick metal plate is located between the plates of the capacitor, as shown above. Which of the following best shows the distribution of charge on the thick plate?

(A) 

(B) 

(C) 

(D) 



35. At the instant shown above, an electron is moving to the right along a straight line midway between two identical bar magnets. Which of the following describes the path of the electron as it continues to move?

(A) It remains on the straight line and passes completely between the magnets.
(B) It curves upward and strikes the top magnet.
(C) It curves downward and reverses direction before it enters the space between the magnets.
(D) It stops and reverses direction, then moves to the left along the same straight line.

36. Which of the following procedures can a student follow to give a metallic sphere a positive charge by induction?

(A) Touching the sphere with a positively charged rod
(B) Placing a negatively charged rod near the sphere
(C) Placing a positively charged rod near the sphere, grounding the sphere, and then removing the connection to ground
(D) Placing a negatively charged rod near the sphere, grounding the sphere, and then removing the connection to ground

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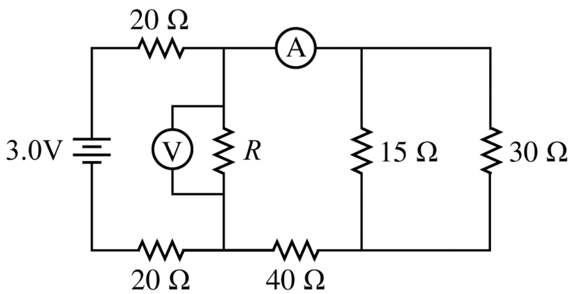
Questions 37-38 refer to the following material.



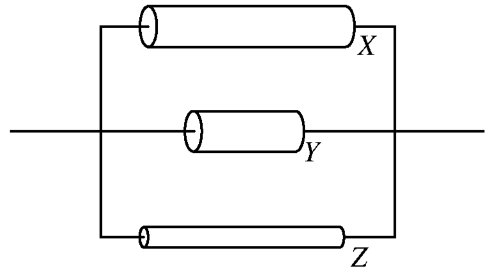
In the circuit shown above, the current through the ammeter is 20 mA and the voltmeter indicates 1.0 V.

37. What is the current through the $40\ \Omega$ resistor?

(A) 7.5 mA
(B) 10 mA
(C) 20 mA
(D) 40 mA

38. The resistance of resistor R is most nearly

(A) 50 Ω
(B) 33 Ω
(C) 20 Ω
(D) 14 Ω



39. The figure above represents a section of a circuit containing three resistors, *X*, *Y*, and *Z*, of different sizes but made of the same material. Which of the following correctly ranks the current in the resistors?

(A) $I_Z > I_X > I_Y$
(B) $I_Z = I_X > I_Y$
(C) $I_Y = I_X = I_Z$
(D) $I_Y > I_X > I_Z$

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40. Three identical, small cork spheres are released from rest in a uniform electric field directed downward toward the floor. Sphere X is uncharged, but spheres Y and Z are charged. Sphere Z remains suspended in the field. Spheres X and Y fall downward, but sphere X takes a longer time to reach the floor. What are the signs of the charges on spheres Y and Z?

	Sphere Y	Sphere Z
(A)	Negative	Negative
(B)	Negative	Positive
(C)	Positive	Positive
(D)	Positive	Negative

41. Two charged objects are held at a distance *d* apart. Their mutual gravitational force is equal to their mutual electrostatic force. Which of the following must be true of the charges and masses of the objects, if charge is expressed in C and mass is expressed in kg?

(A) The magnitude of the product of the charges must equal the magnitude of the product of the masses.
(B) The magnitude of the product of the charges must be much less than the magnitude of the product of the masses.
(C) The magnitude of the product of the charges must be much greater than the magnitude of the product of the masses.
(D) The charges must be equal and the masses must be equal.

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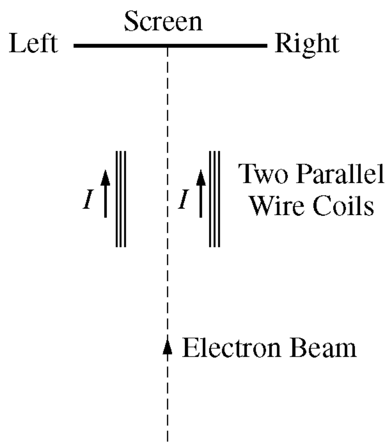
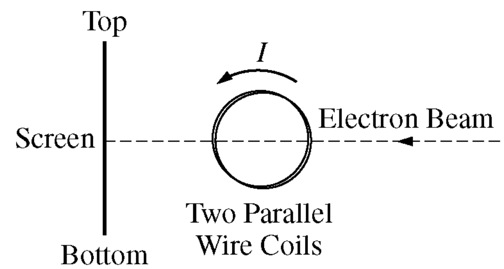


Top View



Side View

42. A beam of electrons travels between two parallel wire coils, as shown in the figures above. When the coils carry no current, the electron beam is undeflected and hits the center of the screen, as indicated by the dashed line. When a constant current *I* in the indicated direction is created in the coils, the electron beam is deflected toward which edge of the screen?

(A) The top
(B) The bottom
(C) The left
(D) None; it is not deflected.

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43. An absorption spectrum, observed for light traveling through interstellar gases, appears as a broad spectrum of light with isolated dark lines at frequencies characteristic of the molecules in the gases. Which of the following is primarily responsible for the location of the dark absorption lines in the spectrum?

(A) The characteristic velocities of the molecules in the gas
(B) The transition of electrons between discrete energy states within the gas molecules
(C) The percent of the gas molecules that were ionized by absorption of energy
(D) The fluctuations in density of molecules present in the interstellar gas cloud

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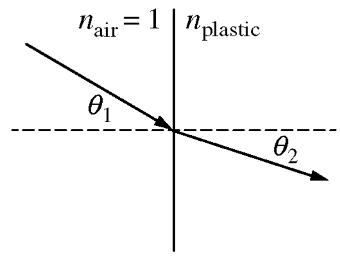
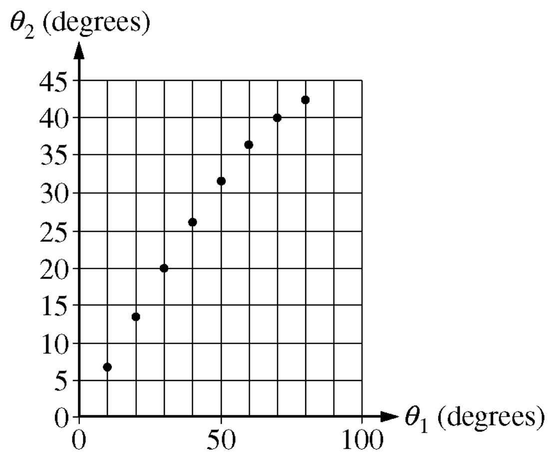
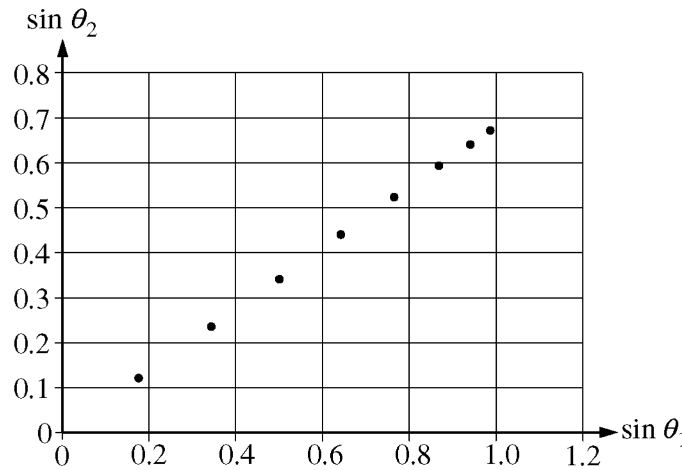


Figure 1

44. A student performs an experiment to determine the index of refraction of a plastic block. The student shines a laser beam from air ($n_{air} = 1$) into a piece of plastic ($n_{plastic}$) at an angle of incidence θ_1 and measures the angle of refraction θ_2 , as shown in Figure 1 above. Measurements are taken as θ_1 is increased. From the data the student produces the two graphs shown below.



Graph 1



Graph 2

Which of the following is equal to the index of refraction of the plastic block?

(A) The slope of the best-fit line for graph 1
(B) The slope of the best-fit line for graph 2
(C) The inverse of the slope of the best-fit line for graph 1
(D) The inverse of the slope of the best-fit line for graph 2

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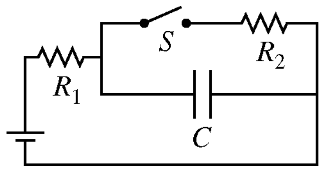
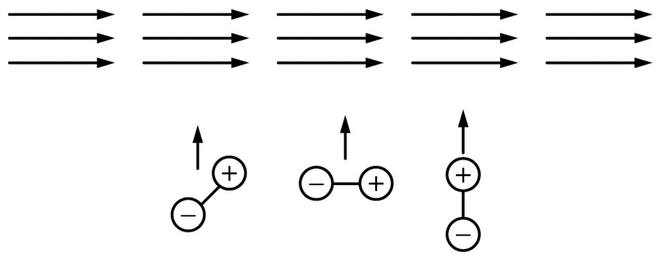


45. In the circuit represented above, two resistors (R_1 and R_2), a capacitor C, and an open switch S are connected to a battery. The circuit reaches equilibrium. The switch is then closed, and the circuit is allowed to come to a new equilibrium. Which of the following is a true statement about the energy stored in the capacitor after the switch is closed compared with the energy stored in the capacitor before the switch is closed?

(A) The energy is greater.
(B) The energy is less.
(C) The energy is the same.
(D) The energy cannot be determined without knowing the resistances of the resistors.

GO ON TO THE NEXT PAGE.

Directions: For each of the questions or incomplete statements below, two of the suggested answers will be correct. For each of these questions, you must select both correct choices to earn credit. No partial credit will be earned if only one correct choice is selected. Select the two that are best in each case and then enter both of the appropriate letters in the corresponding space on the answer sheet.



46. The figure above represents part of a student's experiment in which polar molecules are moving toward the top of the page at high speed. The molecules are modeled as atoms with a positive and a negative charge connected by a molecular bond. The molecules pass through a narrow region of uniform electric field directed to the right. Since the molecules have no net charge, the student expects that the field will have no effect on them and is puzzled to find that the molecules have a higher average energy when they emerge on the other side of the field. Which of the following could explain the student's observation? Select two answers.

    (A) Since some molecules enter the field aligned at an angle to the field—like the molecule on the left—the field exerts a torque on them, which causes them to rotate and gives them rotational kinetic energy.
    (B) Since the molecules are polar, they behave as if they have a net charge. The field exerts a net force on them that does work and gives them linear kinetic energy.
    (C) Since some molecules enter the field aligned parallel to its direction—like the molecule in the middle—the field exerts forces in opposite directions on the two atoms, which stretches the molecular bonds and gives the molecules internal energy.
    (D) Since some molecules enter the field aligned perpendicular to its direction—like the molecule on the right—the field exerts forces in opposite directions on the two atoms. The force on the positive charge is greater, so the net force does work and gives them linear kinetic energy.

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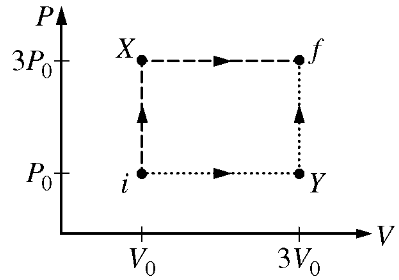
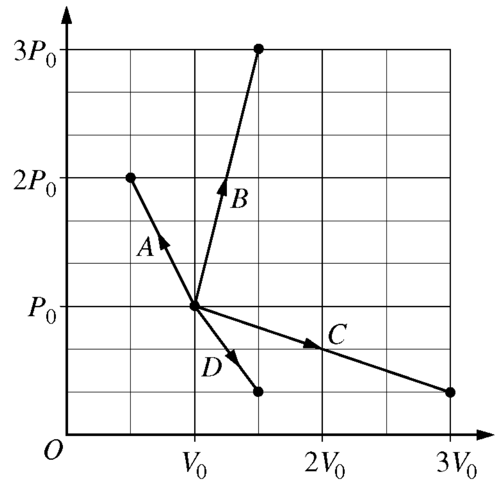


47. A sample of an ideal gas can be taken from state i to state f via two processes, as shown in the above graph of pressure P versus volume V. In one process the gas goes through state X, and in the other process the gas goes through state Y. Which of the following will be the same for both processes? Select two answers.

(A) The change in the internal energy of the gas
(B) The temperature of the gas at the end of the process
(C) The thermal energy transferred to the gas by heating
(D) The work done on the gas



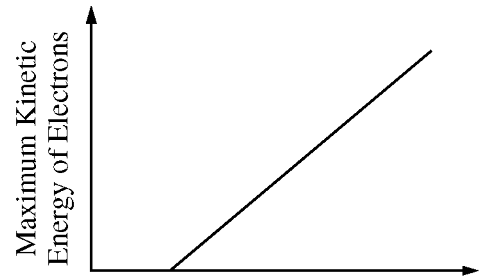
48. Identical samples of gas initially have pressure P_0, volume V_0, and temperature T_0. In some experiments, students take samples through each of the processes shown in the graph above. The final temperature is equal to the initial temperature for which of the processes? Select two answers.

(A) A
(B) B
(C) C
(D) D

GO ON TO THE NEXT PAGE.

49. A beam of electrons is moving at a speed of 6×10^6 m/s. If the beam is incident on each of the following objects, for which of the objects will diffraction be observed? Select two answers.

(A) A human hair (diameter about 10^{-5} m)
(B) A metal crystal (interatomic spacing about 10^{-10} m)
(C) A nanometer-width slit (size about 10^{-9} m)
(D) A narrow paper strip (width about 10^{-3} m)



50. The graph above shows the maximum kinetic energy of electrons released in the photoelectric effect as a function of the frequency of the incident light. This graph is often used as evidence of the particle nature of light. The graph supports which of the following statements? Select two answers.

(A) The number of photoelectrons increases as the frequency increases.
(B) There is a threshold frequency below which no photoemission occurs.
(C) The energy of photoelectrons depends on the energy of the incoming light.
(D) The intensity of the incoming light determines whether photoemission occurs.

GO ON TO THE NEXT PAGE.

S T O P

END OF SECTION I

IF YOU FINISH BEFORE TIME IS CALLED,
YOU MAY CHECK YOUR WORK ON THIS SECTION.

DO NOT GO ON TO SECTION II UNTIL YOU ARE TOLD TO DO SO.

AP® Physics 2 Practice Exam

SECTION II: Free Response

DO NOT OPEN THIS BOOKLET UNTIL YOU ARE TOLD TO DO SO.

At a Glance

Total Time
90 minutes
Number of Questions
4
Percent of Total Score
50%
Writing Instrument
Either pencil or pen with black or dark blue ink
Electronic Device
Calculator allowed
Suggested Time
Approximately 25 minutes each for questions 2 and 3 and 20 minutes each for questions 1 and 4
Weight
Approximate weights:
Questions 2 and 3: 26% each
Questions 1 and 4: 23% each

IMPORTANT Identification Information

PLEASE PRINT WITH PEN:

1. First two letters of your last name ☐☐
   First letter of your first name ☐
2. Date of birth
   ☐☐ ☐☐ ☐☐☐☐
   Month Day Year
3. Six-digit school code
   ☐☐☐☐☐☐
4. Unless I check the box below, I grant the College Board the unlimited right to use, reproduce, and publish my free-response materials, both written and oral, for educational research and instructional purposes. My name and the name of my school will not be used in any way in connection with my free-response materials. I understand that I am free to mark "No" with no effect on my score or its reporting.
   No, I do not grant the College Board these rights. ☐

Instructions

The questions for Section II are printed in this booklet. You may use any blank space in the booklet for scratch work, but you must write your answers in the spaces provided for each answer. A table of information and lists of equations that may be helpful are in the booklet. Calculators, rulers, and straightedges may be used in this section.

