2020

AP CollegeBoard

Please note: Some of the questions in this former practice exam may no longer perfectly align with the AP exam. Even though these questions do not fully represent the 2020 exam, teachers indicate that imperfectly aligned questions still provide instructional value. Teachers can consult the Question Bank to determine the degree to which these questions align to the 2020 Exam.

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From the 2019 Administration

AP® CollegeBoard

AP® Physics 2: Algebra-Based

Practice Exam

NOTE: This is a modified version of the 2019 AP Physics 2: Algebra-Based Exam.

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Note: This publication shows the page numbers that appeared in the ***2018–19 AP Exam Instructions*** book and in the actual exam. This publication was not repaginated to begin with page 1.

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AP Physics 1: Algebra-Based Exam

Regularly Scheduled Exam Date: Tuesday afternoon, May 7, 2019
Late-Testing Exam Date: Thursday morning, May 23, 2019

AP Physics 2: Algebra-Based Exam

Regularly Scheduled Exam Date: Friday afternoon, May 10, 2019
Late-Testing Exam Date: Thursday afternoon, May 23, 2019

Section I	**Total Time:** 1 hour and 30 minutes Calculator allowed **Number of Questions:** 40 *(The number of questions may vary slightly depending on the form of the exam.)* **Percent of Total Score:** 50% **Writing Instrument:** Pencil required
Section II	**Total Time:** 1 hour and 30 minutes Calculator allowed **Number of Questions Physics 1:** 5 **Number of Questions Physics 2:** 4 **Percent of Total Score:** 50% **Writing Instrument:** Pen with black or dark blue ink, or pencil

What Proctors Need to Bring to This Exam

- ☐ Exam packets
- ☐ Answer sheets
- ☐ AP Student Packs
- ☐ *2018-19 AP Coordinator's Manual*
- ☐ This book—*2018-19 AP Exam Instructions*
- ☐ AP Exam Seating Chart template
- ☐ School Code and Homeschool/Self-Study Codes
- ☐ Extra calculators
- ☐ Extra rulers or straightedges
- ☐ Pencil sharpener
- ☐ Container for students' electronic devices (if needed)
- ☐ Extra No. 2 pencils with erasers
- ☐ Extra pens with black or dark blue ink
- ☐ Extra paper
- ☐ Stapler
- ☐ Watch
- ☐ Signs for the door to the testing room
  - "Exam in Progress"
  - "Phones of any kind are prohibited during the test administration, including breaks"

Before Distributing Exams: Check that the title on all exam covers is ***Physics 1: Algebra-Based*** or ***Physics 2: Algebra-Based***. If there are any exam booklets with a different title, contact the AP coordinator immediately.

Students are permitted to use rulers, straightedges, and four-function, scientific, or graphing calculators for these entire exams (Sections I and II). Before starting the exam administration, make sure each student has an appropriate calculator, and any student with a graphing calculator has a model from the approved list on page 53 of the *2018-19 AP Coordinator's Manual*. See pages 50–53 of the *AP Coordinator's Manual* for more information. If a student does not have an appropriate calculator or has a graphing calculator not on the approved list, you may provide one from your supply. If the student does not want to use the calculator you provide or does not want to use a calculator at all, they must hand copy, date, and sign the release statement on page 52 of the *AP Coordinator's Manual*.

Students may have no more than two calculators on their desks. Calculators may not be shared. Calculator memories do not need to be cleared before or after the exam. Students with Hewlett-Packard 48–50 Series and Casio FX-9860 graphing calculators may use cards designed for use with these calculators. Proctors should make sure infrared ports (Hewlett-Packard) are not facing each other. **Since graphing calculators can be used to store data, including text, proctors should monitor that students are using their calculators appropriately. Attempts by students to use the calculator to remove exam questions and/or answers from the room may result in the cancellation of AP Exam scores.**

Tables containing equations commonly used in physics are included in each AP Exam booklet, for use during the entire exam. Students are NOT allowed to bring their own copies of the equation tables to the exam room.

SECTION I: Multiple Choice

› **Do not begin the exam instructions below until you have completed the appropriate General Instructions for your group.**

Make sure you begin the exam at the designated time. Remember, you must complete a seating chart for this exam. See pages 295–296 for a seating chart template and instructions. See the *2018-19 AP Coordinator's Manual* for exam seating requirements (pages 56–59).

Physics 1: Algebra-Based

If you are giving the regularly scheduled exam, say:

It is Tuesday afternoon, May 7, and you will be taking the AP Physics 1: Algebra-Based Exam. Look at your exam packet and confirm that the exam title is "AP Physics 1: Algebra-Based." Raise your hand if your exam packet contains any title other than "AP Physics 1: Algebra-Based," and I will help you.

If you are giving the alternate exam for late testing, say:

It is Thursday morning, May 23, and you will be taking the AP Physics 1: Algebra-Based Exam. Look at your exam packet and confirm that the exam title is "AP Physics 1: Algebra-Based." Raise your hand if your exam packet contains any title other than "AP Physics 1: Algebra-Based," and I will help you.

Physics 2: Algebra-Based

If you are giving the regularly scheduled exam, say:

It is Friday afternoon, May 10, and you will be taking the AP Physics 2: Algebra-Based Exam. Look at your exam packet and confirm that the exam title is "AP Physics 2: Algebra-Based." Raise your hand if your exam packet contains any title other than "AP Physics 2: Algebra-Based," and I will help you.

If you are giving the alternate exam for late testing, say:

It is Thursday afternoon, May 23, and you will be taking the AP Physics 2: Algebra-Based Exam. Look at your exam packet and confirm that the exam title is "AP Physics 2: Algebra-Based." Raise your hand if your exam packet contains any title other than "AP Physics 2: Algebra-Based," and I will help you.

Once you confirm that all students have the correct exam, say:

In a moment, you will open the exam packet. By opening this packet, you agree to all of the AP Program's policies and procedures outlined in the *2018-19 Bulletin for AP Students and Parents*.

You may now remove the shrinkwrap from the outside only of your exam packet. Do not open the Section I booklet; do not remove the shrinkwrap from the Section II materials. Put the white seals and the shrinkwrapped Section II booklet aside. . . .

Carefully remove the AP Exam label found near the top left of your exam booklet cover. Place it on page 1 of your answer sheet on the light blue box near the top right corner that reads "AP Exam Label."

If students accidentally place the exam label in the space for the number label or vice versa, advise them to leave the labels in place. They should not try to remove the label; their exam can still be processed correctly.

Listen carefully to all my instructions. I will give you time to complete each step. Please look up after completing each step. Raise your hand if you have any questions.

Give students enough time to complete each step. Don't move on until all students are ready.

Read the statements on the front cover of the Section I booklet. . . .

Sign your name and write today's date. . . .

Now print your full legal name where indicated. . . .

Turn to the back cover of your exam booklet and read it completely. . . .

Give students a few minutes to read the entire cover.

Are there any questions? . . .

You will now take the multiple-choice portion of the exam. You should have in front of you the multiple-choice booklet and your answer sheet. You may never discuss the multiple-choice exam content at any time in any form with anyone, including your teacher and other students. If you disclose the multiple-choice exam content through any means, your AP Exam score will be canceled.

Open your answer sheet to page 2. You must complete the answer sheet using a No. 2 pencil only. Mark all of your responses on pages 2 and 3 of your answer sheet. Remember, for numbers 1 through 45 on answer sheet page 2, mark only the single best answer to each question. The answer sheet has circles marked A–E for each of these questions. For this exam, you will use only the circles marked A–D. For numbers 131 through 135 at the bottom of answer sheet page 3, mark the two

best answer choices for each question. Completely fill in the circles. If you need to erase, do so carefully and completely. No credit will be given for anything written in the exam booklet. Scratch paper is not allowed, but you may use the margins or any blank space in the exam booklet for scratch work. Rulers, straightedges, and calculators may be used for the entire exam. You may place these items on your desk. Are there any questions? . . .

You have 1 hour and 30 minutes for this section. Open your Section I booklet and begin.

Note Start Time _____. Note Stop Time _____.

Check that students are marking their answers in pencil on their answer sheets and that they have not opened their shrinkwrapped Section II booklets. You should also make sure that Hewlett-Packard calculators' infrared ports are not facing each other and that students are not sharing calculators.

After 1 hour and 20 minutes, say:

There are 10 minutes remaining.

After 10 minutes, say:

Stop working. Close your booklet and put your answer sheet on your desk, faceup. Make sure you have your AP number label and an AP Exam label on page 1 of your answer sheet. Sit quietly while I collect your answer sheets.

Collect an answer sheet from each student. Check that each answer sheet has an AP number label and an AP Exam label.

After all answer sheets have been collected, say:

Now you must seal your exam booklet using the white seals you set aside earlier. Remove the white seals from the backing and press one on each area of your exam booklet cover marked "PLACE SEAL HERE." Fold each seal over the back cover. When you have finished, place the booklet on your desk, faceup. I will now collect your Section I booklet. . . .

Collect a Section I booklet from each student. Check that each student has signed the front cover of the sealed 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. Please put all of your calculators under your chair. Your calculators and all items you placed under your chair at the beginning of this exam, including your Student Pack, must stay there, and you are not permitted to open or access them in any way. Leave your shrinkwrapped Section II packet on your desk during the break. You are not allowed to consult teachers, other students, notes, textbooks, or any other resources during the break. You may not make phone calls, send text messages, check email, use a social networking site, or access any electronic or communication device. You may not leave the designated break area. Remember, you may never discuss the multiple-choice exam content with anyone, and if you disclose the content through any means, your AP Exam score will be canceled. Are there any questions? . . .

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

SECTION II: Free Response

After the break, say:

May I have everyone's attention? Place your Student Pack on your desk. . . .

You may now remove the shrinkwrap from the Section II packet, but do not open the exam booklet until you are told to do so. . . .

Read the bulleted statements on the front cover of the exam booklet. Look up when you have finished. . . .

Now take an AP number label from your Student Pack and place it on the shaded box. If you don't have any AP number labels, write your AP number in the box. Look up when you have finished. . . .

Read the last statement. . . .

Using your pen, print the first, middle, and last initials of your legal name in the boxes and print today's date where indicated. This constitutes your signature and your agreement to the statements on the front cover. . . .

Now turn to the back cover. Using your pen, complete Items 1 through 3 under "Important Identification Information.". . .

Read Item 4. . . .

Are there any questions? . . .

If this is your last AP Exam, you may keep your Student Pack. Place it under your chair for now. Otherwise if you are taking any other AP Exams this year, leave your Student Pack on your desk and I will collect it now. . . .

Read the information on the back cover of the exam booklet. Do not open the booklet until you are told to do so. Look up when you have finished. . . .

Collect the Student Packs from students who are taking any other AP Exams this year.

Then say:

Are there any questions? . . .

Rulers, straightedges, and calculators may be used for Section II. Be sure these items are on your desk. . . .

You have 1 hour and 30 minutes to complete Section II. You are responsible for pacing yourself, and you may proceed freely from one question to the next.

If you are giving the ***AP Physics 1: Algebra-Based Exam***, say:
Section II has 5 questions. It is suggested that you spend approximately 25 minutes each for questions 2 and 3, and 13 minutes each for questions 1, 4, and 5.

If you are giving the ***AP Physics 2: Algebra-Based Exam***, say:
Section II has 4 questions. It is suggested that you spend approximately 25 minutes each for questions 2 and 3, and 20 minutes each for questions 1 and 4.

You must write your answers in the exam booklet using a pen with black or dark blue ink or a No. 2 pencil. If you use a pencil, be sure that your writing is dark enough to be easily read. If you need more paper to complete your responses, raise your hand. At the top of each extra sheet of paper you use, write only:

- **your AP number,**
- **the exam title, and**
- **the question number you are working on.**

Do not write your name. Are there any questions? . . .

You may begin.

Note Start Time _____. Note Stop Time _____.

You should also make sure that Hewlett-Packard calculators' infrared ports are not facing each other and that students are not sharing calculators.

After 1 hour and 20 minutes, say:

There are 10 minutes remaining.

After 10 minutes, say:

Stop working and close your exam booklet. Place it on your desk, faceup. . . .

If any students used extra paper for a question in the free-response section, have those students staple the extra sheet(s) to the first page corresponding to that question in their free-response exam booklets. Complete an Incident Report after the exam and return these free-response booklets with the extra sheets attached in the Incident Report return envelope (see page 68 of the *2018-19 AP Coordinator's Manual* for complete details).

Then say:

Remain in your seat, without talking, while the exam materials are collected. . . .

Collect a Section II booklet from each student. Check for the following:

- Exam booklet front cover: The student placed an AP number label on the shaded box and printed their initials and today's date.
- Exam booklet back cover: The student completed the "Important Identification Information" area.

When all exam materials have been collected and accounted for, return to students any electronic devices you may have collected before the start of the exam.

If you are giving the regularly scheduled exam, say:

You may not discuss or share the free-response exam content with anyone unless it is released on the College Board website in about two days. Your AP Exam score results will be available online in July.

If you are giving the alternate exam for late testing, say:

None of the content in this exam may ever be discussed or shared in any way at any time. Your AP Exam score results will be available online in July.

If any students completed the AP number card at the beginning of this exam, say:

Please remember to take your AP number card with you. You will need the information on this card to view your scores and order AP score reporting services online.

Then say:

You are now dismissed.

After-Exam Tasks

Be sure to give the completed seating chart to the AP coordinator. Schools must retain seating charts for at least six months (unless the state or district requires that they be retained for a longer period of time). Schools should not return any seating charts in their exam shipments unless they are required as part of an Incident Report.

NOTE: If you administered exams to students with accommodations, review the *2018-19 AP Coordinator's Manual* and the *2018-19 AP SSD Guidelines* for information about completing the Nonstandard Administration Report (NAR) form, and returning these exams.

The exam proctor should complete the following tasks if asked to do so by the AP coordinator. Otherwise, the AP coordinator must complete these tasks:

- Complete an Incident Report for any students who used extra paper for the free-response section. (Incident Report forms are provided in the coordinator packets sent with the exam shipments.) **These forms must be completed with a No. 2 pencil.** It is best to complete a single Incident Report for multiple students per exam subject, per administration (regular or late testing), as long as all required information is provided. Include all exam booklets with extra sheets of paper in an Incident Report return envelope (see page 68 of the *2018-19 AP Coordinator's Manual* for complete details).
- Return all exam materials to secure storage until they are shipped back to the AP Program. (See page 27 of the *2018-19 AP Coordinator's Manual* for more information about secure storage.) Before storing materials, check the "School Use Only" section on page 1 of the answer sheet and:
  - Fill in the appropriate section number circle in order to access a separate AP Instructional Planning Report (for regularly scheduled exams only) or subject score roster at the class section or teacher level. See "Post-Exam Activities" in the *2018-19 AP Coordinator's Manual*.
  - Check your list of students who are eligible for fee reductions and fill in the appropriate circle on their registration answer sheets.

Name:_____

Answer Sheet for AP Physics 2: Algebra-Based

Practice Exam, Section I

No.	Answer
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	
16	
17	
18	
19	
20	

No.	Answer	
21		
22		
23		
24		
25		
26		
27		
28		
29		
30		
31		
32		
33		
34		
35		
36		
131		
132		
133		
134		

AP® Physics 2: Algebra-Based Exam

SECTION I: Multiple Choice

2019

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

At a Glance

Total Time
1 hour and 30 minutes
Number of Questions
40
Percent of Total Score
50%
Writing Instrument
Pencil required
Electronic Device
Calculator allowed

Instructions

Section I of this exam contains 40 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.

Because this section offers only four answer options for each question, do not mark the (E) answer circle for any question. If you change an answer, be sure that the previous mark is erased completely.

For questions 1 through 36, select the single best answer choice for each question. After you have decided which of the choices is best, completely fill in the corresponding circle on the answer sheet. Here is a sample question and answer.

Sample Question	Sample Answer
Chicago is a (A) state (B) city (C) country (D) continent	Ⓐ ● Ⓒ Ⓓ Ⓔ

For questions 131 through 134, select the two best answer choices for each question. After you have decided which two choices are best, completely fill in the two corresponding circles on the answer sheet. Here is a sample question and answer.

Sample Question	Sample Answer
New York is a (A) state (B) city (C) country (D) continent	● ● Ⓒ Ⓓ

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.