All final numerical answers should include appropriate units. Credit for your work depends on demonstrating that you know which physical principles would be appropriate to apply in a particular situation. Therefore, you should show your work for each part in the space provided after that part. If you need more space, be sure to clearly indicate where you continue your work. Credit will be awarded only for work that is clearly designated as the solution to a specific part of a question. Credit also depends on the quality of your solutions and explanations, so you should show your work.

Write clearly and legibly. Cross out any errors you make; erased or crossed-out work will not be scored. You may lose credit for incorrect work that is not crossed out.

Manage your time carefully. You may proceed freely from one question to the next. You may review your responses if you finish before the end of the exam is announced.

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, $N_0 = 6.02 \times 10^{23}$ mol^{-1}	Universal gravitational constant, $G = 6.67 \times 10^{-11}$ m^3/kg•s^2
Universal gas constant, $R = 8.31$ J/(mol•K)	Acceleration due to gravity at Earth's surface, $g = 9.8$ 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,	$h = 6.63 \times 10^{-34} \text{ J•s} = 4.14 \times 10^{-15} \text{ eV•s}$
	$hc = 1.99 \times 10^{-25} \text{ J•m} = 1.24 \times 10^{3} \text{ eV•nm}$
Vacuum permittivity,	$\varepsilon_0 = 8.85 \times 10^{-12} \text{ C}^2/\text{N•m}^2$
Coulomb's law constant,	$k = 1/4\pi\varepsilon_0 = 9.0 \times 10^{9} \text{ N•m}^2/\text{C}^2$
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

θ	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

$v_x = v_{x0} + a_x t$

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

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

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

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

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

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

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

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

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

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

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

$\omega = \omega_0 + \alpha t$

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

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

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

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

$L = I\omega$

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

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

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

a = acceleration
d = distance
E = energy
F = force
f = frequency
h = height
I = rotational inertia
K = kinetic energy
k = spring constant
L = angular momentum
ℓ = 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
α = angular acceleration
μ = coefficient of friction
θ = angle
τ = torque
ω = 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

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

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

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

$\Delta U_E = q\Delta V$

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

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

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

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

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

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

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

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

$P = I\,\Delta V$

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

$R_s = \sum_i R_i$

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

$C_p = \sum_i C_i$

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

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

A = area
B = magnetic field
C = capacitance
d = distance
E = electric field
$\mathcal{E}$ = emf
F = force
I = current
ℓ = length
P = power
Q = charge
q = point charge
R = resistance
r = separation
t = time
U = potential (stored) energy
V = electric potential
v = speed
ρ = resistivity
θ = angle
Φ = 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® PHYSICS 2 EQUATIONS

FLUID MECHANICS AND THERMAL PHYSICS

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

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

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

$$F_b = \rho V g$$

$$A_1 v_1 = A_2 v_2$$

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

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

$$PV = nRT = Nk_B T$$

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

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

$$\Delta U = Q + W$$

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
ρ = 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
λ = wavelength
ϕ = 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
λ = wavelength
θ = angle

GEOMETRY AND TRIGONOMETRY

Rectangle
$A = bh$

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

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

Rectangular solid
$V = \ell wh$

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

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

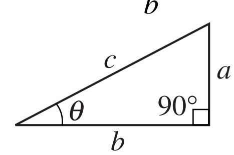
A = area
C = circumference
V = volume
S = surface area
b = base
h = height
ℓ = length
w = width
r = radius

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

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

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

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



PHYSICS 2

Section II

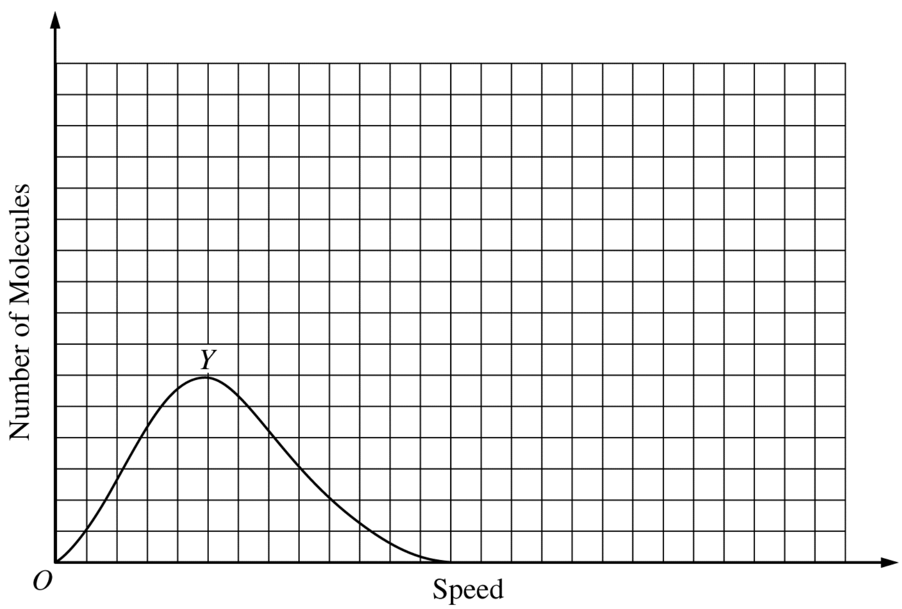
4 Questions

Time—90 minutes

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

1. (10 points, suggested time 20 minutes)
Three samples of a gas, *X*, *Y*, and *Z*, are prepared. Each sample contains the same number of molecules, but the samples are at different temperatures. The temperature of sample *X* is T_X, the temperature of sample *Y* is lower than that of sample *X*, and the temperature of sample *Z* is lower than that of sample *Y* $(T_X > T_Y > T_Z)$.

(a) The graph below shows the distribution of the speeds of the molecules in sample *Y*. On the graph, sketch and label possible distributions for sample *X* and sample *Z*.



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The three samples with initial temperatures $T_X > T_Y > T_Z$ are placed in thermal contact, with sample *Z* in the middle, as shown below, and the samples are insulated from their surroundings. The samples can exchange thermal energy but not gas molecules. The samples eventually reach equilibrium, with a final temperature greater than T_Y .

X	*Z*	*Y*

(b) In a few sentences, describe the change over time in the average kinetic energy of the molecules of each sample, from initial contact until they reach equilibrium. Explain how these changes relate to the energy flow between the pairs of samples that are in contact.

Sample *X*

Sample *Y*

Sample *Z*

(c) Indicate whether the net entropy of sample *X* increases, decreases, or remains the same as a result of the process of reaching equilibrium.

____ Increases ____ Decreases ____ Remains the same

Justify your answer at the microscopic level.

(d) For the three-sample system, indicate whether the entropy of the system increases, decreases, or remains the same.

____ Increases ____ Decreases ____ Remains the same

Justify your answer.

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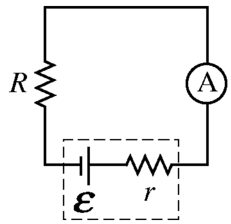

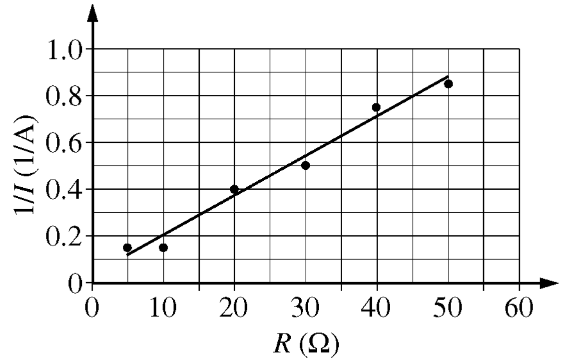

2. (12 points, suggested time 25 minutes)
Students are given some resistors with various resistances, a battery with internal resistance, and an ammeter. They are asked to determine the emf $\mathcal{E}$ and internal resistance r of the battery using just this equipment. Working with the circuit shown above, they insert each resistor into the circuit and measure the current I in the circuit each time they insert a resistor. From their data, the students generate a graph of $1/I$ as a function of the resistance R of each resistor, as shown above.

(a)

i. Write an algebraic equation describing the circuit that includes $\mathcal{E}$, R, r, and I.

ii. Use your equation and the graph to calculate the emf of the battery and the internal resistance of the battery.

GO ON TO THE NEXT PAGE.

The students are now given a voltmeter and a new resistor *X* to use with the resistors, battery, and ammeter they already have. They are asked to determine whether resistor *X* is ohmic.

(b)

i. Using standard symbols for circuit elements, as in the previously shown circuit, draw a diagram of a circuit that the students could use to determine whether resistor *X* is ohmic, including the appropriate placement of the meters. Clearly label your diagram.

ii. Describe the procedure you would use with your circuit to get enough data to determine whether resistor *X* is ohmic.

iii. What would you graph using your data, and what would you look for on your graph to determine whether resistor *X* is ohmic?

(c) Would your procedure or data analysis in part (b) need to be different if the internal resistance of the battery was nonohmic? Justify your answer.

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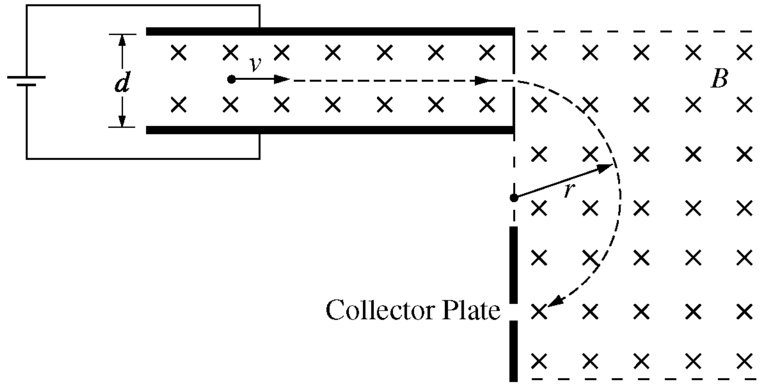

3. (12 points, suggested time 25 minutes)

A particle with unknown mass and charge is projected into the apparatus shown above. The particle moves with constant speed v as it passes undeflected through a pair of parallel plates, as shown above. The plates are separated by a distance d, and a constant potential difference V is maintained between them. A uniform magnetic field of magnitude B directed into the page exists both in the region between the plates and in the region to the right of the plates that is enclosed by the dashed lines. In the region to the right of the plates, the particle's path is circular with radius r. Assume the effects of gravity are negligible compared to other forces.

(a) Explain why the particle moves through the parallel plates undeflected in terms of the forces exerted on the particle.

(b) What is the sign of the charge on the particle? Justify your answer.

GO ON TO THE NEXT PAGE.

A magnetic field of 0.30 T is applied with the plate separation at 5.0×10^{-3} m. Singly ionized particles with various speeds enter the region between the plates, and only those with speed 2.0×10^{6} m/s are undeflected as they pass between the plates. These particles then reach the collector plate a distance of 0.42 m below the point at which they left the region between the parallel plates.

(c) Based on your explanation in part (a), derive an algebraic expression for the potential difference that must be applied to produce the motion of the undeflected particles. Use that expression to calculate the numerical value of the potential difference.

(d) By analyzing the circular part of the motion, derive an algebraic expression for the mass of the particles. Use that expression to calculate a numerical value for the mass.

(e) A scientist wants to use the apparatus to separate singly ionized atoms of ^{12}C and ^{14}C in order to use the ^{14}C in radiocarbon dating. Describe how the motion of the two isotopes of carbon in both regions of the apparatus leads to their separation, appropriately relating your description to the algebraic equations you wrote in parts (c) and (d).

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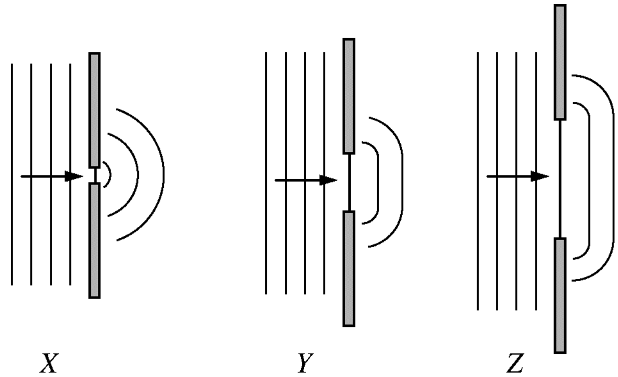

4. (10 points, suggested time 20 minutes)
The figures above labeled *X*, *Y*, and *Z* represent plane waves of the same wavelength incident on barriers that have openings of different sizes. Also shown are the shapes of the wave fronts beyond the barriers.

(a) One model of waves treats every point on a wave front as a point source. Give a clear, coherent, paragraph-length description of how this model can be used to explain the shape of the wave fronts beyond the barriers.

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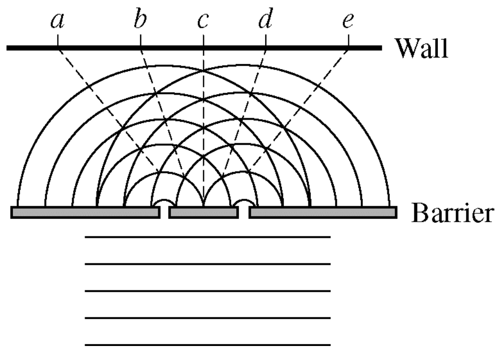
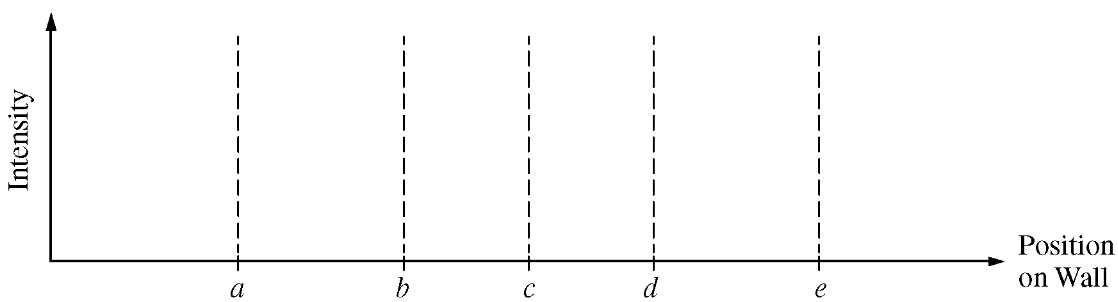


The figure above represents another plane wave incident on a barrier with two identical openings, creating an interference pattern on the wall. Some positions in the pattern on the wall are labeled.

(b) In a few sentences, describe how the point-source model described in part (a) and the figure above can be used to explain the formation of the interference pattern on the wall.

(c) On the axes below, sketch the intensity of the waves that are incident on the wall. The labels correspond to the positions noted in the figure above.



GO ON TO THE NEXT PAGE.

S T O P

END OF EXAM

**IF YOU FINISH BEFORE TIME IS CALLED,
YOU MAY CHECK YOUR WORK ON THIS SECTION.**

Notes on the Practice Exam

Introduction

This section provides a description of how the questions in the AP Physics 2 Practice Exam correspond to the components of the curriculum framework included in the *AP® Physics 1: Algebra-Based and AP® Physics 2: Algebra-Based Course and Exam Description*. For each of the questions in the AP Practice Exam, the essential knowledge, science practices, and targeted learning objectives from the curriculum framework are indicated.

In addition, the multiple-choice and free-response questions include the following features:

- For multiple-choice questions, the correct response is indicated with a justification for why it is correct. There are additional explanations that address why the other responses are incorrect.
- Free-response questions include scoring guidelines as well as descriptions of student responses that would represent "strong, good, and weak" levels. These scoring guidelines demonstrate how the essential knowledge and application of the science practices are assessed in each free-response question.

The AP Physics 2 Exam is approximately 3 hours in length. There are two sections, each accounting for 50 percent of the student's exam score.

Section I is 90 minutes long and consists of 50 multiple-choice questions presented as discrete questions or questions in sets. These multiple-choice questions include two question types: single-select questions and multi-select questions having two correct answers (students need to select both correct answers to earn credit). Section I begins with 45 single-select questions, followed directly by five multi-select questions.