Form I
Form Code 4PBP4-S
84

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 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 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 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

$v_x = v_{x0} + a_x t$

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

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

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

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

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

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

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

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

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

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

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

$\omega = \omega_0 + \alpha t$

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

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

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

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

$L = I\omega$

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

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

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

a = acceleration
A = amplitude
d = distance
E = energy
F = force
f = frequency
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
y = height
α = angular acceleration
μ = coefficient of friction
θ = angle
τ = torque
ω = angular speed

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

$\Delta U_g = mg\,\Delta y$

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

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

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

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

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

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

ELECTRICITY AND MAGNETISM

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

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

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

$\Delta U_E = q\Delta V$

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

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

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

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

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

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

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

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

$P = I\,\Delta V$

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

$R_s = \sum_i R_i$

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

$C_p = \sum_i C_i$

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

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

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

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

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

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

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

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

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

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

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

AP® PHYSICS 2 EQUATIONS

FLUID MECHANICS AND THERMAL PHYSICS

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

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

$P = P_0 + \rho g h$

$F_b = \rho V g$

$A_1 v_1 = A_2 v_2$

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

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

$PV = nRT = Nk_BT$

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

$W = -P\Delta V$

$\Delta U = Q + W$

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

WAVES AND OPTICS

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

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

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

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

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

$\Delta L = m\lambda$

$d\sin\theta = m\lambda$

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

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

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

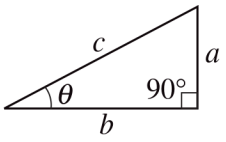
A = area
C = circumference
V = volume
S = surface area
b = base
h = height
ℓ = length
w = width
r = radius

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

Time—1 hour and 30 minutes

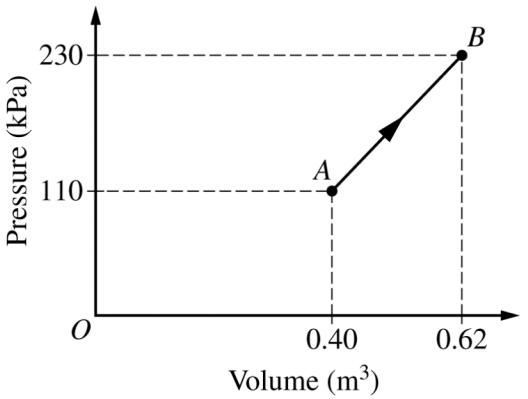
40 Questions

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 fill in the corresponding circle on the answer sheet.

1. Radioactive element X has a half-life of approximately 50 days. Radioactive element Y has a half-life of approximately 100 days. A 0.8 g sample of element X and a 0.8 g sample of element Y are weighed and examined. Some time later, both samples are measured again and 0.2 g of element X remains. How much of element Y remains?

   (A) 0.1 g
   (B) 0.2 g
   (C) 0.4 g
   (D) 0.8 g



2. A sample of a gas is in a container with a movable piston. Only one action is performed to take the gas from state *A* to state *B* via the process shown in the above graph of pressure as a function of volume. Which of the following could be the one action?

   (A) Gas molecules were removed from the container.
   (B) Thermal energy was added to the gas.
   (C) The piston was pulled out.
   (D) The gas was allowed to freely expand.

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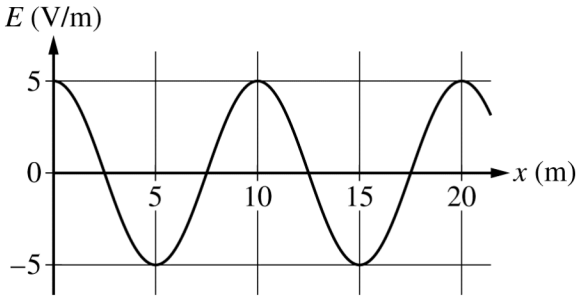


3. The graph above shows the electric field E of an electromagnetic wave as a function of position x at a particular instant. Which of the following equations, where all quantities are assumed to have units consistent with the graph, best represents the graph?

   (A) $E = 10\cos(2\pi x/10)$
   (B) $E = 10\cos(2\pi x/5)$
   (C) $E = 5\cos(2\pi x/10)$
   (D) $E = 5\cos(2\pi x/5)$

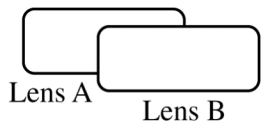
4. Some students observe that a hollow metal sphere hanging on an insulating string is attracted to a positively charged rod. They decide that this is evidence that the sphere could also be charged. The answer to which of the following questions might determine whether they are correct?

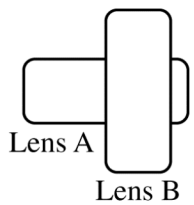
   (A) Is the sphere still attracted when the positively charged rod is placed on the other side of the sphere?
   (B) Is the sphere repelled by a negatively charged rod?
   (C) Is the attraction of the sphere to the rod weaker when the distance between them is increased?
   (D) Is the attraction of the sphere to the rod stronger when the charge on the rod is doubled?

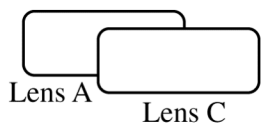
5. Two identical containers, X and Y, each contain one mole of an ideal monatomic gas. The atoms in container X have a higher average kinetic energy than those in container Y. The containers are thermally insulated from the external environment and placed into thermal contact with each other at time $t = 0$. Which of the following accurately describes the interactions between containers X and Y?

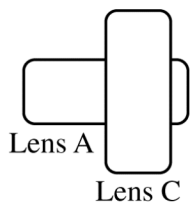
   (A) The net result is that energy is transferred from container X to container Y.
   (B) The amount of energy transferred between the containers depends on the type of atoms each contains.
   (C) After equilibrium is reached, the atoms in container X will still have a different average kinetic energy than those in container Y.
   (D) All the atoms in container X slow down, and all the atoms in container Y speed up.

6. A student has three sunglass lenses. Lenses A and B have identical polarization patterns, and lens C is not polarized. Which of the following arrangements of lenses would have the most light blocked where the lenses overlap?

   (A)
   

   (B)
   

   (C)
   

   (D)
   

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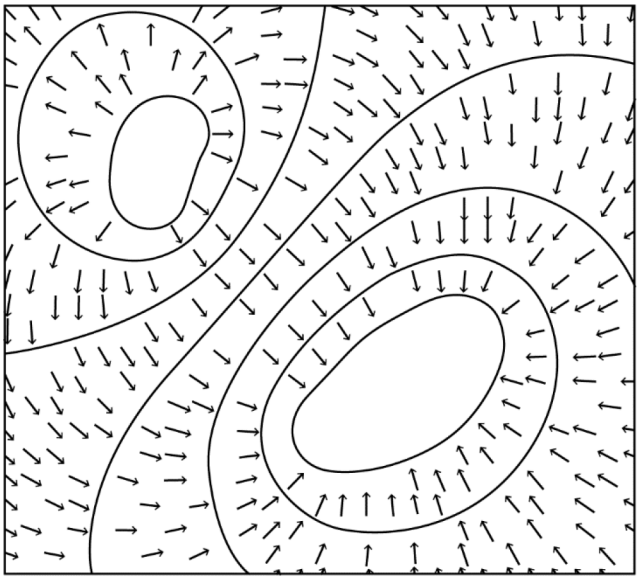

7. Some students drew the figure above as a representation that could be either a topographic (elevation) map, with the arrows representing the direction of downward slope, or electric equipotentials and electric field direction near some charged particles. Which of the following correctly describes what is inside the empty regions for each representation?

	Topographic Map	Electric Potentials and Field
(A)	Peak at upper left; valley at lower right	Negative charge at upper left; positive charge at lower right
(B)	Peak at upper left; valley at lower right	Positive charge at upper left; negative charge at lower right
(C)	Valley at upper left; peak at lower right	Negative charge at upper left; positive charge at lower right
(D)	Valley at upper left; peak at lower right	Positive charge at upper left; negative charge at lower right

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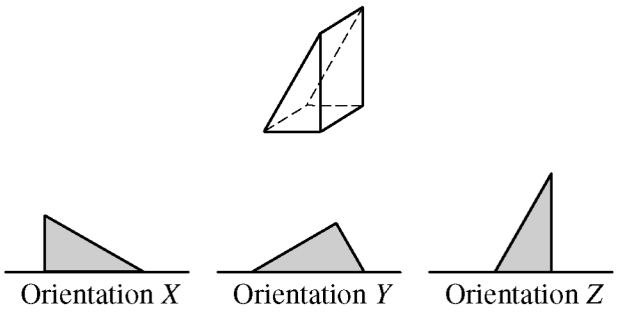
Questions 8-9 refer to the following material.