Section II is 90 minutes long and consists of four free-response questions of the following types:

- Experimental design — pertains to designing and describing an investigation, analysis of authentic lab data, and observations to identify patterns or explain phenomena
- Qualitative/quantitative translation — requires translating between quantitative and qualitative justification and reasoning
- Short answer questions — one of which will require a paragraph-length coherent argument

Section	Timing	Scoring	Question Type	Number of Questions
I: Multiple Choice	90 minutes	50% of exam score		
			Single-select (discrete questions and questions in sets with one correct answer)	45
			Multi-select (discrete questions with two correct answers)	5
				Total – 50

Section	Timing	Scoring	Question Type	Number of Questions
II: Free Response	90 minutes	50% of exam score		
			Experimental Design	1
			Qualitative/ Quantitative Translation	1
			Short Answer	2
				Total – 4

All of the questions on the exam are designed to measure the student's understanding of the big ideas, enduring understandings, and essential knowledge, and the student's application of this understanding through the science practices.

Multiple-Choice Section

In Section I, there are 50 multiple-choice questions. These questions represent the knowledge and skills students should know, understand, and be able to apply.

Students will be allowed to use a calculator on the entire AP Physics 2 exam — including both the multiple-choice and free-response sections. Tables containing equations commonly used in physics will be provided for students to use during the entire AP Physics 2 exam.

Information for Multiple-Choice Questions 1–50

Question 1

Essential Knowledge	2.C.5 Between two oppositely charged parallel plates with uniformly distributed electric charge, at points far from the edges of the plates, the electric field is perpendicular to the plates and is constant in both magnitude and direction.
Science Practice	1.1 The student can connect phenomena and models across spatial and temporal scales. 7.1 The student can create representations and models of natural or man-made phenomena and systems in the domain.
Learning Objective	2.C.5.3 The student is able to represent the motion of an electrically charged particle in the uniform field between two oppositely charged plates and express the connection of this motion to projectile motion of an object with mass in the Earth's gravitational field.

(A)	This option is incorrect. The electric field between the plates exerts a *steady* force directed up-the-page. Path A would result from the proton receiving a brief "jolt" toward the negative plate but then traveling freely with no forces exerted upon it.
(B)	**This option is correct. The motion is analogous to a ball thrown sideways. The ball's horizontal velocity stays constant while the ball gains vertical velocity at a constant rate due to uniform gravitational field, leading to a curved trajectory. The same reasoning applies here, with the uniform electric field making the proton "fall" toward the upper plate.**
(C)	This option is incorrect. The proton would follow this path only if no electric force were exerted on it, or if a down-the-page force canceled the up-the-page electric force.
(D)	This option is incorrect. The proton is positively charged and is therefore attracted to the upper plate and repelled from the lower one.

Question 2

Essential Knowledge	2.E.2 Isolines in a region where an electric field exists represent lines of equal electric potential, referred to as equipotential lines.
Science Practice	6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models. 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.
Learning Objective	2.E.2.2 The student is able to predict the structure of isolines of electric potential by constructing them in a given electric field and make connections between these isolines and those found in a gravitational field.

(A)	This option is incorrect. The field vectors are vertical, but not the isolines. By definition, when an object travels along an isoline, the system neither gains nor loses potential energy. But the system loses potential energy when an object "falls" in the direction of the field.
(B)	**This option is correct. By definition, when an object moves along an isoline, the system neither gains nor loses potential energy. Because the field vectors are purely vertical, the isolines must be purely horizontal. That way, an object moving along an isoline neither "rises" nor "falls" with respect to the field; in other words, the system neither gains nor loses potential energy.**
(C)	This option is incorrect. The electric isolines must be perpendicular to the electric field vectors at all points, or else a component of a charged object's motion along an isoline would be parallel to the field, causing a change in potential energy — which contradicts the definition of isoline. To be perpendicular to vertical field vectors, the isolines must be horizontal everywhere, which means they must be straight, not curved.
(D)	This option is incorrect, by the reasoning of (C) applied to the gravitational field. This question is approximating the gravitational field as uniform near the Earth's surface, which means the gravitational field vectors all point in the same direction.

Question 3

Essential Knowledge	6.F.2 Electromagnetic waves can transmit energy through a medium and through a vacuum.
Science Practice	1.1 The student can create representations and models of natural or man-made phenomena and systems in the domain.
Learning Objective	6.F.2.1 The student is able to describe representations and models of electromagnetic waves that explain the transmission of energy when no medium is present.

(A)	**This option is correct. Electromagnetic waves, like waves on a string, are transverse: the direction of the "disturbance" is perpendicular to the direction in which the waves travel, i.e., the direction in which energy is transmitted. Here, the electric and magnetic "disturbances" are *y*-directed and *z*-directed; therefore the waves must be traveling perpendicular to both of those transverse disturbances, along the *x*-axis.**
(B)	This option is incorrect. A transverse wave moves and carries energy perpendicular to the direction of the "disturbance," which here includes the *y*-directed electric disturbance.
(C)	This option is incorrect. A transverse wave moves and carries energy perpendicular to the direction of the "disturbance," which here includes the *z*-directed magnetic disturbance.
(D)	This option is incorrect. A transverse wave transmits energy exactly perpendicular to the direction of the "disturbance," which here means perpendicular to the *y* and *z* axes. Only the *x*-axis satisfies this condition.

Question 4

Essential Knowledge	4.E.3 The charge distribution in a system can be altered by the effects of electric forces produced by a charged object.
Science Practice	1.1 The student can create representations and models of natural or man-made phenomena and systems in the domain. 1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	4.E.3.4 The student is able to construct a representation of the distribution of fixed and mobile charge in insulators and conductors that predicts charge distribution in processes involving induction or conduction.

(A)	**This option is correct. When S2 touches S1, the electric potentials of the spheres equalize, which happens only if S1 "shares" some of its excess positive charge with S2. (More precisely, electrons flow from S2 to S1.) By the same reasoning, S2 "shares" some of its excess charge with S3 when they touch. So, all three spheres end up positive.**
(B)	This option is incorrect. If the spheres were non-conducting, then S1 might "keep" all its excess positive charge. But the spheres are conductors. So, when S1 touches S2, some "free" electrons on S2, attracted by the positive charge of S1, flow onto S1. This leaves S2 with a net positive charge (i.e., an electron deficit). The same thing then happens when S2 touches S3.
(C)	This option is incorrect. It would only occur if all the excess charge gets transferred when each pair of spheres touch. When S1 touches S2, their charges equalize instead of S2 ending up with *all* the excess positive charge. That's because charge flows from one sphere to the other until the spheres have the same electric potential, which for identical spheres means the charges equalize.
(D)	This option is incorrect. When S1 touches S2, their charges equalize instead of S2 ending up with *all* the excess positive charge, as explained in (C).

Question 5

Essential Knowledge	5.B.9 Kirchhoff's loop rule describes conservation of energy in electrical circuits. The application of Kirchhoff's laws to circuits is introduced in Physics 1 and further developed in Physics 2 in the context of more complex circuits, including those with capacitors.
Science Practice	6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	5.B.9.5 The student is able to use conservation of energy principles (Kirchhoff's loop rule) to describe and make predictions regarding electrical potential difference, charge, and current in steady-state circuits composed of various combinations of resistors and capacitors.

(A)	This option is incorrect. The current through a given bulb is $I = \Delta V_{\text{bulb}}/R$ where ΔV_{bulb} is the potential drop across that bulb. Therefore, equal potential drops across the bulbs would indicate equal currents. But bulb 1 has more current through it than the other bulbs do because the current "splits" before heading through bulb 2 or 3.
(B)	This option is incorrect. Because the potential drop between two points is path-independent, the potential drop across bulb 2 must equal the combined potential drop across 3 and 4: $\Delta V_2 = \Delta V_3 + \Delta V_4$. Because these potential drops are nonzero, ΔV_2 must be greater than, not equal to, ΔV_3.
(C)	**This option is correct. Because the current through a bulb is $I = \Delta V_{\text{bulb}}/R$, where ΔV_{bulb} is the potential drop across that bulb, and because the resistances are all equal, it follows that the bulb with the greatest current is the bulb with the greatest ΔV_{bulb}. So, ΔV_1 is greatest, by the reasoning of (A). Similarly, because the same current flows through bulbs 3 and 4 in series, ΔV_3 must equal ΔV_4. Because the potential drop between the two junctions is path-independent, the potential drop across bulb 2 must equal the combined potential drop across 3 and 4: $\Delta V_2 = \Delta V_3 + \Delta V_4$. Therefore, ΔV_2 must be greater than ΔV_3 and ΔV_4.**
(D)	This option is incorrect. It implies that some current gets "used up" in bulb 3; however, all the current through 3 also flows through 4. Because those currents are equal and those bulbs have equal resistance, the potential drops across 3 and 4 are equal.

Question 6

Essential Knowledge	4.E.5 The values of currents and electric potential differences in an electric circuit are determined by the properties and arrangement of the individual circuit elements such as sources of emf, resistors, and capacitors. 5.C.3 Kirchhoff's junction rule describes the conservation of electric charge in electrical circuits. Because charge is conserved, current must be conserved at each junction in the circuit. Examples should include circuits that combine resistors in series and parallel. [Physics 2: includes capacitors in steady-state situations. For circuits with capacitors, situations should be limited to open circuit, just after circuit is closed, and a long time after the circuit is closed.]
Science Practice	6.4 The student can make claims and predictions about natural phenomena based on scientific theories and model.
Learning Objective	4.E.5.1 The student is able to make and justify a quantitative prediction of the effect of a change in values or arrangements of one or two circuit elements on the currents and potential differences in a circuit containing a small number of sources of emf, resistors, capacitors, and switches in series and/or parallel. 5.C.3.4 The student is able to predict or explain current values in series and parallel arrangements of resistors and other branching circuits using Kirchhoff's junction rule and relate the rule to the law of charge conservation.

(A)	This option is incorrect. At the junction, I_a "splits," with some flowing through bulb 2 and the rest flowing through bulb 3. Therefore the current through bulb 2 is less than I_a.
(B)	This option is incorrect. This is the current through bulb 2 before the switch is closed, and also a long time after the switch is closed, when current no longer flows through the capacitor. But *immediately* after the switch is closed, the capacitor acts as short circuit providing a resistance-less path around bulb 4.
(C)	**This option is correct. Immediately after the switch is closed, the capacitor has no charge built up on it and therefore generates no potential difference. It therefore behaves like a resistance-less wire; all current through bulb 3 "sidesteps" bulb 4 and flows through the capacitor instead. At that time, the branch of the circuit containing bulbs 3 and 4 has one bulb's worth of resistance instead of two bulb's worth. The current through bulb 1 therefore splits equally between bulb 2 and bulb 3.**
(D)	This option is incorrect. At all times, the resistance of the branch containing bulbs 3 and 4 is the same or greater than the resistance of the branch containing bulb 2. Therefore the current through bulb 2 is never less than $I_a/2$.

Question 7

Essential Knowledge	5.B.9 Kirchhoff's loop rule describes conservation of energy in electrical circuits. The application of Kirchhoff's laws to circuits is introduced in Physics 1 and further developed in Physics 2 in the context of more complex circuits, including those with capacitors. 5.C.3 Kirchhoff's junction rule describes the conservation of electric charge in electrical circuits. Because charge is conserved, current must be conserved at each junction in the circuit. Examples should include circuits that combine resistors in series and parallel. [Physics 2: includes capacitors in steady-state situations. For circuits with capacitors, situations should be limited to open circuit, just after circuit is closed, and a long time after the circuit is closed.]
Science Practice	6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	5.B.9.5 The student is able to use conservation of energy principles (Kirchhoff's loop rule) to describe and make predictions regarding electrical potential difference, charge, and current in steady-state circuits composed of various combinations of resistors and capacitors. 5.C.3.4 The student is able to predict or explain current values in series and parallel arrangements of resistors and other branching circuits using Kirchhoff's junction rule and relate the rule to the law of charge conservation.

(A)	This option is incorrect. Once the capacitor reaches its "final" charge, current no longer flows through it, and therefore all the current through bulb 3 also flows through bulb 4. Therefore, significant current flows through bulb 4.
(B)	This option is incorrect. While the capacitor is charging, current flows through the capacitor's segment of the circuit, "diverting" current away from bulb 4 and therefore dimming bulb 4. Once the capacitor is "fully" charged, no current is diverted and hence bulb 4 is just as bright as before.
(C)	**This option is correct. Once the capacitor reaches its "final" charge, current no longer flows through it — as was the case *before* the switch was closed. As a result, all the bulbs are exactly as bright as they were before the switch was closed.**
(D)	This option is incorrect. Soon after the switch is closed, the short circuit around bulb 4 reduces the overall resistance of the circuit, and some of the bulbs get brighter (though not bulb 4, as explained in B above). A long time after the switch is closed, the capacitor is "fully" charged and hence a dead end to current; the circuit's overall resistance has returned to its value before the switch was closed.

Question 8

Essential Knowledge	6.E.3 When light travels across a boundary from one transparent material to another, the speed of propagation changes. At a non-normal incident angle, the path of the light ray bends closer to the perpendicular in the optically slower substance. This is called refraction.
Science Practice	6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	6.E.3.3 The student is able to make claims and predictions about path changes for light traveling across a boundary from one transparent material to another at non-normal angles resulting from changes in the speed of propagation.

(A)	**This option is correct. By Snell's law, a higher index of refraction results in a smaller angle of transmission; the ray in the middle layer is closer to horizontal. The ray hits the middle-layer/air boundary above the point shown in the figure. For that reason, and also because the angle of transmission into the air is less than before (because the angle of incidence is less), the ray exits the air layer above point Y.**
(B)	This option is incorrect. If the glass were replaced by a substance whose n were *less* than that of glass, the ray in the middle layer would be angled more sharply downward and would exit the air below Y. But as explained in (A), *increasing* the n of the middle layer has the opposite effect.
(C)	This option is incorrect. Changing the index of refraction of the middle layer changes the path of the ray.
(D)	This option is incorrect. Knowing the exact n would enable us to find exactly how far above Y the ray now exits the air. But the reasoning of (A) above holds for any n greater than n_{glass}.

Question 9

Essential Knowledge	6.E.4 The reflection of light from surfaces can be used to form images.
Science Practice	1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 2.2. The student can apply mathematical routines to quantities that describe natural phenomena.
Learning Objective	6.E.4.2 The student is able to use quantitative and qualitative representations and models to analyze situations and solve problems about image formation occurring due to the reflection of light from surfaces.

(A)	**This option is correct. By tracing rays and "backtracking" them to locate the virtual image behind the mirror, the student can confirm that the image is magnified and upright (unflipped).**
(B)	This option is incorrect. This situation produces a blur because rays from the object reflect off the mirror parallel to one another, never converging or diverging to form an image.
(C)	This option is incorrect. By tracing rays, you can confirm that the image is magnified and inverted (flipped).
(D)	This option is incorrect. By tracing rays, you can confirm that the image is reduced in size and inverted (flipped).

Question 10

Essential Knowledge	5.B.10 Bernoulli's equation describes the conservation of energy in fluid flow.
Science Practice	2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
Learning Objective	5.B.10.3 The student is able to use Bernoulli's equation and the continuity equation to make calculations related to a moving fluid.
(A)	This option is incorrect. It could stem from taking into account the potential energy terms (ρgh) but not the kinetic energy terms, $(1/2)\rho v^2$.
(B)	**This option is correct. From the continuity equation $(A_1 v_1 = A_2 v_2)$, because the diameter of the pipe triples between A and B, its cross-sectional area increases by a factor of 9, and hence the water's speed at B is one ninth its speed at A, namely 1.0 m/s. From Bernoulli's equation, setting $y = 0$ in the lower pipe, we then get $2.0 \times 10^5 \text{ Pa} + 0 + (1/2)(1.0 \times 10^3 \text{ kg/m}^3)(9.0 \text{ m/s})^2 =$ $P_B + (1.0 \times 10^3 \text{ kg/m}^3)(10 \text{ m/s}^2)(8.0 \text{ m}) + (1/2)(1.0 \times 10^3 \text{ kg/m}^3)(1.0 \text{ m/s})^2$. In solving for P_2, it saves time to neglect the last term on the right-hand side, which is smaller than the other terms, and divide everything through by the density of water, $(1.0 \times 10^3 \text{ kg/m}^3)$.**
(C)	This option is incorrect. It could stem from substituting the given pressure into the side of the equation describing point B and solving for the pressure at point A.
(D)	This option is incorrect. It could stem from the Bernoulli equation, having the water speeds reversed (1.0 m/s at A, and 9.0 m/s at B), while also substituting the given pressure into the side of the equation describing point B and solving for the pressure at point A.