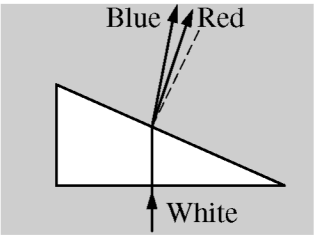


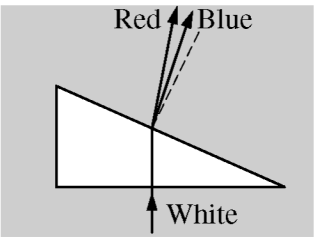
A hollow prism in the shape of a right triangle is shown in the figure above. The prism is filled with a liquid and can be placed in any of the three orientations shown.

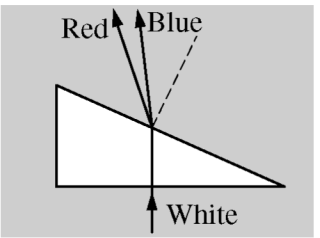
8. The liquid-filled prism is placed in a large tank containing a different liquid and sinks to the bottom of the tank. F_X is the magnitude of the buoyant force exerted on the prism by the liquid in the tank when the prism is in orientation X. F_Y and F_Z are the buoyant forces for orientations Y and Z. Which of the following correctly ranks the three buoyant forces?

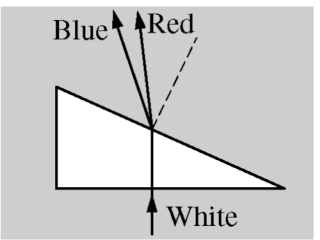
   (A) $F_Y < F_X < F_Z$
   (B) $F_Z < F_X < F_Y$
   (C) $(F_X = F_Y) < F_Z$
   (D) $F_X = F_Y = F_Z$

9. The prism is emptied of liquid. It is then submerged in another liquid with refractive indexes of 1.3 for red light and 1.4 for blue light. A beam of white light enters the prism. Which of the diagrams below shows the paths of red and blue light rays as they exit the prism?

(A)


(B)


(C)


(D)


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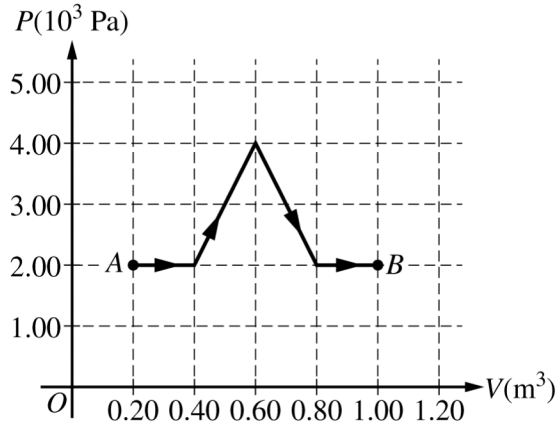
10. A proton moving to the right in the plane of the page with speed v enters a magnetic field of magnitude B directed toward the top of the page. What is the direction of the initial magnetic force that is exerted on the proton?

(A) Toward the top of the page
(B) Into the page
(C) Out of the page
(D) No direction, because there is no magnetic force on the proton



11. A simple ideal gas is enclosed in a cylinder with a movable piston. The gas is initially in state A at a temperature of 190 K and is taken from state A to state B along the path shown in the graph above of pressure P as a function of volume V. What is the temperature of the gas in state B ?

(A) 38 K
(B) 190 K
(C) 380 K
(D) 950 K

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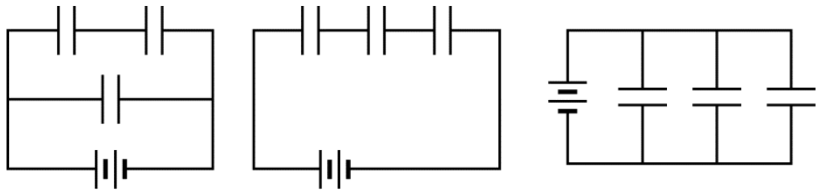


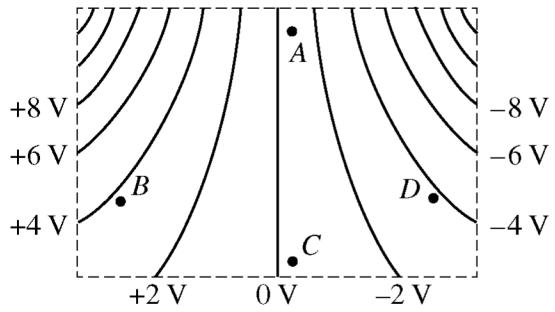
12. The figures above show three circuits, each containing the same battery and identical capacitors. Which circuit has the largest stored charge when it reaches steady state?

(A) X
(B) Y
(C) Z
(D) All three store the same charge.

---

13. A fixed quantity of an ideal monatomic gas is enclosed in a container of fixed volume. Which of the following is true and helps explain why a decrease in the temperature of the gas results in a decrease in its pressure?

(A) The speed of each of the molecules decreases, so the molecules all exert less force on the container when they collide with it.
(B) The average speed of the collection of gas molecules decreases, so on average the molecules exert less force on the container when they collide with it.
(C) The speed of only the fastest molecules decreases, so the molecules have fewer collisions with the container.
(D) The speeds of the molecules are more evenly distributed across all possible values, so the molecules have fewer collisions with the container.



14. The figure above shows lines of equal electric potential in a region of space in the plane of the page. At which labeled point is the magnitude of the electric field greatest?

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

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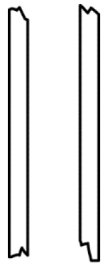


15. A student is doing experiments involving magnetic fields with the two long wires shown above, which are in the plane of the page. The student connects the ends of the left wire to a battery, creating a current in the wire toward the bottom of the page. What is the direction of the magnetic field at the location of the right wire?

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

16. A proton and an electron are held a short distance apart and released from rest. The only nonnegligible forces on the particles are the electrostatic forces they exert on each other. Which of the following statements is true?

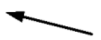
(A) The magnitude of the electrostatic force exerted on the proton by the electron is greater than that exerted on the electron by the proton.
(B) The magnitude of the acceleration of the proton is less than the magnitude of the acceleration of the electron.
(C) The proton must move a larger distance to have the same magnitude change in potential energy as the electron.
(D) The proton must move the same distance to have the same change in speed as the electron.

17. Three charged particles are near each other but isolated from other objects. Particle L has a charge of $+2.0\ \mu C$ and is located $4.0\ cm$ above the origin on the positive y-axis. Particle M has a charge of $-4.0\ \mu C$ and is located $8.0\ cm$ directly below particle L. Particles L and M are fixed in place. Particle N has a charge of $-1.0\ \mu C$ and is released from rest at 3.0 cm from the origin on the positive x-axis. Which of the following shows the initial direction of motion of particle N ?

(A) 

(B) 

(C) 

(D) 

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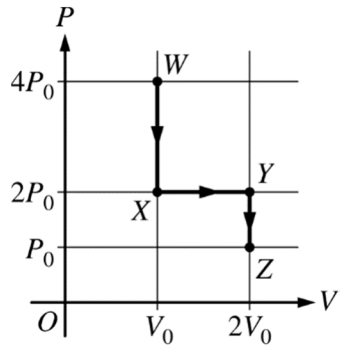
Questions 18-20 refer to the following material.



A monatomic ideal gas in a sealed container is taken from state W to state Z through intermediate states X and Y, as shown in the above graph of pressure P as a function of volume V.