Question 11

Essential Knowledge	5.F.1 The continuity equation describes conservation of mass flow rate in fluids. Examples should include volume rate of flow, mass flow rate.
Science Practice	2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
Learning Objective	5.F.1.1 The student is able to make calculations of quantities related to flow of a fluid, using mass conservation principles (the continuity equation).
(A)	This option is incorrect. By confusing diameter with area, one would therefore think that the total exit diameter is half that of the entry diameter, which would require an exit velocity twice that of the entry velocity.
(B)	This option is incorrect. Confusing diameter with area, and comparing the entry diameter to only one of the exit diameters gives a 4 to 1 ratio of entry to exit diameter which requires 4 times the entry velocity.
(C)	**This option is correct. The area through which fluid enters is 8 times the area through which fluid leaves. The volume entering each second must equal the volume leaving each second so the fluid must leave at eight times the rate it enters.**
(D)	This option is incorrect. By comparing entry area with only one of the exit areas one would obtain a 16 to 1 ratio of areas, requiring 16 times the entry velocity.

Question 12

Essential Knowledge	5.B.6 Energy can be transferred by thermal processes involving differences in temperature; the amount of energy transferred in this process of transfer is called heat.
Science Practice	1.2 The student can describe representations and models of natural or man-made phenomena and systems in the domain.
Learning Objective	5.B.6.1 The student is able to describe the models that represent processes by which energy can be transferred between a system and its environment because of differences in temperature: conduction, convection, and radiation.

(A)	This option is incorrect. The slabs are in thermal equilibrium with the room, so both are at room temperature.
(B)	**This option is correct. The slabs are in thermal equilibrium with the room and at the same temperature, but perception of temperature depends on the rate of thermal energy transfer. Metal has higher thermal conductivity than wood, so it feels colder when touched by the warmer hand of the student.**
(C)	This option is incorrect. If room temperature were hotter than body temperature, the metal slab would feel warmer due to a higher rate of thermal energy transfer.
(D)	This option is incorrect. Although the slabs are at the same temperature, the perception of temperature depends on the rate of heat transfer to the materials and the metal slab has higher thermal conductivity.

Question 13

Essential Knowledge	7.B.1 The approach to thermal equilibrium is a probability process.
Science Practice	6.2 The student can construct explanations of phenomena based on evidence produced through scientific practices.
Learning Objective	7.B.1.1 The student is able to construct an explanation, based on atomic-scale interactions and probability, of how a system approaches thermal equilibrium when energy is transferred to it or from it in a thermal process.

(A)	This option is incorrect. Thermal convection in a fluid can be confused with thermal conduction in the solid spoon.
(B)	This option is incorrect. Thermal radiation will transfer some thermal energy, but in the solid spoon this process would not be the primary process for thermal energy transfer.
(C)	**This option is correct. At the molecular scale, higher temperature means higher kinetic energy and momentum of molecules. Collisions between higher momentum and lower momentum molecules will tend to transfer momentum and kinetic energy from higher momentum molecules to the lower momentum ones. This results in energy transfer from the hotter regions to the cooler regions of the spoon until the material reaches thermal equilibrium.**
(D)	This option is incorrect. Historically a fluid flow analogy for thermal energy transfer reflected the idea that ‘heat’ was a substance that could flow from place to place.

Question 14

Essential Knowledge	3.A.4 If one object exerts a force on a second object, the second object always exerts a force of equal magnitude on the first object in the opposite direction.
Science Practice	6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models. 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big idea.
Learning Objective	3.A.4.2 The student is able to use Newton's third law to make claims and predictions about the action-reaction pairs of forces when two objects interact.

(A)	**This option is correct. The force exerted on the moving charged object by the magnet and the force exerted on the magnet by the moving charged object are an interaction described by Newton's third law and have equal magnitudes and opposite directions.**
(B)	This option is incorrect. The forces exerted in the interaction must be in opposite directions. Thinking about a magnet as attracting an object such as a small piece of steel, one would reason that the third law force would therefore attract the magnet to the right.
(C)	This option is incorrect. The forces exerted in the interaction must be in opposite directions.
(D)	This option is incorrect. All forces are interactions described by Newton's third law, therefore if there is a force exerted on the moving charged object by the magnet there must be a force exerted on the magnet by the moving charged object.

Question 15

Essential Knowledge	4.E.4 The resistance of a resistor, and the capacitance of a capacitor, can be understood from the basic properties of electric fields and forces, as well as the properties of materials and their geometry.
Science Practice	5.1 The student can analyze data to identify patterns or relationships.
Learning Objective	4.E.4.3 The student is able to analyze data to determine the effect of changing the geometry and/or materials on the resistance or capacitance of a circuit element and relate results to the basic properties of resistors and capacitors.

(A)	This option is incorrect. To determine if a wire is ohmic would require a data set of current measurements for different potential differences for a single wire.
(B)	**This option is correct. The resistance of a wire is determined by the length, cross-sectional area and resistivity of the material. Because the lengths and diameters are the same, and the same battery is used with each wire, the materials must be different in order for there to be different resistances resulting in different currents.**
(C)	This option is incorrect. The resistance of the wires does depend on the size and shape, but also on the material. Because the size and shape of all the wires are the same, this would not account for the different resistance.
(D)	This option is incorrect. If the wires have different resistances, any internal resistance of the battery would mean different terminal voltages, but without measuring the voltage across the wires, no conclusion can be made about the internal resistance of the battery.

Question 16

Essential Knowledge	1.B.2 There are only two kinds of electric charge. Neutral objects or systems contain equal quantities of positive and negative charge, with the exception of some fundamental particles that have no electric charge. 4.E.3 The charge distribution in a system can be altered by the effects of electric forces produced by a charged object.
Science Practice	6.4 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas. 1.1 The student can create representations and models of natural or man-made phenomena and systems in the domain.
Learning Objective	1.B.2.2 The student is able to make a qualitative prediction about the distribution of positive and negative electric charges within neutral systems as they undergo various processes. 4.E.3.4 The student is able to construct a representation of the distribution of fixed and mobile charge in insulators and conductors that predicts charge distribution in processes involving induction or conduction.

(A)	This option is incorrect. Because X and Z repel, they must have net charges of the same sign. If Y had a net charge of the same sign as Z it would also be repelled by Z.
(B)	This option is incorrect. Because X and Z repel, they must have net charges of the same sign.
(C)	This option is incorrect. X and Z have the same charge due to transfer of electrons between the rods and the fur, not motion of charges along the rods. No charging process occurred with end Y to give it a net charge.
(D)	**This option is correct. Because ends X and Z are the same materials and were rubbed with the same fur, they will have the same sign of charge and will repel each other. End Y was not rubbed, will have no net charge and is attracted to end Z by the polarization induced by the presence of end Z.**

Question 17

Essential Knowledge	4.E.3 The charge distribution in a system can be altered by the effects of electric forces produced by a charged object.
Science Practice	1.1 The student can create representations and models of natural or man-made phenomena and systems in the domain. 4.2 The student can design a plan for collecting data to answer a particular scientific question.
Learning Objective	4.E.3.4 The student is able to construct a representation of the distribution of fixed and mobile charge in insulators and conductors that predicts charge distribution in processes involving induction or conduction. 4.E.3.5 The student is able to explain and/or analyze the results of experiments in which electric charge rearrangement occurs by electrostatic induction, or is able to refine a scientific question relating to such an experiment by identifying anomalies in a data set or procedure.

(A)	This option is incorrect. The positive rod attracts electrons to the right side of A leaving the left side positively charged. Touching B to A allows electrons from B to move to the left side of A until the left side of A is neutral. When B is removed it will have lost electrons to A, which will therefore have a net negative charge.
(B)	This option is incorrect. Removing the rod before breaking the connection between B and A allows electrons that moved from B to A to return to B, therefore both B and A will have no net charge.
(C)	**This option is correct. The positive rod attracts electrons to the right side of B leaving the left side positively charged. Touching A to B allows electrons from A to move to the left side of B. When B is removed from A, A is left with a net positive charge, which is the desired outcome.**
(D)	This option is incorrect. As in choice (B), removing the rod before separating the spheres results in both spheres ending with no net charge.

Question 18

Essential Knowledge	3.C.3 A magnetic force results from the interaction of a moving charged object or a magnet with other moving charged objects or another magnet.
Science Practice	1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
Learning Objective	3.C.3.1 The student is able to use right-hand rules to analyze a situation involving a current-carrying conductor and a moving electrically charged object to determine the direction of the magnetic force exerted on the charged object due to the magnetic field created by the current-carrying conductor.

(A)	This option is incorrect. The magnetic field due to the electric current is directed into the page at the location of the charged object. The force exerted by the field on the charged object must be perpendicular to the magnetic field vector, not parallel to it.
(B)	This option is incorrect. The magnetic field due to the electric current is directed into the page at the location of the charged object. The force exerted by the field on the charged object must be perpendicular to the magnetic field vector, not anti-parallel to it.
(C)	**This option is correct. The magnetic field due to the electric current is directed into the page at the location of the charged object. The force exerted on the moving charge by the field is perpendicular to both the field vector and the velocity vector and for a positive charge is directed to the right.**
(D)	This option is incorrect. A mistake in determining the direction of the magnetic field or applying the right-hand rule for the field's effect on the point charge could give this option.

Question 19

Essential Knowledge	3.C.2 Electric force results from the interaction of one object that has an electric charge with another object that has an electric charge.
Science Practice	2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
Learning Objective	3.C.2.3 The student is able to use mathematics to describe the electric force that results from the interaction of several separated point charges (generally 2 to 4 point charges, though more are permitted in situations of high symmetry).

(A)	**This option is correct. Assuming force to the right is positive, the net force on A is $-4kQ^2/9 + 2kQ^2/1$. The net force on B is $8kQ^2/4 - 2kQ^2/1$ and the net force on C is $-8kQ^2/4 + 4kQ^2/9$. The question asks for magnitude of net force, so $F_A = F_C = \left\|2kQ^2/1 - 4kQ^2/9\right\|$ and $F_B = 0$.**
(B)	This option is incorrect. The two outside point charges exert forces in opposite directions and of equal magnitude on the point charge B, therefore the net force on B is zero and it cannot be the greatest in magnitude.
(C)	This option is incorrect. This answer choice has the magnitude of force on B greater than the force on C, which cannot be true. The two outside point charges exert forces in opposite directions and of equal magnitude on the point charge; therefore the net force on B is zero.
(D)	This option is incorrect. If the force to the right is considered to be positive, then the net force on A is $-4kQ^2/9 + 2kQ^2/1$. The net force on B is $8kQ^2/4 - 2kQ^2/1$ and the net force on C is $-8kQ^2/4 + 4kQ^2/9$. Because the net force on A is equal to the net force on C, this answer choice cannot be true.

Question 20

Essential Knowledge	3.B.2 Free-body diagrams are useful tools for visualizing forces being exerted on a single object and writing the equations that represent a physical situation.
Science Practice	1.1 The student can create representations and models of natural or man-made phenomena and systems in the domain. 1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
Learning Objective	3.B.2.1 The student is able to create and use free-body diagrams to analyze physical situations to solve problems with motion qualitatively and quantitatively.

(A)	This option is incorrect. Because the tension and weight are both downward, the weight cannot be greater than the buoyant force, as this would leave the tension with a negative value.
(B)	This option is incorrect. The block is in static equilibrium, so the net force on the block is zero. Because there are three vertical forces on the block—the buoyant force, the weight, and the tension, no two of those forces in opposite directions could be equal to each other.
(C)	**This option is correct. Because the block is in static equilibrium, the net force on the block is zero. Net force is the vector sum of buoyant force upward and both tension and weight downward. Therefore, the buoyant force has to be greater than either of the individual downward forces.**
(D)	This option is incorrect. Changing the density of the liquid does change the buoyant force, but a buoyant force is still exerted on the block. Because the block is in static equilibrium, the net force on the block is zero. Net force is the vector sum of buoyant force upward and both tension and weight downward. Therefore, the buoyant force has to be greater than either of the individual downward forces.

Question 21

Essential Knowledge		5.B.9 Kirchhoff's loop rule describes conservation of energy in electrical circuits. The application of Kirchhoff's laws to circuits is introduced in Physics 1 and further developed in Physics 2 in the context of more complex circuits, including those with capacitors.
Science Practice		1.5 The student can re-express key elements of natural phenomena across multiple representations in the domain.
Learning Objective		5.B.9.8 The student is able to translate between graphical and symbolic representations of experimental data describing relationships among power, current, and potential difference across a resistor.
(A)	This option is incorrect. The slope of the graph should be equal to the potential difference because $P = VI$, but this value, 0.3 V, is not a correct calculation of the slope.	
(B)	This option is incorrect. This choice is the area under the graph line at the point (1,6), but the area of a power vs. current graph does not give you the potential difference. It could also be an incorrect calculation of the slope between two data points that are not on the line.	
(C)	This option is incorrect. This choice represents an incorrect calculation of slope, using two data points that are not on the best fit line.	
(D)	**This option is correct. Electrical power is equal to the product of potential difference and current** $(P = VI)$**. A graph of power as a function of current has potential difference as its slope. Using any two points on the best-fit line (such as 1,6 and 0,0), the slope is** $6.0\ \text{W/A}$ **or 6.0 V.**	

Question 22

Essential Knowledge		3.C.3 A magnetic force results from the interaction of a moving charged object or a magnet with other moving charged objects or another magnet.
Science Practice		5.1 The student can analyze data to identify patterns or relationships.
Learning Objective		3.C.3.2 The student is able to plan a data collection strategy appropriate to an investigation of the direction of the force on a moving electrically charged object caused by a current in a wire in the context of a specific set of equipment and instruments and analyze the resulting data to arrive at a conclusion.
(A)	This option is incorrect. An electron is negative and an alpha is positive, so they would curve in opposite directions in the magnetic field (according to the right hand rule) — not in the same direction as shown in the diagram.	
(B)	This option is incorrect. An electron is negative and an alpha is positive, so they would curve in opposite directions in a magnetic field — not the same direction.	
(C)	**This option is correct. Using a right hand rule to determine force exerted on a charged particle moving in a magnetic field, the force is in the same direction on both particles only if they have the same type of charge. Setting the expression for centripetal force equal to magnetic force, the radius of curvature is equal to mv/qB. Both the alpha and positron are positive, but the alpha has twice the charge and four times the mass, so the alpha takes path 2 with a larger radius.**	
(D)	This option is incorrect. Both the alpha and positron are positive, but the alpha has twice the charge and four times the mass. This answer choice incorrectly has the particle with smaller mass-to-charge ratio taking the path of larger radius.	

Question 23

Essential Knowledge	1.A.4 Atoms have internal structures that determine their properties. 7.C.4 Photon emission and absorption processes are described by probability.
Science Practice	1.1 The student can create representations and models of natural or man-made phenomena and systems in the domain. 1.2 The student can describe representations and models of natural or man-made phenomena and systems in the domain.
Learning Objective	1.A.4.1 The student is able to construct representations of the energy level structure of an electron in an atom and to relate this to the properties and scales of the systems being investigated. 7.C.4.1 The student is able to construct or interpret representations of transitions between atomic energy states involving the emission and absorption of photons. [For questions addressing stimulated emission, students will not be expected to recall the details of the process, such as the fact that the emitted photons have the same frequency and phase as the incident photon; but given a representation of the process, students are expected to make inferences such as figuring out from energy conservation that because the atom loses energy in the process, the emitted photons taken together must carry more energy than the incident photon.]

(A)	This option is incorrect. The n = 5 to n = 4 transition selected here does not have the smallest spacing and therefore does not have the smallest energy and longest wavelength.
(B)	**This option is correct. The longest wavelength light has the lowest frequency** $(c = f\lambda)$ **and thus the lowest energy** $(E = hf)$**. On this diagram, lower energy transitions are shown with smaller spacing between lines. The n = 4 to n = 3 transition has the smallest spacing and thus smallest energy and longest wavelength.**
(C)	This option is incorrect. The n = 3 to n = 2 transition does not have the smallest spacing and thus does not have the smallest energy and longest wavelength.
(D)	This option is incorrect. The n = 2 to n = 1 transition selected here has the largest spacing and thus would have the largest energy and shortest wavelength — not the longest wavelength.