18. What is the total work done on the gas as it goes from state W to state Z ?

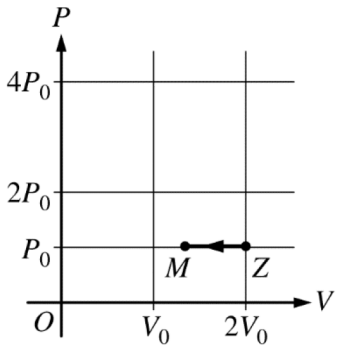
(A) 0
(B) $-P_0V_0$
(C) $-2P_0V_0$
(D) $-4P_0V_0$

19. The internal energy of the gas in state X is the same as that in which other state?

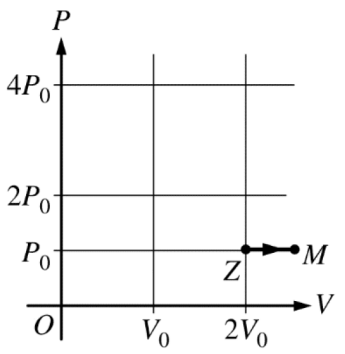
(A) W
(B) Y
(C) Z
(D) None of the other states

20. The gas is now taken from state Z to state M via an isovolumetric process in which its temperature increases. Which of the following graphs could represent this process?

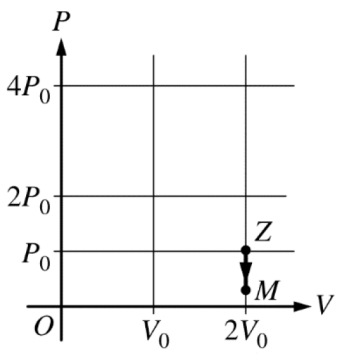
(A)



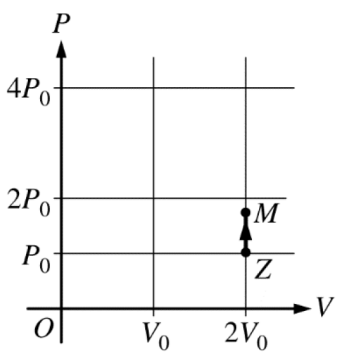
(B)



(C)



(D)



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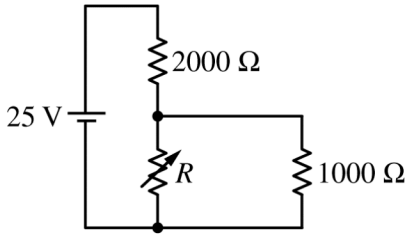
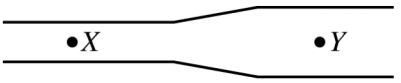


21. In the circuit shown above, R is a variable resistor. What resistance must R have so that the voltage across the $1000\,\Omega$ resistor is 5.0 V?

(A) 400 Ω
(B) 500 Ω
(C) 1000 Ω
(D) 5000 Ω



22. Water flows from left to right through the horizontal section of pipe shown above. At point X the speed of the water is $4\ \text{m/s}$, and at Y it is $2\ \text{m/s}$. The density of water is $1000\ \text{kg/m}^3$. What is the difference in water pressure between points X and Y?

(A) Zero
(B) 1000 Pa
(C) 2000 Pa
(D) 6000 Pa

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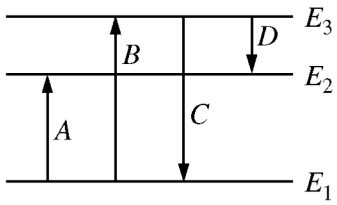

23. The figure above is an energy-level diagram for a hypothetical atom. The four transitions shown include the absorption of red light and the absorption of blue light. Which transition corresponds to the absorption of red light?

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



24. The figures above represent three metal spheres on insulating stands. Initially sphere *A* has charge $+Q$, and spheres *B* and *C* are uncharged. Spheres *B* and *C* are in contact when sphere *A* is brought near sphere *B* but does not touch it, as shown on the left. Sphere *C* is then separated from sphere *B*, as shown on the right. Which of the following best describes the final charges on spheres *B* and *C*?

	Sphere *B*	Sphere *C*
(A)	Positive	Uncharged
(B)	Positive	Negative
(C)	Uncharged	Positive
(D)	Negative	Positive

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25. Which of the following helps explain why the buoyant force exerted on an object submerged in a fluid on Earth is always directed upward?

(A) The buoyant force forms a Newton's third law pair with the force of gravity on the object.

(B) The fluid pressure exerts a force that balances the weight of the object, which means pressure is only exerted upward on the object.

(C) Fluid pressure is exerted on all surfaces of an object and increases with depth. The horizontal forces due to the pressure cancel, but the vertical forces do not.

(D) The surface tension between fluid molecules tends to resist the object moving downward through the surface of the fluid. This resistive force causes a net force upward.

θ_i (degrees)	θ_r (degrees)
0	0
16	10.8
32	20.4
48	30.1
64	37.9
80	39.8

26. A student measures the incident angle θ_i and the refracted angle θ_r of a beam of light that travels through air and then enters a material of unknown index of refraction. The student's data for several angles are shown in the table above. Which of the following procedures should the student follow so that the slope of a best-fit line will be the index of refraction of the material?

(A) Graph θ_r as a function of θ_i.

(B) Graph θ_i as a function of θ_r.

(C) Graph $\sin\theta_r$ as a function of $\sin\theta_i$.

(D) Graph $\sin\theta_i$ as a function of $\sin\theta_r$.

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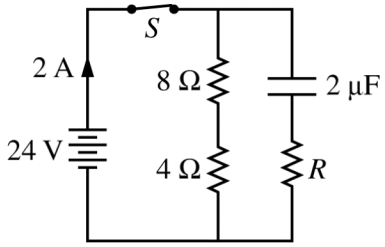

27. In the circuit above, the current through the battery a long time after switch S is closed is 2 A. What is the resistance of resistor R ?

(A) 6 Ω
(B) 10 Ω
(C) 12 Ω
(D) The resistance of resistor R cannot be determined from information about the steady state.

28. A student holds a lens 40 cm from an object and observes an enlarged image on a screen on the opposite side of the lens. Which of the following could be the type of lens and its focal length?

	Type of Lens	Focal Length
(A)	Diverging	30 cm
(B)	Diverging	50 cm
(C)	Converging	30 cm
(D)	Converging	50 cm

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GO ON TO THE NEXT PAGE.

Questions 29-31 refer to the following material.

Cosmic rays bombard Earth's upper atmosphere, creating subatomic particles called muons, which then stream toward the surface of Earth at nearly the speed of light. The muon is not a nucleon. It is an unstable fundamental particle with most properties the same as those of an electron but with a larger mass. In a frame of reference at rest with respect to the muon, the muon decays with a half-life of approximately 2.2×10^{-6} s.

29. The number of muons that reach Earth's surface without decaying is higher than would be expected from the known half-life for muon decay. The measured discrepancy arises because the muons are moving close to the speed of light. Which of the following is a consequence of the high speed of the muons and best explains the measured discrepancy?

    (A) Time intervals as measured in Earth's rest frame are different from time intervals measured in the rest frame of a muon, so more muons reach Earth's surface.
    (B) The size of a muon as measured on Earth is different from the size measured in the rest frame of a muon, so it is easier for a muon to reach Earth's surface
    (C) The mass of a muon as measured on Earth is different from the mass measured in the rest frame of a muon, so the acceleration due to gravity is different.
    (D) Energies of muons as measured on Earth are different from the energies measured in the rest frame of a muon, so different interactions occur with the atmosphere.

30. Which of the following could be the decay products of a negatively charged muon?

    (A) An electron and a positron
    (B) A neutron and an electron
    (C) Two electrons and a proton
    (D) An electron, a neutrino, and an antineutrino

31. In the most common form of muon decay, the total mass of the measured products is found to be much less than the mass of the muon. Which of the following best explains the measured discrepancy in mass?

    (A) The energy equivalent of the lost mass is transferred to the products, so they have a greater total potential energy than the muon had.
    (B) The energy equivalent of the lost mass is transferred to the products, so they have a greater total kinetic energy than the muon had.
    (C) Relativistic effects cause the total muon energy to be measured as larger and the total product energy to be measured as smaller than the same measurements in the reference frame of the particles.
    (D) Relativistic effects cause the muon mass to be measured as larger and the product masses to be measured as smaller than the same measurements in the reference frame of the particles.

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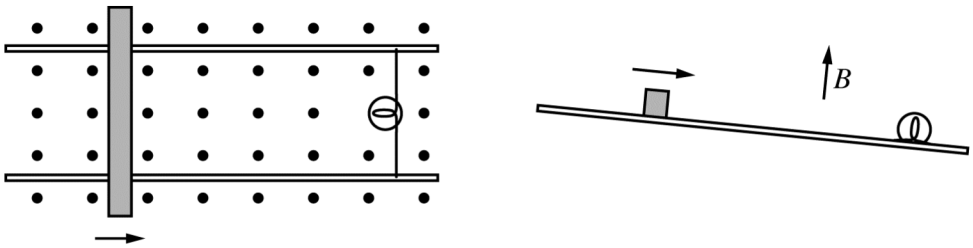

Top View Side View

32. The system in the figure above consists of a conducting bar moving with negligible friction along a pair of stationary parallel conducting rails that are connected to a lightbulb, forming a circuit. The rails are slightly tilted from horizontal, and the system is in a uniform magnetic field B that is perpendicular to the plane of the rails and pointing up. As the bar slides downward along the rails, a current is induced that causes the bulb to light. Which of the following statements is true about the energy in the system or the forces exerted on the sliding bar?

(A) The gravitational potential energy of the circuit-magnetic field-Earth system is converted only to kinetic energy of the sliding bar.
(B) The gravitational potential energy of the circuit-magnetic field-Earth system increases due to the work done by the magnetic field on the moving bar.
(C) The motion of the bar is determined by the magnetic force due to the induced current and a component of the force of gravity, which are in the same direction.
(D) The motion of the bar is determined by the magnetic force due to the induced current and a component of the force of gravity, which are in opposite directions.

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33. Which type of electromagnetic radiation, visible light $\left(\lambda \approx 10^{-6}\ \text{m}\right)$ or microwaves $\left(\lambda \approx 10^{-2}\ \text{m}\right)$, exhibits more diffraction when interacting with everyday objects, and why?

(A) Visible light, because there is more visible light emitted from everyday objects than there are microwaves.
(B) Visible light, because its waves have a higher energy than microwaves do.
(C) Microwaves, because they are easier to produce than visible light waves, since visible light preferentially behaves like photons.
(D) Microwaves, because their wavelength is longer than that of visible light.

34. A container is filled with an ideal gas at a high gauge pressure and sealed with a cork of radius R that has been inserted into a circular opening of radius R. The force exerted on the cork by the gas has magnitude F. If the radii of the opening and cork are increased to $2R$, what will be the magnitude of the new force exerted on the cork by the gas?

(A) $F/4$
(B) $F/2$
(C) $2F$
(D) $4F$

Voltmeter Reading (V)	Ohmmeter Reading (Ω)
9.9	100
9.8	50
9.1	10
8.3	5
6.7	2

35. A student has a nonideal 10 V battery, some resistors, a voltmeter, and an ohmmeter and wants to determine the internal resistance of the battery and whether the resistors are ohmic. The student uses the ohmmeter to measure the resistance of each resistor. The student then connects the voltmeter across the battery terminals and one at a time connects each resistor to the battery. The table above shows the student's data. Which of the following indicates what can be concluded about the battery and resistors?

(A) The internal resistance of the battery is negligible, and the resistors are nonohmic.
(B) The internal resistance of the battery is negligible, and the ohmic nature of the resistors cannot be confirmed using only one potential difference measurement each.
(C) The internal resistance of the battery is about $1\ \Omega$, and the resistors are ohmic.
(D) The internal resistance of the battery is about $1\ \Omega$, and the ohmic nature of the resistors cannot be confirmed using only one potential difference measurement each.

36. An object is placed 25.0 cm in front of a convex mirror with a radius of curvature of 30.0 cm. Where is the image located?

(A) 9.38 cm behind the mirror
(B) 13.6 cm behind the mirror
(C) 37.5 cm in front of the mirror
(D) 150 cm in front of the mirror

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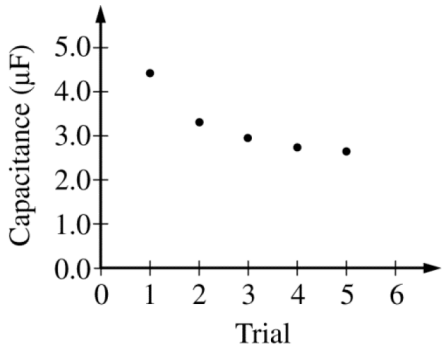
Directions: For each of the questions or incomplete statements below, two of the suggested answers will be correct. For each of these questions, you must select both correct choices to earn credit. No partial credit will be earned if only one correct choice is selected. Select the two that are best in each case and then fill in the corresponding circles that begin with number 131 on the answer sheet.



131. A student conducts an experiment to investigate the relationship between the geometry of a capacitor and its capacitance. The student can adjust both the area and separation of the capacitor plates. The capacitance is measured using the capacitance setting on a digital multimeter. The student conducts five trials, numbering them in order from 1 to 5, and creates the graph of capacitance as a function of trial number shown above. Which of the following describes how the capacitor geometry could have been changed between successive trials to generate this data? Select two answers.

(A) Both the plate area and separation were increased.
(B) The plate area was increased, and the plate separation was held constant.
(C) The plate area was held constant, and the plate separation was increased.
(D) The plate area was increased, and the plate separation was decreased.

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132. In scenario 1, a test charge is placed at location P in an external electric field. In scenario 2, the test charge is removed and a new test charge with a slightly different charge is placed at location P. Which of the following quantities will be the same in both scenarios? Select two answers.

(A) The electric potential energy of the test charge-field system
(B) The electric potential at location P
(C) The electric field at location P
(D) The electric force exerted on the test charge

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133. Which of the following proposed reactions are allowed by the law of conservation of electric charge? Select two answers.

(A) $n \rightarrow p^{+} + e^{-} + \nu$

(B) ${}^{3}_{1}\mathrm{H} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{7}_{4}\mathrm{Be} + \gamma$

(C) ${}^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$

(D) ${}^{234}_{90}\mathrm{Th} \rightarrow {}^{234}_{89}\mathrm{Ac} + e^{-} + \nu$

134. Which of the following data can be used to calculate the focal length of a thin converging lens? Select two answers.

(A) The distance from the lens to the object and the distance from the lens to the image
(B) The distance from the lens to the object and the magnification and orientation of the image
(C) The distance from the lens to the object and the height and orientation of the image
(D) The distance from the lens to the image and the height and orientation of the image

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GO ON TO THE NEXT PAGE.

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.

MAKE SURE YOU HAVE DONE THE FOLLOWING.

- **PLACED YOUR AP NUMBER LABEL ON YOUR ANSWER SHEET**
- **WRITTEN AND GRIDDED YOUR AP NUMBER CORRECTLY ON YOUR ANSWER SHEET**
- **TAKEN THE AP EXAM LABEL FROM THE FRONT OF THIS BOOKLET AND PLACED IT ON YOUR ANSWER SHEET.**

AP® Physics 2: Algebra-Based Exam

SECTION II: Free Response

2019

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

At a Glance

Total Time
1 hour and 30 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: 27% 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.

Form I
Form Code 4PBP4-S

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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 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 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 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

$v_x = v_{x0} + a_x t$

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

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

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

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

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

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

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

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

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

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

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

$\omega = \omega_0 + \alpha t$

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

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

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

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

$L = I\omega$

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

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

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

a = acceleration
A = amplitude
d = distance
E = energy
F = force
f = frequency
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
y = height
α = angular acceleration
μ = coefficient of friction
θ = angle
τ = torque
ω = angular speed

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

$\Delta U_g = mg\,\Delta y$

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

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

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

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

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

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

ELECTRICITY AND MAGNETISM

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

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

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

$\Delta U_E = q\Delta V$

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

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

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

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

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

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

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

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

$P = I\,\Delta V$

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

$R_s = \sum_i R_i$

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

$C_p = \sum_i C_i$

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

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

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

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

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

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

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

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

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

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

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

AP® PHYSICS 2 EQUATIONS

FLUID MECHANICS AND THERMAL PHYSICS

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

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

$P = P_0 + \rho gh$

$F_b = \rho Vg$

$A_1 v_1 = A_2 v_2$

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

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

$PV = nRT = Nk_BT$

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

$W = -P\Delta V$

$\Delta U = Q + W$

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

WAVES AND OPTICS

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

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

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

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

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

$\Delta L = m\lambda$

$d\sin\theta = m\lambda$

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

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

GEOMETRY AND TRIGONOMETRY

Rectangle
$A = bh$

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

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

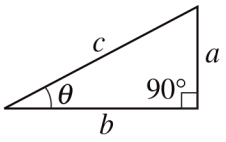
Rectangular solid
$V = \ell wh$

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

Time—1 hour and 30 minutes

4 Questions

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

1. (10 points, suggested time 20 minutes)

   A group of students is asked to design a heater for an indoor swimming pool using an electrically insulated current-carrying wire. The energy from the wire heats the water. The heater should deliver 10 kW of power to the water in the pool.