Question 24

Essential Knowledge	5.C.1 Electric charge is conserved in nuclear and elementary particle reactions, even when elementary particles are produced or destroyed. Examples should include equations representing nuclear decay.
Science Practice	6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	5.C.1.1 The student is able to analyze electric charge conservation for nuclear and elementary particle reactions and make predictions related to such reactions based upon conservation of charge.

(A)	This option is incorrect. The eight heliums (He) produced account for 16 positive charges, so the emission of 10 negative charges $\left(\beta^-\right)$ leaves an imbalance of 4 negative. This answer choice does not conserve charge.
(B)	This option is incorrect. The eight heliums (He) produced account for 16 positive charges, so the emission of 8 negative charges $\left(\beta^-\right)$ leaves an imbalance of 2 negative and charge is not conserved.
(C)	**This option is correct. Because beta particles do not have mass number, conservation of charge is used to balance the reaction. The change in atomic number from the element uranium (U) to lead** (Pb) **is a reduction of 10 positive charges. The eight heliums** (He) **account for production of 16 positive charges, so there needs to be 6 negative charges** $\left(\beta^-\right)$ **emitted also for a net change of zero.**
(D)	This option is incorrect. The eight heliums (He) produced account for 16 positive charges, so the emission of only 5 negative charges $\left(\beta^-\right)$ leaves an imbalance of 1 positive and charge is not conserved.

Question 25

Essential Knowledge		7.C.1 The probabilistic description of matter is modeled by a wave function, which can be assigned to an object and used to describe its motion and interactions. The absolute value of the wave function is related to the probability of finding a particle in some spatial region. (Qualitative treatment only, using graphical analysis.)
Science Practice		1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
Learning Objective		7.C.1.1 The student is able to use a graphical wave function representation of a particle to predict qualitatively the probability of finding a particle in a specific spatial region.
(A)	This option is incorrect. The amplitude at $x = 0.7$ m is about 1, so $\Psi^2 = 1$, which is not the greatest value among the answer choices.	
(B)	**This option is correct. The greatest probability of locating the wave is at a position along the x-axis where the magnitude of the amplitude is the greatest, or where Ψ^2 has the greatest value. This occurs at $x = 2.0$ m, where the magnitude of Ψ is 3 and Ψ^2 is 9.**	
(C)	This option is incorrect. The amplitude at $x = 2.5$ m is about 1.5, so Ψ^2 does not have the greatest value among the answer choices.	
(D)	This option is incorrect. The amplitude at $x = 4.0$ m is zero, so this answer choice represents the smallest probability among the answer choices given — not the largest.	

Question 26

Essential Knowledge		4.C.4 Mass can be converted into energy and energy can be converted into mass.
Science Practice		2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
Learning Objective		4.C.4.1 The student is able to apply mathematical routines to describe the relationship between mass and energy and apply this concept across domains of scale.
(A)	This option is incorrect. The signs on m_{Ba}, m_{Kr}, and m_U terms are incorrect and the one neutron on the left has incorrectly been omitted.	
(B)	This option is incorrect. The Δm is the difference in mass number between one side of the equation and the other. The signs on m_{Ba}, m_{Kr}, and m_U terms are incorrect.	
(C)	This option is incorrect. The one neutron on the left has not been accounted for in the expression, so Δm is not correctly determined.	
(D)	**This option is correct. These expressions use mass-energy conservation $\left(\Delta E = \Delta mc^2\right)$ to calculate energy. The Δm is the difference in mass between the reactants and the products. The $2m_n$ in the expression is the correct net change between one neutron on the left and three on the right.**	

Question 27

Essential Knowledge	6.E.5 The refraction of light as it travels from one transparent medium to another can be used to form images.
Science Practice	5.1 The student can analyze data to identify patterns or relationships.
Learning Objective	6.E.5.2 The student is able to plan data collection strategies, perform data analysis and evaluation of evidence, and refine scientific questions about the formation of images due to refraction for thin lenses.

(A)	**This option is correct. Start with the thin lens equation, $1/f = 1/s_o + 1/s_i$ and rearrange the terms to show reciprocal of image distance as a function of reciprocal of object distance, as in the graph: $1/s_i = -1/s_o + 1/f$. In this $y = mx + b$ form, it's clear that the slope is -1 and the y-intercept is equal to the reciprocal of the focal length. The y-intercept is 2.0, so the focal length is 0.5 m.**
(B)	This option is incorrect. The value 1.0 is the magnitude of the slope, which would be $-s_o/s_i$ and is not a correct calculation of focal length.
(C)	This option is incorrect. The y-intercept is 2.0. This answer choice does not take the reciprocal of the intercept to correctly determine the focal length.
(D)	This option is incorrect. The y-intercept is 2.0, so the focal length is 0.5 m. This answer choice may represent the product of the *x* and *y* intercepts, which is not a correct calculation.

Question 28

Essential Knowledge	6.E.5 The refraction of light as it travels from one transparent medium to another can be used to form images.
Science Practice	1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
Learning Objective	6.E.5.1 The student is able to use quantitative and qualitative representations and models to analyze situations and solve problems about image formation occurring due to the refraction of light through thin lenses.

(A)	**This option is correct. Magnification is the absolute value of the ratio of image height to object height, which is the same ratio as image distance to object distance (s_i/s_o). When $s_i = 2\text{ m}$, $1/s_i$ is 0.5, which corresponds to $(1/s_o)$ equal to 1.5. Then s_o equals $2/3$ and the magnification is $1/3$.**
(B)	This option is incorrect. This is a calculation of the magnitude of the slope of the line, but the slope of this graph does not give you the magnification.
(C)	This option is incorrect. Magnification is the absolute value of the ratio of image height to object height, but this answer choice incorrectly calculates the ratio of object height to image height.
(D)	This option is incorrect. It could be chosen if one looked at the value of the image distance (2 m) instead of its reciprocal.

Question 29

Essential Knowledge	7.A.1 The pressure of a system determines the force that the system exerts on the walls of its container and is a measure of the average change in the momentum, the impulse of the molecules colliding with the walls of the container. The pressure also exists inside the system itself, not just at the walls of the container.
Science Practice	2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
Learning Objective	7.A.1.2 Treating a gas molecule as an object (i.e., ignoring its internal structure), the student is able to analyze qualitatively the collisions with a container wall and determine the cause of pressure, and at thermal equilibrium, to quantitatively calculate the pressure, force, or area for a thermodynamic problem given two of the variables.

(A)	This option is incorrect. This choice omits the force that accounts for the weight of the lid.
(B)	**This option is correct. The minimum upward force is equal to the net downward force on the lid, which is the sum of the weight of the lid and the net downward force due to air. The pressure outside is greater than pressure inside, so net pressure times the area of the lid is net force due to air.** $\sum F_{up} = \sum F_{down} = \left(1.01\times10^5 - 0.40\times10^5\right)\left(\pi r^2\right) + 200\text{N} = 7.7\times10^3\,\text{N}$
(C)	This option is incorrect. The calculation for this option incorrectly used only the outside pressure and has omitted the pressure of the gas inside, using only 1.01×10^5 times the area.
(D)	This option is incorrect. This option incorrectly added the pressures inside and outside the container instead of subtracting them.

Question 30

Essential Knowledge	7.A.2 The temperature of a system characterizes the average kinetic energy of its molecules.
Science Practice	7.1 The student can connect phenomena and models across spatial and temporal scales.
Learning Objective	7.A.2.1 The student is able to qualitatively connect the average of all kinetic energies of molecules in a system to the temperature of the system.
(A)	This option is incorrect. Constant temperature indicates a constant average kinetic energy, but speeds of individual molecules will vary. This answer choice has incorrectly assumed that molecular speeds must stay constant if temperature is constant.
(B)	**This option is correct. If the room temperature is constant and the container and air are in equilibrium, the average translational kinetic energy of molecules remains constant. However, speeds of individual molecules will vary due to collisions between them.**
(C)	This option is incorrect. The statement comes from an assumption that the molecules will lose kinetic energy as the container sits, but for that to be true the temperature would have to decrease. If the room is kept at constant temperature, the container should remain in equilibrium and at constant temperature.
(D)	This option is incorrect. This answer choice is impossible in a situation where temperature remains constant and the room and container are in equilibrium. The average kinetic energy would increase only if temperature increased.

Question 31

Essential Knowledge	3.C.3 A magnetic force results from the interaction of a moving charged object or a magnet with other moving charged objects or another magnet.
Science Practice	4.2 The student can analyze data to identify patterns or relationships. 5.1 The student can design a plan for collecting data to answer a particular scientific question.
Learning Objective	3.C.3.2 The student is able to plan a data collection strategy appropriate to an investigation of the direction of the force on a moving electrically charged object caused by a current in a wire in the context of a specific set of equipment and instruments and analyze the resulting data to arrive at a conclusion.
(A)	This option is incorrect. Using a right hand rule and $F_B = qv_\perp B$, holding the object motionless would not produce any magnetic force, because v = 0.
(B)	This option is incorrect. Using a right hand rule, the magnetic field lines are circles centered on the wire. Moving the object in a circle in the x-z plane means it is moving along a field line, so the velocity is always parallel to the field. Using $F_B = qv_\perp B$, there is no magnetic force.
(C)	This option is incorrect. Moving the object in the -x direction will produce a magnetic force on the object in the –y direction, changing the tension in the string, which the students will not be able to observe directly.
(D)	**This option is correct. With the direction of current given, using a right hand rule, the magnetic field near the small object is directed into the page (in the –z direction). Using a right hand rule and $F_B = qv_\perp B$, moving the object in the +y direction will produce a magnetic force on the object in the –x direction, which the students should be able to observe.**

Question 32

Essential Knowledge	2.C.1 The magnitude of the electric force F exerted on an object with electric charge q by an electric field E is $F = qE$. The direction of the force is determined by the direction of the field and the sign of the charge, with positively charged objects accelerating in the direction of the field and negatively charged objects accelerating in the direction opposite the field. This should include a vector field map for positive point charges, negative point charges, spherically symmetric charge distributions, and uniformly charged parallel plates.
Science Practice	6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	2.C.1.1 The student is able to predict the direction and the magnitude of the force exerted on an object with an electric charge q placed in an electric field E using the mathematical model of the relation between an electric force and an electric field: $F = qE$; a vector relation.

(A)	This option is incorrect. Its direction is too far toward the left to be aligned with the electric field vectors, which are directed more to the upper left on the diagram.
(B)	**This option is correct. The electric force on a positive charge is in the same direction as the electric field $\left(\bar{F} = q\bar{E}\right)$. At point P, the field vectors are directed toward the top of the page and to the left, but not too extremely in either of those directions, so the force is in the same direction.**
(C)	This option is incorrect. The direction of electric force indicated by the answer choice would be correct only if the point P were moved to the right in the diagram. The force vector shown is not aligned with the electric field at point P.
(D)	This option is incorrect. The electric force vector shown is not aligned with the electric field at point P. This force vector would only be correct if the point P were moved to the right and slightly below the point charge.

Question 33

Essential Knowledge	2.C.2 The magnitude of the electric field vector is proportional to the net electric charge of the object(s) creating that field. This includes positive point charges, negative point charges, spherically symmetric charge distributions, and uniformly charged parallel plates.
Science Practice	2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
Learning Objective	2.C.2.1 The student is able to qualitatively and semi-quantitatively apply the vector relationship between the electric field and the net electric charge creating that field.

(A)	This option is incorrect. Particles 2 and 4 have a magnitude intermediate between that of 1 and 3. See the explanation for correct option D.
(B)	This option is incorrect. The clear area representing electric field vectors of largest magnitude is largest for particle 1 and smallest for particle 3, so this answer choice has the correct answer reversed.
(C)	This option is incorrect. Particles 2 and 4 have a magnitude intermediate between that of 1 and 3. See the explanation for correct option D.
(D)	**This option is correct. Vectors with largest magnitude are not shown, so the blank areas represent regions with larger magnitude of electric field. Since the field is proportional to q/r^2, a larger blank area corresponds to a larger charge. The area is largest for particle 1 and smallest for particle 3.**

Question 34

Essential Knowledge	2.C.5 Between two oppositely charged parallel plates with uniformly distributed electric charge, at points far from the edges of the plates, the electric field is perpendicular to the plates and is constant in both magnitude and direction. 4.E.3 The charge distribution in a system can be altered by the effects of electric forces produced by a charged object.
Science Practice	1.1 The student can create representations and models of natural or man-made phenomena and systems in the domain. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models. 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big idea.
Learning Objective	2.C.5.1 The student is able to create representations of the magnitude and direction of the electric field at various distances (small compared to plate size) from two electrically charged plates of equal magnitude and opposite signs, and is able to recognize that the assumption of uniform field is not appropriate near edges of plates. 4.E.3.2 The student is able to make predictions about the redistribution of charge caused by the electric field due to other systems, resulting in charged or polarized objects.

(A)	**This option is correct. The longer line (upper) on the battery connection indicates the pole of higher potential (considered positive). Thus, conventional current will flow counterclockwise in the external circuit, making the upper plate of the capacitor positive and bottom plate negative. The thick plate in the middle will have opposite charges induced by the charged plates so that it essentially creates two capacitors in series. Because of fringe effects near the ends of the thick plate the charges will move a little closer, creating the distribution as shown.**
(B)	This option is incorrect. The diagram for this answer choice has incorrectly reversed the charges on the thick metal plate.
(C)	This option is incorrect. This answer choice has incorrectly ignored the fringe effects. Charges will move a little closer near the ends of the plates, creating the distribution as shown in answer choice A.
(D)	This option is incorrect. The diagram for this answer choice has incorrectly reversed the signs of charges on the inner plate and also has neglected fringe effects.

Question 35

Essential Knowledge	2.D.1 The magnetic field exerts a force on a moving electrically charged object. That magnetic force is perpendicular to the direction of velocity of the object and to the magnetic field and is proportional to the magnitude of the charge, the magnitude of the velocity and the magnitude of the magnetic field. It also depends on the angle between the velocity, and the magnetic field vectors. Treatment is quantitative for angles of 0°, 90°, or 180° and qualitative for other angles. 3.B.1 If an object of interest interacts with several other objects, the net force is the vector sum of the individual forces.
Science Practice	2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models. 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big idea.
Learning Objective	2.D.1.1 The student is able to apply mathematical routines to express the force on a moving charged object due to a magnetic field. 3.B.1.4 The student is able to predict the motion of an object subject to forces exerted by several objects using an application of Newton's second law in a variety of physical situations.

(A)	**This option is correct. In this view, the field lines from each bar magnet exit the N pole and loop around to enter the S pole. Since the bar magnets are identical, when they are placed as shown the components of the field that do <u>not</u> point from left to right tend to cancel. Midway between the magnets, the field is exactly from left to right. A charged particle (positive or negative) would be moving along the field lines — not crossing them — so no magnetic force would be exerted on the particle.**
(B)	This option is incorrect. The particle would only curve upward on the diagram if there were a net magnet field directed out of the page. In this symmetrical situation with identical magnets, that would not be true.
(C)	This option is incorrect. The electron would only curve downward on the page if there were a net magnetic field directed into the page in the space between the magnets. The bar magnets are identical, so there is no net field into the page.
(D)	This option is incorrect. The electron would not stop and reverse direction unless there was a magnetic force directed to the left on the electron as it moves to the right. Using the right hand rule, there could be no magnetic force in line with the direction of motion of the electron.

Question 36

Essential Knowledge		5.C.2 The exchange of electric charges among a set of objects in a system conserves electric charge.
Science Practice		4.2 The student can design a plan for collecting data to answer a particular scientific question.
Learning Objective		5.C.2.2 The student is able to design a plan to collect data on the electrical charging of objects and electric charge induction on neutral objects and qualitatively analyze that data.
(A)	This option is incorrect. Touching the sphere constitutes a "conduction method", not an "induction method".	
(B)	This option is incorrect. Bringing the negatively charged object near the sphere is the initial step of induction, but it is not sufficient. This polarizes the sphere, but does not leave the sphere with a new net charge.	
(C)	This option is incorrect. This option correctly describes an induction process, but it would leave the metallic sphere charged negatively after the process.	
(D)	**This option is correct. The choice includes all of the necessary components for successfully inducing a charge. Bring a negatively charged object (opposite sign) close to a metal object. The charges on the sphere become polarized. The grounding allows the negative charges on the polarized sphere a pathway to leave the sphere, leaving the sphere positively charged. The interruption of the ground ensures the negative charge cannot return to the sphere, leaving the sphere a net positive charge.**	

Question 37

Essential Knowledge		5.C.3 Kirchhoff's junction rule describes the conservation of electric charge in electrical circuits. Because charge is conserved, current must be conserved at each junction in the circuit. Examples should include circuits that combine resistors in series and parallel. [Physics 2: includes capacitors in steady-state situations. For circuits with capacitors, situations should be limited to open circuit, just after circuit is closed, and a long time after the circuit is closed.]
Science Practice		6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective		5.C.3.4 The student is able to predict or explain current values in series and parallel arrangements of resistors and other branching circuits using Kirchhoff's junction rule and relate the rule to the law of charge conservation.
(A)	This option is incorrect. 7.5 mA is not a valid current value for any part of this circuit.	
(B)	This option is incorrect.	
(C)	**This option is correct. The 40 ohm resistor and the ammeter are located in equivalent positions in the circuit. No matter what the direction of current through the ammeter, it will split at one of the junctions on either side of the ammeter, and recombine when it reaches the corresponding junction on either side of the 40 ohm resistor. So the 40 ohm resistor also has a current of 20 mA.**	
(D)	This option is incorrect. A current of 40 mA is larger than the measured 20 mA through the ammeter. This would violate the principle of conservation of charge.	

Question 38

Essential Knowledge	5.C.3 Kirchhoff's junction rule describes the conservation of electric charge in electrical circuits. Because charge is conserved, current must be conserved at each junction in the circuit. Examples should include circuits that combine resistors in series and parallel. [Physics 2: includes capacitors in steady-state situations. For circuits with capacitors, situations should be limited to open circuit, just after circuit is closed, and a long time after the circuit is closed.]
Science Practice	1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
Learning Objective	5.C.3.5 The student is able to determine missing values and direction of electric current in branches of a circuit with resistors and NO capacitors from values and directions of current in other branches of the circuit through appropriate selection of nodes and application of the junction rule.

(A)	This option is incorrect. It is the equivalent resistance of the section of the circuit to the right of R. A 50 ohm resistor would lead to a net resistance of 25 ohms for this entire right section of the circuit that includes R. This value would not result in equal division of the potential difference as described in option B.
(B)	**This option is correct. The voltage across the parallel multi branch section to the right of resistor R is 1.0 Volt, the same as the measurement on the voltmeter. Since the two 20 ohm resistors are in equivalent positions, they share equally the remaining 2 volts supplied by the battery. This means that the net resistance of the rest of the circuit must also be 20 ohms. The equivalent resistance of the section of the circuit to the right of R is 50 ohms — added in "parallel" to the unknown resistor must give 20 ohms. The value that will give 20 ohms is 33.3 ohms {i.e., $\left(1/33.3\right)+\left(1/50\right)=1/20$ }.**
(C)	This option is incorrect. It may come from realizing that the given 20 ohm resistors share the remaining 2 volts potential difference, that is have 1 volt each, and assuming that R must equal them to also have 1 volt. A resistance of 20 ohms would yield a net resistance of 14 ohms for the entire right section of the circuit that includes R. This value would not result in the correct equal division of the potential difference as described in option B.
(D)	This option is incorrect. A value of 14 ohms yields a net resistance of 11 ohms for the entire right section of the circuit that includes R. This value would not result in the correct equal division of the potential difference as described in option B.

Question 39

Essential Knowledge	4.E.4 The resistance of a resistor, and the capacitance of a capacitor, can be understood from the basic properties of electric fields and forces, as well as the properties of materials and their geometry.
Science Practice	2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	4.E.4.1 The student is able to make predictions about the properties of resistors and/or capacitors when placed in a simple circuit, based on the geometry of the circuit element and supported by scientific theories and mathematical relationships.

(A)	This option is incorrect. This choice follows in order of the resistances of the conductors.
(B)	This option is incorrect. This choice is ranking the lengths of the conductors.
(C)	This option is incorrect. There are clearly different lengths and areas. This would not lead to identical currents for these three conductors.
(D)	**This option is correct. Current is proportional to the cross sectional area of the conductor and inversely proportional to length of the conductor. Conductors X and Y have the same cross sectional area and Y has clearly the smaller length. Conductors X and Z have the same length, but X has a larger cross sectional area. This leads to the conclusion that $I_y > I_x > I_z$.**

Question 40

Essential Knowledge	2.C.1 The magnitude of the electric force F exerted on an object with electric charge q by an electric field E is $F = qE$. The direction of the force is determined by the direction of the field and the sign of the charge, with positively charged objects accelerating in the direction of the field and negatively charged objects accelerating in the direction opposite the field. This should include a vector field map for positive point charges, negative point charges, spherically symmetric charge distributions, and uniformly charged parallel plates.
Science Practice	6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models. 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big idea.
Learning Objective	2.C.1.1 The student is able to predict the direction and the magnitude of the force exerted on an object with an electric charge q placed in an electric field E using the mathematical model of the relation between an electric force and an electric field: $F = qE$; a vector relation.

(A)	This option is incorrect. Evidence to support sphere Y being a negative charge would either be suspended (like sphere Z), or drifting upward. If sphere Y did move downward (with a negative charge), it would fall "slower" than sphere X.
(B)	This option is incorrect. Sphere Z could not be in a suspended state with a positive charge. A positive charge would give the sphere two downward forces acting on it — and therefore no way for it to be suspended.
(C)	This option is incorrect. As in answer choice (B), the choice of sphere Z being positive implies this choice is incorrect.
(D)	**This option is correct. Because the field is directed downward, the sphere Z must have a negative charge to be in suspended state (upward F_E and a downward weight vector). Sphere Y falls "faster" than the uncharged sphere, this makes sense if it has a positive charge. This results in two downward forces (gravitational plus electrostatic) and a resultant downward force greater than the neutral sphere, thus falling "faster".**

Question 41

Essential Knowledge		3.G.1 Gravitational forces are exerted at all scales and dominate at the largest distance and mass scales.
Science Practice		7.1 The student can connect phenomena and models across spatial and temporal scales.
Learning Objective		3.G.1.2 The student is able to connect the strength of the gravitational force between two objects to the spatial scale of the situation and the masses of the objects involved and compare that strength to other types of forces.
(A)	This option is incorrect. The products of the charges cannot equal the products of the masses — this would not be a dimensionally correct comparison. It ignores the fact that the size of the physical constants G and k must be considered.	
(B)	**This option is correct. The ratio of charge products to mass products is equivalent to G/k (which is approximately 10^{-20}). This implies that the products of the charges are much, much less than the products of the masses.**	
(C)	This option is incorrect. This option is the inverse of the correct relationship.	
(D)	This option is incorrect. The masses being equal or the charges being equal does not allow for a comparison of the two types of forces (gravitational versus electrostatic). The actual value of the masses or charges would need to be known to make a comparison.	

Question 42

Essential Knowledge		3.C.3 A magnetic force results from the interaction of a moving charged object or a magnet with other moving charged objects or another magnet.
Science Practice		1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
Learning Objective		3.C.3.1 The student is able to use right-hand rules to analyze a situation involving a current-carrying conductor and a moving electrically charged object to determine the direction of the magnetic force exerted on the charged object due to the magnetic field created by the current-carrying conductor.
(A)	This option is incorrect. This would be a correct choice if the beam were a beam of protons. It could also be chosen if the direction of the field was incorrectly reversed.	
(B)	**This option is correct. The B field created by the coil is directed toward the left in the top view. The proper use of the right hand rule for force necessitates that the electron beam will be forced downward.**	
(C)	This option is incorrect. The moving charge does not "follow" the B field line to the left.	
(D)	This option is incorrect. There is clearly a magnetic field directed perpendicular to the charge's velocity; this means there will be a magnetic deflecting force in some direction.	

Question 43

Essential Knowledge	1.A.4 Atoms have internal structures that determine their properties. 7.C.4 Photon emission and absorption processes are described by probability.
Science Practice	1.1 The student can create representations and models of natural or man-made phenomena and systems in the domain.
Learning Objective	1.A.4.1 The student is able to construct representations of the energy level structure of an electron in an atom and to relate this to the properties and scales of the systems being investigated. 7.C.4.1 The student is able to construct or interpret representations of transitions between atomic energy states involving the emission and absorption of photons. [For questions addressing stimulated emission, students will not be expected to recall the details of the process, such as the fact that the emitted photons have the same frequency and phase as the incident photon; but given a representation of the process, students are expected to make inferences such as figuring out from energy conservation that because the atom loses energy in the process, the emitted photons taken together must carry more energy than the incident photon.]

(A)	This option is incorrect. The velocities of the gas molecules are directly related to the kinetic energy of the gas molecules (which relates to temperature of the gas). The speeds have no relation to the absorption spectrum.
(B)	**This option is correct. The "location" of the dark lines is directly related to the color (and associated energy of that wavelength) of the light absorbed by the gas. This energy of this particular color is directly related to the transition of the electrons or the different "energy levels" in this particular gas.**
(C)	This option is incorrect. The percent of gas ionized would relate more closely to the relative absence of color from the spectrum (brightness/darkness) but not to the "location" of the dark spot in the spectrum.
(D)	This option is incorrect. The fluctuation of density might affect how many molecules get ionized, but not where the spectrum's dark spots are located.

Question 44

Essential Knowledge	6.E.3 When light travels across a boundary from one transparent material to another, the speed of propagation changes. At a non-normal incident angle, the path of the light ray bends closer to the perpendicular in the optically slower substance. This is called refraction.
Science Practice	5.1 The student can analyze data to identify patterns or relationships. 5.2 The student can refine observations and measurements based on data analysis. 5.3 The student can evaluate the evidence provided by data sets in relation to a particular scientific question.
Learning Objective	6.E.3.2 The student is able to plan data collection strategies as well as perform data analysis and evaluation of the evidence for finding the relationship between the angle of incidence and the angle of refraction for light crossing boundaries from one transparent material to another (Snell's law).

(A)	This option is incorrect. Graph 1 is clearly not a linear relationship and therefore does not have a best –fit line from which a slope can be extracted.
(B)	This option is incorrect. Snell's law does give a linear relationship between the sine of the incident angle and the sine of the refracted angle, but the slope of this data is a value less than one — and indices of refraction of common materials are greater than one.
(C)	This option is incorrect. Graph 1 is clearly not a linear relationship and therefore does not have a best -fit line from which a slope can be extracted.
(D)	**This option is correct. Snell's law yields a linear relationship between the sine of incident angle and the sine of the refracted angle — in this case $n_{air}\sin\theta_1 = n_{plastic}\sin\theta_2$. So the index of the plastic is the inverse of the slope. One can also note that the slope of this graph is approximately 0.7, and since the indices of common materials are greater than 1 the refractive index must be the inverse of slope.**

Question 45

Essential Knowledge	5.B.9 Kirchhoff's loop rule describes conservation of energy in electrical circuits. The application of Kirchhoff's laws to circuits is introduced in Physics 1 and further developed in Physics 2 in the context of more complex circuits, including those with capacitors.
Science Practice	6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	5.B.9.5 The student is able to use conservation of energy principles (Kirchhoff's loop rule) to describe and make predictions regarding electrical potential difference, charge, and current in steady-state circuits composed of various combinations of resistors and capacitors.

(A)	This option is incorrect. It would be impossible for the capacitor to gain energy in this scenario. The capacitor has to initially drive charge around the new loop through R_2, thus losing potential energy at the expense of energy lost through heat in the resistor.
(B)	**This option is correct. In the initial state, there is no current at equilibrium and the potential difference across the fully charged capacitor is the entire battery potential. When the switch is closed, there will be current in both resistors, so there is a potential difference across R_1. Thus the new potential difference across the capacitor is less and $\frac{1}{2}CV^2$ will have a lower value. Another way to think about it is that charge will be moved by the capacitor through the new "loop" created when R_2 is included in the circuit. This will reduce the charge and the potential difference across the capacitor, thus reducing the energy.**
(C)	This option is incorrect. There must be a loss of energy as the capacitor moves charge through the new loop.
(D)	This option is incorrect. The values of the resistors are not necessary to know that there was an energy change in the capacitor.

Question 46

Essential Knowledge	5.B.2 A system with internal structure can have internal energy, and changes in a system's internal structure can result in changes in internal energy. [Physics 2: charged object in electric fields and examining changes in internal energy with changes in configuration.] 5.B.5 Energy can be transferred by an external force exerted on an object or system that moves the object or system through a distance. The process is called doing work on a system. The amount of energy transferred by this mechanical process is called work. Energy transfer in mechanical or electrical systems may occur at different rates. Power is defined as the rate of energy transfer into, out of, or within a system. [A piston filled with gas getting compressed or expanded is treated in Physics 2 as a part of thermodynamics.]
Science Practice	1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models. 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.
Learning Objective	5.B.2.1 The student is able to calculate the expected behavior of a system using the object model (i.e., by ignoring changes in internal structure) to analyze a situation. Then, when the model fails, the student can justify the use of conservation of energy principles to calculate the change in internal energy due to changes in internal structure because the object is actually a system. 5.B.5.4 The student is able to make claims about the interaction between a system and its environment in which the environment exerts a force on the system, thus doing work on the system and changing the energy of the system (kinetic energy plus potential energy). 5.B.5.5 The student is able to predict and calculate the energy transfer to (i.e., the work done on) an object or system from information about a force exerted on the object or system through a distance.

(A)	**This option is correct. The electric field is directed to the right, therefore a force will be exerted to the right on the positive end, creating a torque and initiating clockwise rotation of the molecule. Likewise, the field exerts a force to the left on the negative end, also initiating a torque and clockwise rotation. This external torque on the molecule produces rotational kinetic energy, adding to the total kinetic energy of the molecule.**
(B)	This option is incorrect. The molecules do not have a net charge, even though they are polar.
(C)	**This option is correct. Some molecules will enter the field aligned with the direction of the field, so the electric field exerts a force to the right on the positive end of the molecule and a force to the left on the negative end of the molecule ($F = qE$), stretching the molecular bonds and increasing internal energy of the molecules.**
(D)	This option is incorrect. Because the molecules have no net charge, the magnitude of charge on each end of the polar molecules is the same. If the charges are the same, the force exerted on each end is the same, i.e., equal in magnitude but opposite in direction.

Question 47

Essential Knowledge	5.B.7 The first law of thermodynamics is a specific case of the law of conservation of energy involving the internal energy of a system and the possible transfer of energy through work and/or heat. Examples should include P-V diagrams — isovolumetric processes, isothermal processes, isobaric processes, and adiabatic processes. No calculations of internal energy change from temperature change are required; in this course, examples of these relationships are qualitative and/or semi-quantitative.
Science Practice	1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
Learning Objective	5.B.7.3 The student is able to use a plot of pressure versus volume for a thermodynamic process to make calculations of internal energy changes, heat, or work, based upon conservation of energy principles (i.e., the first law of thermodynamics).

(A)	**This option is correct. The change in internal energy of the gas depends only on change in temperature $(\Delta U \propto \Delta T)$. The difference in temperature between point *i* and point *f* will be the same, regardless of path.**
(B)	**This option is correct. Temperature at each point depends on the pressure and volume at that point $(PV = nRT)$. The temperature at point *f* will be determined by P and V at that point, not on the path during the process.**
(C)	This option is incorrect. The first law of thermodynamics (energy conservation) states that change in internal energy is the sum of thermal energy gain and work done on the gas $(\Delta U = Q + W)$. The process through point X has more work done by the gas (which is considered negative using the above equation) than the process through point Y. Because the change in internal energy is the same for both, more thermal energy must be added during the process through point X.
(D)	This option is incorrect. Regardless of sign convention used, work is calculated as the area between the process "curve" and the volume axis. It is clear that the area for the process through X is different than the area through process Y.