   (a) The students use wire that has a cross-sectional area of $1.3 \times 10^{-5}\ \text{m}^2$ and a resistivity of $3.0 \times 10^{-6}\ \Omega\text{•m}$. They have access to a 240 V power supply. Calculate the length of the wire needed to construct the heater.

   (b) The wire is completely submerged in the water, and the heater is turned on. After a while, both the water and the air above it are noticeably warmer.

      i. Identify and describe both the primary process that transfers energy through the wire's electrical insulation and the primary process that transfers energy through the water.

      Electrical Insulation

      Water

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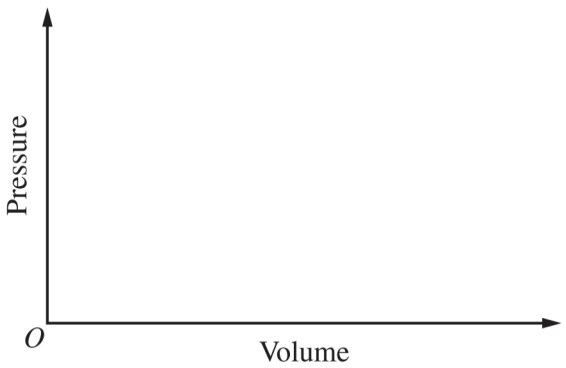
ii. The door to the pool area is open, and the air outside is colder than the air in the pool area. The heater must remain on to maintain a constant water temperature that is greater than the air temperature in the pool area. Explain how the first and second laws of thermodynamics can be applied to show that this must occur.

The door to the pool area is then closed so that energy transfer and air transfer into and out of the area are negligible. After some time the air in the pool area becomes warmer.

(c) On the graph below, sketch the thermodynamic process that the air in the pool area undergoes as it becomes warmer. Compare the amount Q of energy transferred to the air by heating to the change ΔU in the air's internal energy.

Sketch the Process



Compare Q and ΔU

(d) When the temperature of the room is 276 K, the air pressure is 1.0×10^5 Pa. Calculate the force exerted by the air in the room on a door that measures 2.0 m by 0.90 m when the temperature of the room is 310 K.

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GO ON TO THE NEXT PAGE.

2. (12 points, suggested time 25 minutes)

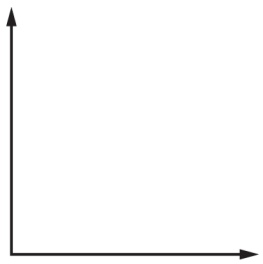
Students use a lightbulb, a screen, and a meterstick to determine the focal length of a concave mirror from a graph.

(a)

i. Describe a procedure that could be used to collect appropriate data and the measurements to be taken.

- Label the axes below with the quantities to be graphed.
- Draw a clearly labeled diagram of the experimental setup.
- Describe the procedure and indicate the quantities to be measured.

Label the Axes



Describe the Procedure

Draw a Diagram

ii. Describe how the focal length can be determined from the graph.

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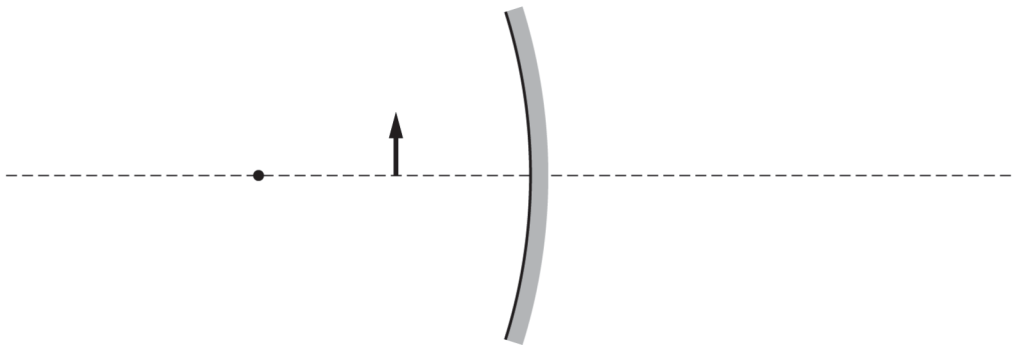
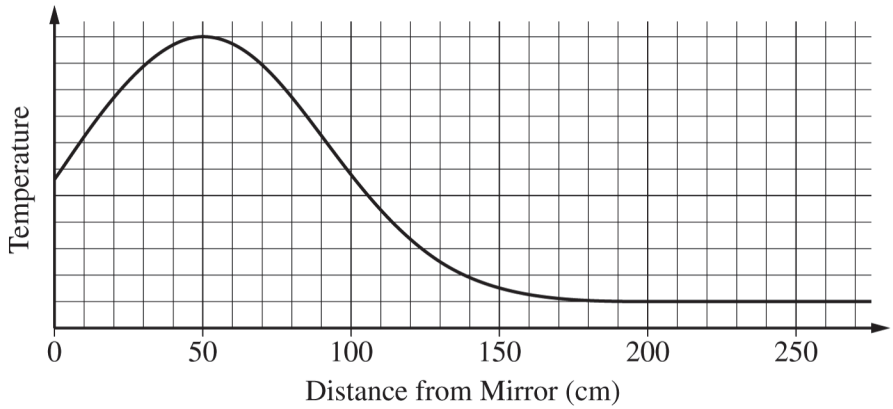
(b) The figure below represents one arrangement of a concave mirror and an object. The dot represents the focal point of the mirror and the arrow represents the object. Draw a ray diagram to illustrate the formation of the image that includes at least two rays and the resulting image.



(c) Some students take the concave mirror outside and hold it with the concave side facing the Sun. The students want to locate the image of the Sun. They measure the temperature of the air in front of the mirror along the principal axis and graph the air temperature as a function of distance from the mirror. The graph below is their best-fit curve to the data.



i. Based on the curve, at what distance from the mirror would you expect to find the image of the Sun?

ii. Use a relevant equation to explain how your response to (c)(i) relates to the focal length of the mirror.

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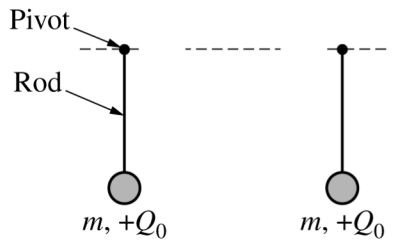

Figure 1

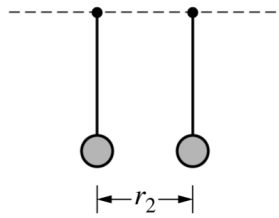

Figure 2

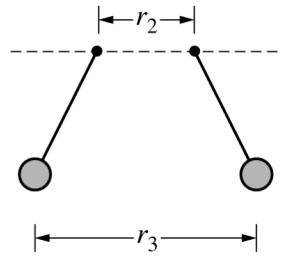

Figure 3

Note: Figure 1 not drawn to scale.

3. (12 points, suggested time 25 minutes)

Two insulating spheres with mass *m* and charge $+Q_0$ are near Earth's surface, suspended vertically from identical light, stiff rods with pivots at the top, as shown in Figure 1. The spheres are initially far apart. The pivots are locked so the rods remain vertical while the spheres are moved together by external forces until the spheres are a distance r_2 from each other, as shown in Figure 2. Finally, the pivots are held a distance r_2 apart and unlocked, and the rods are allowed to swing out until the spheres momentarily come to rest a distance r_3 apart, as shown in Figure 3. The pivots are always at the same height.

(a) Consider the system that includes only the two spheres, with Earth external to the system.

i. Write an expression for the work done moving the spheres horizontally from far apart to a separation of r_2. Express your answer in terms of Q_0, r_2, and physical constants, as appropriate.

ii. The total energy of the two-sphere system (with Earth still external to the system) changes as the system goes from the configuration in Figure 2 to the configuration in Figure 3. Explain how the energy changes in terms of the forces exerted on the system.