Question 48

Essential Knowledge	7.A.3 In an ideal gas, the macroscopic (average) pressure (P), temperature (T), and volume (V), are related by the equation $PV = nRT$.
Science Practice	5.1 The student can analyze data to identify patterns or relationships.
Learning Objective	7.A.3.3 The student is able to analyze graphical representations of macroscopic variables for an ideal gas to determine the relationships between these variables and to ultimately determine the ideal gas law $PV = nRT$.

(A)	**This option is correct. Use the ideal gas law, $PV = nRT$; therefore $T = PV/nR$. Because n and R are constant for these samples, we only need to examine the product PV in each case. For process A, the initial product is P_0V_0 and the final product is $(1/2P_0)(2V_0)$, so the products are equal and temperature does not change.**
(B)	This option is incorrect. For process B, the initial product is P_0V_0 and the final product is $(3P_0)(1.5V_0)$, so they are not equal and thus the temperature changes.
(C)	**This option is correct. Use the ideal gas law, $PV = nRT$, so $T = PV/nR$. Because n and R are constant for these samples, we examine only the product PV in each case to see if T is constant. For process C, the initial product is P_0V_0 and the final product is $(1/3P_0)(3V_0)$, so the products are equal and temperature does not change.**
(D)	This option is incorrect. For process D, the initial product is P_0V_0 and the final product is $(1/3P_0)(1.5V_0)$, so they are not equal and therefore the temperature changes.

Question 49

Essential Knowledge	6.G.1 Under certain regimes of energy or distance, matter can be modeled as a classical particle.
Science Practice	6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models. 7.1 The student can connect phenomena and models across spatial and temporal scales.
Learning Objective	6.G.1.1 The student is able to make predictions about using the scale of the problem to determine at what regimes a particle or wave model is more appropriate.

(A)	This option is incorrect. An electron at the speed given has a de Broglie wavelength $\lambda = h/p$ of 1.2×10^{-10} m. The width of the human hair (on the order of 10^{-5} m) is too large (by too many orders of magnitude) to diffract electrons.
(B)	**This option is correct. An electron moving at** 6 m/s **has a de Broglie wavelength** $(\lambda = h/p)$ **as calculated:** $\lambda = (6.63 \times 10^{-34}\,\text{J} \cdot \text{s})/(9.11 \times 10^{-31}\ \text{kg})(6 \times 10^{6}\ \text{m/s}) = 1.2 \times 10^{-10}\ \text{m}$ **The opening must be small (within several orders of magnitude of the wavelength). The width of the interatomic spacing in the crystal is close enough to the wavelength for interference diffraction to occur, as shown by the well known Davisson-Germer experiment.**
(C)	**This option is correct. An electron at the speed given has a de Broglie wavelength** $(\lambda = h/p)$**. Using the mass of an electron and Planck's constant:** $\lambda = (6.63 \times 10^{-34}\,\text{J} \cdot \text{s})/(9.11 \times 10^{-31}\ \text{kg})(6 \times 10^{6}\ \text{m/s}) = 1.2 \times 10^{-10}\ \text{m}$ **The opening must be small (within several orders of magnitude of the wavelength). The width of the slit is within about one order of magnitude larger than the wavelength, so diffraction of electrons could occur.**
(D)	This option is incorrect. An electron at the speed given has a de Broglie wavelength $\lambda = h/p$ of 1.2×10^{-10} m. The width of the paper strip is too large (by too many orders of magnitude) for diffraction of electrons to occur.

Question 50

Essential Knowledge	6.F.3 Photons are individual energy packets of electromagnetic waves, with $E_{photon} = hf$, where h is Planck's constant and f is the frequency of the associated light wave.
Science Practice	6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	6.F.3.1 The student is able to support the photon model of radiant energy with evidence provided by the photoelectric effect.

(A)	This option is incorrect. As frequency increases, the energy of each photon increases but not necessarily the number of photons.
(B)	**This option is correct. The maximum kinetic energy of electrons is equal to the energy of photons striking the metal $(E = hf)$ minus the work function of the metal:** $\mathrm{K_{max}} = \mathrm{hf} - \Phi$**. When K is zero,** $\mathrm{hf} = \Phi$ **and the frequency is called the threshold frequency, below which no photoemission occurs. The threshold frequency is the x-intercept on this graph.**
(C)	**This option is correct. The maximum kinetic energy of electrons is equal to the energy of photons striking the metal $(E = hf)$ minus the work function of the metal:** $\mathrm{K_{max}} = \mathrm{hf} - \Phi$**. When K is zero,** $\mathrm{hf} = \Phi$ **and the frequency is called the threshold frequency, below which no photoemission occurs. The threshold frequency is the x-intercept on this graph, and K increases as frequency increases beyond the threshold.**
(D)	This option is incorrect. Intensity of light is not a factor, as each photon must have frequency above the threshold frequency to produce emission. This choice incorrectly assumes that increasing intensity, which increases total energy, will produce photoemission and does not consider the quantum effect.

Answers to Multiple-Choice Questions

1 – B	14 – A	27 – A	40 – D
2 – B	15 – B	28 – A	41 – B
3 – A	16 – D	29 – B	42 – B
4 – A	17 – C	30 – B	43 – B
5 – C	18 – C	31 – D	44 – D
6 – C	19 – A	32 – B	45 – B
7 – C	20 – C	33 – D	46 – A, C
8 – A	21 – D	34 – A	47 – A, B
9 – A	22 – C	35 – A	48 – A, C
10 – B	23 – B	36 – D	49 – B, C
11 – C	24 – C	37 – C	50 – B, C
12 – B	25 – B	38 – B	
13 – C	26 – D	39 – D	

Free-Response Section

Section II is the free-response part of the exam. This section contains four free-response questions, and the student will have a total of 90 minutes to complete them all.

Information for Free-Response Question 1

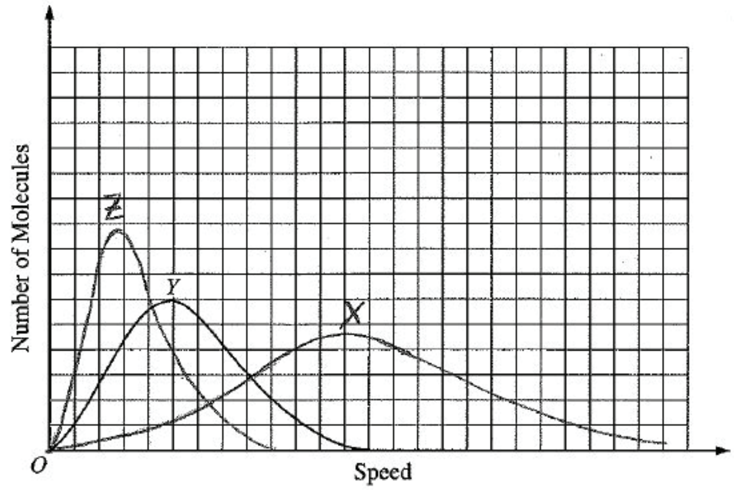
Timing	The student should spend approximately 20 minutes on this question.
Essential Knowledge	4.C.3 Energy is transferred spontaneously from a higher temperature system to a lower temperature system. The process of transferring energy is called heating. The amount of energy transferred is called heat. 5.B.7 The first law of thermodynamics is a specific case of the law of conservation of energy involving the internal energy of a system and the possible transfer of energy through work and/or heat. Examples should include P-V diagrams isovolumetric processes, isothermal processes, isobaric processes, and adiabatic processes. No calculations of internal energy change from temperature change are required; in this course, examples of these relationships are qualitative and/or semi-quantitative. 7.A.2 The temperature of a system characterizes the average kinetic energy of its molecules. 7.B.2 The second law of thermodynamics describes the change in entropy for reversible and irreversible processes. Only a qualitative treatment is considered in this course.
Science Practice	6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models. 7.1 The student can connect phenomena and models across spatial and temporal scales.
Learning Objectives	4.C.3.1 The student is able to make predictions about the direction of energy transfer due to temperature differences based on interactions at the microscopic level. 5.B.7.1 The student is able to predict qualitative changes in the internal energy of a thermodynamic system involving transfer of energy due to heat or work done and justify those predictions in terms of conservation of energy principles. 7.A.2.2 The student is able to connect the statistical distribution of microscopic kinetic energies of molecules to the macroscopic temperature of the system and to relate this to thermodynamic processes. 7.B.2.1 The student is able to connect qualitatively the second law of thermodynamics in terms of the state function called entropy and how it (entropy) behaves in reversible and irreversible processes.

Characteristics of a STRONG Response	Part (a) The student is able to • Identify which sample of gas has greatest probable speed based on temperature • Identify which sample of gas has the broadest distribution of molecular speeds based on temperature Part (b) The student is able to • Exhibit an understanding that energy flows from systems of higher temperature to systems of lower temperature • Exhibit an understanding that higher temperature corresponds to higher kinetic energy • Exhibit an understanding that all three samples end up at the same temperature • Exhibit an understanding that the energy flow for a sample can change direction. In this scenario that the kinetic energy of sample Y decreases then increases. • Arrive at the correct conclusions about the energy flow for each of the three samples Part (c) The student is able to indicate that the entropy decreases and provide a correct or consistent justification that relates the spread of molecular distribution to entropy. Part (d) The student is able to indicate that the entropy of the system increases and explain that the entropy of a closed system increases for an irreversible process.
Characteristics of a GOOD Response	Part (a) The student is able to graph one of the two quantities accurately, either greatest probable speed or distribution of molecular speeds for each sample relative to the other samples on the graph. Part (b) The student is able to exhibit an understanding that energy flows from systems of higher temperature to systems of lower temperatures and that higher temperature corresponds to higher kinetic energy. The student indicates that equilibrium will be reached but does not indicate that all three samples end up at the same temperature. Part (c) The student is able to indicate that the entropy decreases for sample X and provides a reasonable attempt at a justification. Part (d) The student is able to indicate that the entropy of the system increases but is not able to explain.

Characteristics of a WEAK Response	Part (a) The student is able to graph one of the two quantities accurately, either greatest probable speed or distribution of molecular speeds for each sample relative to the other samples on the graph. Part (b) The student is able to exhibit an understanding about energy flow and that equilibrium will be reached but there is limited understanding of what indicates equilibrium and explanation of the energy flow of each sample. Part (c) The student is able to indicate that entropy decreases in sample X but does not provide a reasonable attempt at a justification. Part (d) The student has no understanding about the entropy of a closed irreversible process.

Scoring Guidelines for Free-Response Question 1

Question 1

10 points total	**Distribution of points**
(a) 2 points	
	
For the peak of the curve for *Z* at a smaller speed than *Y*, and *X* at a greater speed than *Y*	1 point
For the curve for *Z* having a higher peak and less spread than *Y*, and *X* with a lower peak and greater spread	1 point
One earned point was deducted for correct curves that are not labeled	
(b) 5 points	
The kinetic energy of *X* decreases. It has the highest temperature and so to reach the same equilibrium temperature as the other samples it must lose energy, which flows into *Z*.	
The kinetic energy of *Y* decreases and then increases. It has a higher temperature than *Z*, and so initially loses energy which flows into *Z*. But it eventually must end up at a higher temperature than it initially had, so the net energy flow must be into *Y*. That can only happen if the direction of energy flow reverses.	
The kinetic energy of *Z* could always increase, or it can increase and then decrease. Initially energy flows into it, since it has the lowest temperature. At some point energy begins to flow from *Z* to *Y*. Whether the temperature and thus the kinetic energy of *Z* continually increases or not depends on how much energy keeps flowing to it from *X*.	
For exhibiting understanding that energy flows from systems at higher temperature to systems at lower temperature	1 point
For exhibiting understanding that higher temperature corresponds to higher kinetic energy	1 point
For exhibiting understanding that the energy flow stops	1 point
For exhibiting understanding that the energy flow for a sample can change direction	1 point
For using the above understanding to indicate that the average kinetic energy of all three samples are the same when equilibrium is reached	1 point

		Distribution of points
(c)	2 points	
	For checking either the correct response or one consistent with the answer to part (b), with a reasonable attempt at justification	1 point
	For a correct or consistent justification that relates the spread of the molecular distribution to entropy	1 point
	For example: The entropy decreases. When the temperature goes down, the spread of the speeds and thus the kinetic energies of the individual molecules is less. This means less disorder and thus less entropy.	
(d)	1 point	
	For correctly indicating that the entropy of the system increases, and explaining that the entropy of a closed system increases for an irreversible process.	1 point

Information for Free-Response Question 2

Timing	The student should spend approximately 25 minutes on this question.
Essential Knowledge	4.E.5 The values of currents and electric potential differences in an electric circuit are determined by the properties and arrangement of the individual circuit elements such as sources of emf, resistors, and capacitors. 5.B.9 Kirchhoff's loop rule describes conservation of energy in electrical circuits. The application of Kirchhoff's laws to circuits is introduced in Physics 1 and further developed in Physics 2 in the context of more complex circuits, including those with capacitors.
Science Practices	6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models. 2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 4.2 The student can design a plan for collecting data to answer a particular scientific question. 5.1 The student can analyze data to identify patterns or relationships. 1.5 The student can re-express key elements of natural phenomena across multiple representations in the domain.
Learning Objectives	4.E.5.2 The student is able to make and justify a qualitative prediction of the effect of a change in values or arrangements of one or two circuit elements on currents and potential differences in a circuit containing a small number of sources of emf, resistors, capacitors, and switches in series and/or parallel. 4.E.5.3 The student is able to plan data collection strategies and perform data analysis to examine the values of currents and potential differences in an electric circuit that is modified by changing or rearranging circuit elements, including sources of emf, resistors, and capacitors. 5.B.9.6 The student is able to mathematically express the changes in electric potential energy of a loop in a multi-loop electrical circuit and justify this expression using the principle of the conservation of energy. 5.B.9.7 The student is able to refine and analyze a scientific question for an experiment using Kirchhoff's loop rule for circuits that includes determination of internal resistance of the battery and analysis of a non-ohmic resistor. 5.B.9.8 The student is able to translate between graphical and symbolic representations of experimental data describing relationships among power, current, and potential difference across a resistor.

Characteristics of a STRONG Response	Part(a)(i) The student is able to write the correct equation with all the required variables. Part(a)(ii) The student is able to • connect the slope of the line to $1/\varepsilon$ • pick two points from the line of best fit to calculate the slope of the line • use the y-intercept of the line to determine the battery's internal resistance • or substitute data from the graph to set up two equations and solve those equations for r and ε. Part (b)(i) The student is able to • draw a circuit that would allow the potential difference across X to be varied • connect the ammeter and voltmeter correctly in the circuit that would allow the current and potential difference to be measured across resistor X. Part(b)(ii) The student is able to • describe a procedure that correctly varies the potential difference across resistor X • indicate that the current and potential difference of resistor X are being measured for more than one trial. Part (b)(iii) The student is able to • indicate that current and potential difference of resistor X are the quantities being graphed • indicate that if resistor X is ohmic then the graph would be linear(a straight line). Part (c) The student is able to • indicate that the procedure changes the external resistance to X and it does not matter how it changes (ohmic or not) because the measurements are for X by itself.

Characteristics of a GOOD Response	Part(a)(i) The student is able to write the correct equation with all the required variables. Part (a)(ii) The student is able to use the data from the graph in an attempt to calculate the emf and internal resistance of the circuit. The student attempts to calculate the slope of the line but does not understand the connection. Part(b)(i) The student is able to • draw a circuit that would allow the potential difference across X to be varied • connect the ammeter or voltmeter in the circuit that would allow the current and potential difference to be measured across resistor X. Part(b)(ii) The student is able to describe a procedure that varies potential difference but does not make more than one trial or does not collect the data necessary to determine whether X is ohmic or not. Part(b)(iii) The student is able to indicate that current and potential difference are being graphed but does not indicate that the data would yield a linear relationship. Part(c) The student is able to indicate the circuit does not have to be different but does not know why.
Characteristics of a WEAK Response	Part(a)(i) The student is able write Ohm's law but does not know how to incorporate internal resistance into the equation. Part(a)(ii) The student attempts to use data from the graph but may only use one point which is substituted into the equation from part(a)(i). Part (b)(i) The student redraws the circuit from the prompt and inserts an ammeter and voltmeter into the circuit. Part(b)(ii) The student attempts to describe a procedure using their circuit but they are unable to vary the potential difference. The student does not indicate that they need the potential difference and current for resistor X. Part(b)(iii) The student indicates quantities to graph, typically indicating voltage and resistance. Part (c) The student does not know how the internal resistance affects the overall resistance with regard to being ohmic or not. The student fails to realize that the internal resistance and resistor R are external to resistor X.

Question 2

12 points total | **Distribution of points**

(a)

(i) 1 point

For a correct equation for the circuit containing all the required variables — 1 point

$\mathcal{E} = (r + R)I$

(ii) 3 points

Slope-intercept method

The above equation can be re-arranged to express $1/I$ as a function of R

$$\frac{1}{I} = \frac{R}{\mathcal{E}} + \frac{r}{\mathcal{E}}$$

The emf is the inverse of the slope of the graph.

For using the slope of the line to determine the emf. — 1 point

For using data from the best-fit line — 1 point

For example:

$$\text{Slope} = \frac{1}{\mathcal{E}} = \frac{(0.8 - 0.2)(1/\text{A})}{(45 - 10)\Omega} = \frac{0.6}{35}\frac{1}{\text{V}}$$

$$\mathcal{E} = \frac{35}{0.6}\text{ V} = 58.3\text{ V}$$

For using the intercept of the line to determine the battery resistance — 1 point

$\text{Intercept} = r/\mathcal{E}$

For example, reading an intercept of $0.03(1/\text{A})$

$r = (\text{Intercept})\mathcal{E} = (0.03(1/\text{A}))(58.3\text{ V}) = 1.75\ \Omega$

Alternate Solution: | *Alternate Points*

Simultaneous equation method

Data is substituted into the equation $\mathcal{E} = (r + R)I$

For using two points to set up two equations — *1 point*

For using data from the best-fit line — *1 point*

For example

$$\mathcal{E} = (r + 45\ \Omega)(1/0.8(1/\text{A}))$$

$$\mathcal{E} = (r + 10\ \Omega)(1/0.2(1/\text{A}))$$

For solving for r and $\mathcal{E}$ — *1 point*

$$(r + 10\ \Omega)(1/0.2(1/\text{A})) = (r + 45\ \Omega)(1/0.8(1/\text{A}))$$

$$(r + 10\ \Omega)(0.8\ 1/\text{A}) = (r + 45\ \Omega)(0.2\ 1/\text{A})$$

Distribution of points

$r(0.8\ 1/\text{A}) - r(0.2\ 1/\text{A}) = (45\ \Omega)(0.2\ 1/\text{A}) - (10\ \Omega)(0.8\ 1/\text{A})$

$r(0.6\ 1/\text{A}) = (9-8)\Omega/\text{A}$

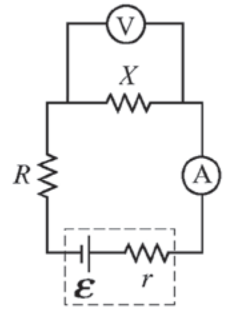
$r = 1/0.6\ \Omega = 1.7\ \Omega$

Using the first simultaneous equation and substituting for r

$\mathcal{E} = (1.7\ \Omega + 45\ \Omega)(1/0.8(1/\text{A})) = 58.3\ \text{V}$

(b)

(i) 2 points



For a design that allows the potential difference across resistor X to be varied	1 point
For an ammeter and a voltmeter connected correctly to measure current and potential difference for resistor X	1 point

(ii) 2 points

For a correct method for varying the potential difference across resistor X.	1 point
For the example circuit shown above, use each of the resistors in turn as resistor R.	
For indicating appropriate measurements for each trial	1 point
For example, for each value of resistor R, measure the potential difference and current for resistor X.	

(iii) 2 points

For indicating appropriate quantities to graph	1 point
For the example described above, graph current as a function of potential difference.	
For indicating an appropriate property of the graph	1 point
For the example described above, the graph would be linear if resistor X was ohmic.	

		Distribution of points
(c)	2 points	
	For correctly indicating ‘yes’ or ‘no’ consistent with circuit drawn, and some reasonable attempt at a correct justification	1 point
	For the example described above, the correct response is ‘no’.	
	For a correct justification	1 point
	For the example described above, the measured values are those for only resistor *X*. Since the point is to change the resistance external to *X*, it does not matter how or why it changes. As long as the measurements are the quantities for *X* by itself the data is legitimate.	

Information for Free-Response Question 3

Timing	The student should spend approximately 25 minutes on this question.
Essential Knowledge	2.C.1 The magnitude of the electric force F exerted on an object with electric charge q by an electric field E is $F = qE$. The direction of the force is determined by the direction of the field and the sign of the charge, with positively charged objects accelerating in the direction of the field and negatively charged objects accelerating in the direction opposite the field. This should include a vector field map for positive point charges, negative point charges, spherically symmetric charge distributions, and uniformly charged parallel plates. 2.D.1 The magnetic field exerts a force on a moving electrically charged object. That magnetic force is perpendicular to the direction of velocity of the object and to the magnetic field and is proportional to the magnitude of the charge, the magnitude of the velocity and the magnitude of the magnetic field. It also depends on the angle between the velocity, and the magnetic field vectors. Treatment is quantitative for angles of $0°$, $90°$, or $180°$ and qualitative for other angles. 3.B.1 If an object of interest interacts with several other objects, the net force is the vector sum of the individual forces.
Science Practices	6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models. 2.2 The student can apply mathematical routines to quantities that describe natural phenomena.
Learning Objectives	2.C.1.1 The student is able to predict the direction and the magnitude of the force exerted on an object with an electric charge q placed in an electric field E using the mathematical model of the relation between an electric force and an electric field: $F = qE$; a vector relation. 2.C.1.2 The student is able to calculate any one of the variables — electric force, electric charge, and electric field — at a point given the values and sign or direction of the other two quantities. 2.D.1.1 The student is able to apply mathematical routines to express the force on a moving charged object due to a magnetic field. 3.B.1.4 The student is able to predict the motion of an object subject to forces exerted by several objects using an application of Newton's second law in a variety of physical situations.

<table>
<tr>
<td>Characteristics of a STRONG Response</td>
<td>
Part (a) The student is able to
• Indicate that there are two forces (electric and magnetic) exerted on the particle
• Indicate that the forces must be equal in magnitude and opposite in direction for the particle to move undeflected.

Part (b) The student is able to
• indicate that the charge is negative, and that because the cross-product of the velocity and the magnetic field is directed upward that means the particle is negative because it curves downward.

Part (c) the student is able to
• Equate the magnitudes of the electric force and magnetic force
• Use the relationship between the field and potential for parallel plates
• Substitute into the resulting equation to solve for potential difference.

Part (d) the student is able to
• Equate the magnitudes of the centripetal and magnetic forces
• Realize that the given distance of the collector plate is the diameter and that radius is needed
• Substitute into the resulting relationship to solve for mass of the particle.

Part (e) the student is able to
• Indicate that the straight-line motion means that all particles regardless of mass and charge will have the same velocity.
• Using the equation from part (d) to indicate that the radius of the circular motion depends on the charge and mass.
• Indicating that for this situation because both particles are isotopes of carbon that the radius will only depend on the mass.
</td>
</tr>
</table>

Characteristics of a GOOD Response	Part (a) the student is able to • Indicate that there are two forces (electric and magnetic) exerted on the particle • Indicate that the forces must be equal in magnitude and opposite in direction for the particle to move undeflected. Part (b) the student is able to • Indicate that the charge is negative but is not able to provide the correct justification Part (c) the student is able to • Equate the magnitudes of the electric force and magnetic force • Attempt to use the relationship between the field and potential for parallel plates and then substitute into the resulting relationship Part (d) the student is able to • Equate the magnitudes of the centripetal and magnetic forces • Substitute into the resulting relationship to solve for mass of the particle but did not realize that the diameter was given, not the radius. Part (e) The student is able to indicate that radius depends on the mass of the isotope.
Characteristics of a WEAK Response	Part (a) the student is able to • Indicate that there are two forces (electric and magnetic) exerted on the particle • Indicate that the two forces are related, but does not explain how. Part (b) the student is able to indicate that there is charge but not the correct sign. Part (c) the student is able to • Equate the magnitudes of the electric force and magnetic force but does not realize the connection between the field and potential for parallel plates and how that can be used to solve for potential difference knowing electric force and magnetic force. Part (d) the student is able to • Equate the magnitudes of the centripetal and magnetic forces • Attempt substitution into the resulting relationship to solve for mass of the particle but did not realize that the diameter was given not the radius. Part (e) the student is able to indicate that radius depends on the mass of the isotope.

Question 3

12 points total	**Distribution of points**
(a) 2 points	
For any indication that both an electric and a magnetic force are exerted on the particle	1 point
For any indication that these forces are equal in magnitude and opposite in direction	1 point
For example: The plates create a vertical electric field that exerts a vertical force on the particle. The cross-product of the velocity and the magnetic field also results in a vertical force. No matter what the charge of the particle, these forces are in opposite directions. Since the charge moves in a straight line they must be equal in magnitude.	
(b) 1 point	
For indicating that the charge is negative and a correct justification	1 point
Examples:	
The cross-product of the velocity and the magnetic field is directed upward. The particle curves downward as it leaves the plates, so it must be negative.	
With the battery connection shown, the top plate is positive and the bottom one is negative. So the electric field is down. The particle would move down without the electric field, as it initially does when it leaves the plates, so the force from the field must be upward. That means the particle is negative.	
(c) 3 points	
$F_B = qvB$	
For equating the magnitudes of the electric and magnetic forces	1 point
$qE = qvB$ so $E = vB$	
For using the relationship between the field and potential for parallel plates, $E = V/d$	1 point
$V/d = vB$	
$V = vBd$	
For correct substitutions	1 point
$V = \left(2.0 \times 10^{6}\ \text{m/s}\right)(0.30\ \text{T})\left(5.0 \times 10^{-3}\ \text{m}\right)$	
$V = 3000\ \text{V}$	

		Distribution of points
(d)	3 points	
	For equating the magnitudes of the centripetal and magnetic forces	1 point
	$mv^2/r = qvB$	
	$m = qBr/v$	
	For realizing that the given distance to the collector plate is the diameter and using $r = 2D$	1 point
	For correct substitutions	1 point
	$m = \left(1.6 \times 10^{-19}\ \text{C}\right)(0.30\ \text{T})(0.21\ \text{m})/\left(2.0 \times 10^{6}\ \text{m/s}\right)$	
	$m = \left(5.04 \times 10^{-27}\ \text{kg}\right)$	
(e)	3 points	
	For any indication that the straight-line motion means that all the particles leaving the plates have the same speed regardless of charge and mass, referencing part (c)	1 point
	For any indication that the radius of the circular motion depends on the charge and mass, as indicated by the equation $m = qBr/v$ from part (d)	1 point
	For any indication that radius depends only on the mass	1 point

Information for Free-Response Question 4

Timing	The student should spend approximately 20 minutes on this question.
Essential Knowledge	6.C.1 When two waves cross, they travel through each other; they do not bounce off each other. Where the waves overlap, the resulting displacement can be determined by adding the displacements of the two waves. This is called superposition. 6.C.2 When waves pass through an opening whose dimensions are comparable to the wavelength, a diffraction pattern can be observed. 6.C.3 When waves pass through a set of openings whose spacing is comparable to the wavelength, an interference pattern can be observed. Examples should include monochromatic double-slit interference.
Science Practices	6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models. 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas. 1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.
Learning Objectives	6.C.1.1 The student is able to make claims and predictions about the net disturbance that occurs when two waves overlap. Examples should include standing waves. 6.C.1.2 The student is able to construct representations to graphically analyze situations in which two waves overlap over time using the principle of superposition. 6.C.2.1 The student is able to make claims about the diffraction pattern produced when a wave passes through a small opening, and to qualitatively apply the wave model to quantities that describe the generation of a diffraction pattern when a wave passes through an opening whose dimensions are comparable to the wavelength of the wave. 6.C.3.1 The student is able to qualitatively apply the wave model to quantities that describe the generation of interference pattern to make predictions about interference patterns that form when waves pass through a set of openings whose spacing and widths are small, but larger than the wavelength.

<table>
<tr><td>Characteristics of a STRONG Response</td><td>Part (a) The student is able to
• Coherently and logically connect the explanation
• Describe X as a point source
• Demonstrate an understanding that the wider opening can be treated as multiple point sources
• Demonstrate that interference of the wave fronts creates the patterns on the far side of the opening and that at the edges there is a lack of interference.

Part (b) The student is able to
• Demonstrate that the figure shows a set of wave fronts
• Demonstrate that the dashed lines lead to points of maxima which are created from interference where the fronts intersect

Part (c) The student is able to
• Construct a graph where the maxima are at the labeled positions on the wall and the minima are in between.
• Show that the highest maxima is located at the central point c and that the height of the other maxima decrease as the position moves away from c on both sides.</td></tr>
<tr><td>Characteristics of a GOOD Response</td><td>Part (a) The student is able to
• Describe a point source
• Demonstrate an understanding of interference being created on the far side of the opening

Part (b) The student is able to
• Demonstrate that maxima in the resulting interference pattern occur where the fronts intersect
• Demonstrate that the dashed lines are connected to the interference pattern on the wall

Part (c) The student is able to construct a graph where the maxima are at the labeled positions and minima in between. However, does not show a decrease in height away from central point c.</td></tr>
<tr><td>Characteristics of a WEAK Response</td><td>Part (a) The student is able to
• Demonstrate some understanding that interference results from the overlap of wave fronts on the far side of the opening
• Demonstrated a very limited understanding of a point source, multiple point sources and interference as a result of wave fronts overlapping

Part (b) The student is able to demonstrate that the figure pertains to a set of wave fronts that intersect and produce a pattern on the wall

Part (c) The student is able to construct a graph that looks like a sine curve and may place the maxima on the labeled positions but all the heights will be the same.</td></tr>
</table>

Scoring Guidelines for Free-Response Question 4

Question 4

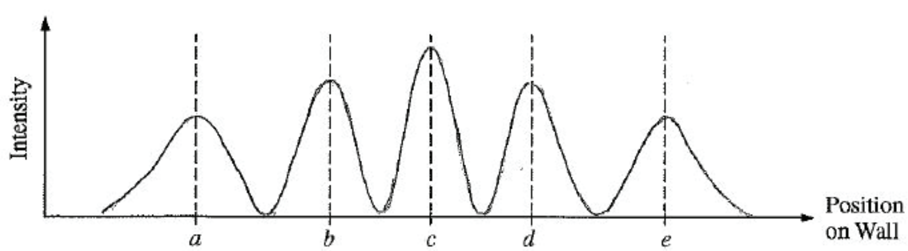
10 points total	**Distribution of points**
(a) 5 points	
For a correct description of *X* as essentially a point source	1 point
For demonstrating understanding that wider openings can be treated as multiple point sources	1 point
For demonstrating understanding that interference of wave fronts creates the pattern on the far side of the opening	1 point
For demonstrating understanding of the lack of interference at the edges	1 point
For coherently connecting the above ideas in a logical explanation	1 point

For example: In *X*, the size of the slit is comparable to the wavelength of the plane waves, so it acts most like a single point source and produces essentially spherical wave fronts. As the slit gets wider in *Y* and *Z*, it acts like an increasing number of point sources. Away from the edges, the spherical wave fronts interfere and the points of constructive interference result in the planar sections that reproduce the incident plane waves. Near the edges, there are no waves on one side to interfere, so the spherical fronts propagate.

(b) 3 points	
For demonstrating understanding that the figure shows a set of wave fronts for each opening	1 point
For demonstrating understanding that maxima in the resulting interference pattern occur where the fronts intersect	1 point
For demonstrating understanding that the dashed lines lead to points of maxima in the resulting interference pattern on the wall	1 point

For example: Each opening creates a set of spherical wave fronts as shown. Assuming the wave fronts denote maximum amplitude, where they cross are points of maximum constructive interference. The dashed lines connect these points, and indicate where the maxima of the pattern on the wall are located.

(c) 2 points



For maxima at the labeled positions on the wall and minima in between	1 point
For showing a decrease in the height of the maxima as position moves away from the central point *c*	1 point

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