(b) Now consider the system that contains both Earth and the two spheres. What is the work done on this new system for the changes in sphere position described in parts (a)(i) and (ii) ? Explain your reasoning.

Part (a)(i) Part (a)(ii)

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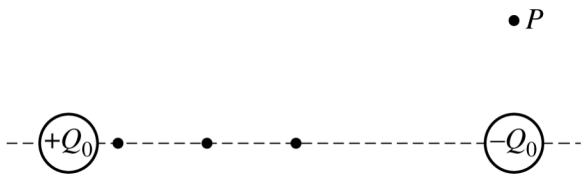
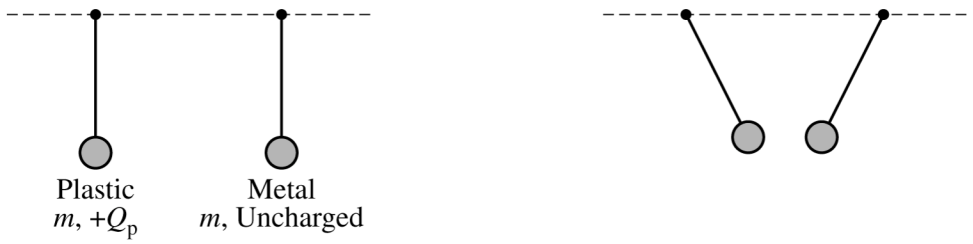
(c) The rods are now held fixed at the positions shown in Figure 3, and negative charge is added to the right sphere so its net charge is $-Q_0$. The circles in the figure below represent the spheres. On the figure, do the following.

- Draw a single vector originating on point *P* that represents the net electric field at that point.
- For each of the dots on the horizontal dashed line, draw an isoline of electric potential that goes through the dot.



(d) In a new situation, the two spheres still have the same mass *m*, but the left sphere is made of plastic and has charge $+Q_p$ and the right sphere is made of metal and is uncharged. The spheres are brought near but do not touch, as shown below on the left. When the rods are allowed to pivot, the spheres move toward each other, as shown on the right. In terms of charge distributions, explain why the force between the spheres is attractive.



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4. (10 points, suggested time 20 minutes)

A uranium-231 nucleus can decay into an alpha particle and a thorium-227 nucleus.

(a) Nuclei in a 500 g sample of uranium-231 undergo this decay. The amount of uranium-231 remaining is measured at the same time every day for a period of eight days. The table below shows the data obtained.

Amount of uranium-231 (g)	500	424	359	305	258	219	186	157	134
Time (days)	0	1	2	3	4	5	6	7	8

According to the data, what is the approximate half-life of uranium-231 ?

(b) One uranium-231 nucleus decays. The uranium nucleus has a mass of 3.835609×10^{-25} kg and is moving in the $-x$-direction with a kinetic energy of 2.5×10^{-13} J before the decay. The thorium nucleus has a mass of 3.769064×10^{-25} kg , and the alpha particle has a mass of 0.066447×10^{-25} kg .

i. Calculate the velocity of the center of mass of the two decay products immediately after the decay. Be sure to specify the direction of the velocity.

ii. Calculate the amount of energy released in the decay of the uranium-231 nucleus.

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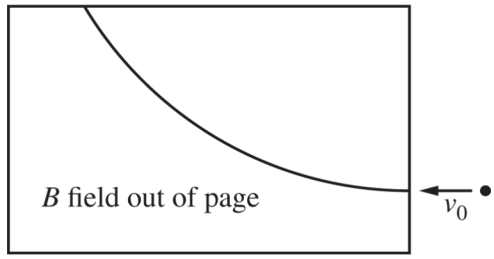
GO ON TO THE NEXT PAGE.



(c) An alpha particle is moving to the left with speed v_0 when it enters a region containing a uniform magnetic field of known magnitude B directed out of the page. The figure above shows the path of the alpha particle through the region. In a coherent paragraph-length response, explain how the charge-to-mass ratio and sign of the charge of the alpha particle can be verified by using the effect of the magnetic field on the path of the particle. Equations or diagrams that support your written description may be included.

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THIS PAGE MAY BE USED FOR SCRATCH WORK.

STOP

END OF EXAM

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

THE FOLLOWING INSTRUCTIONS APPLY TO THE COVERS OF THE SECTION II BOOKLET.

- **MAKE SURE YOU HAVE COMPLETED THE IDENTIFICATION INFORMATION AS REQUESTED ON THE FRONT AND BACK COVERS OF THE SECTION II BOOKLET.**
- **CHECK TO SEE THAT YOUR AP NUMBER LABEL APPEARS IN THE BOX ON THE FRONT COVER.**
- **MAKE SURE YOU HAVE USED THE SAME SET OF AP NUMBER LABELS ON ALL AP EXAMS YOU HAVE TAKEN THIS YEAR.**

Answer Key for AP Physics 2: Algebra-Based

Practice Exam, Section I

Question 1: C
Question 2: B
Question 3: C
Question 4: B
Question 5: A
Question 6: B
Question 7: B
Question 8: D
Question 9: B
Question 10: C
Question 11: D
Question 12: C
Question 13: B
Question 14: A
Question 15: A
Question 16: B
Question 17: A
Question 18: C
Question 19: C
Question 20: D
Question 21: C
Question 22: D
Question 23: A
Question 24: D
Question 25: C
Question 26: D
Question 27: D
Question 28: C
Question 29: A
Question 30: D
Question 31: B
Question 32: D
Question 33: D
Question 34: D
Question 35: D
Question 36: A
Question 131: A,C
Question 132: B,C
Question 133: A,C
Question 134: A,B

Multiple-Choice Section for Physics 2
2019 Course Framework Alignment and Rationales

Question 1

Science Practice	Learning Objective	Topic
6.4	7.C.3.1	Wave Functions and Probability

(A)	Incorrect. In order for the sample of element Y to have $0.1\ \text{g}$ remaining, 300 days must pass. In 300 days, the sample of element X has $0.0125\ \text{g}$ remaining, which is inconsistent with the final mass measurement given.
(B)	Incorrect. This choice represents the assumption that both the sample of element X and the sample of element Y will have the same mass remaining after the same amount of time. Since elements X and Y have different half-lives, there will be different amounts of each remaining between the initial and final measurements.
(C)	**Correct**. After 50 days (one half-life), the sample of element X has $0.4\ \text{g}$ remaining. After 100 days (two half-lives), the sample of element X has $0.2\ \text{g}$ remaining, so 100 days is the time between the initial and final measurements of the samples' masses. Element Y has a half-life of 100 days, so there will be $0.4\ \text{g}$ remaining at the time of the final measurement.
(D)	Incorrect. This choice represents the assumption that the amount of element Y will not change, while the amount of element X changes. From the initial to the final measurements of element X, it is found that 100 days have passed. Element Y has a half-life of 100 days, so there will be half as much of element Y remaining at the time of the final measurement.

Question 2

Science Practice	Learning Objective	Topic
1.4	5.B.7.3	Internal Energy and Energy Transfer

(A)	Incorrect. If gas molecules were removed from the container, the pressure of the gas would decrease, which is inconsistent with the increase in pressure seen in the graph.
(B)	**Correct**. In order for both the pressure and volume to increase, energy needs to be added to the system. This choice represents the only process that could plausibly result in an increase in pressure of the gas in the container.
(C)	Incorrect. Removing the piston entirely will open the system to the surrounding environment. This allows the volume of the gas to increase, but it also means that the pressure of the gas will decrease, which is not what the graph shows.
(D)	Incorrect. Free expansion of a gas results in an increase in volume, which is consistent with the graph. However, it will result in a decrease in pressure, not the increase in pressure that is shown in the graph.

Question 3

Science Practice	Learning Objective	Topic
1.5	6.B.3.1	Periodic Waves

(A)	Incorrect. The wavelength in this choice is correct, but the amplitude indicated in the equation is twice the amplitude of the wave. The amplitude is the maximum displacement from zero, not the difference between the maximum displacement and minimum displacement.
(B)	Incorrect. The amplitude and the wavelength in this choice are incorrect. The amplitude is the maximum displacement from zero, not the difference between the maximum displacement and minimum displacement. The wavelength is the distance between successive peaks, not the distance between peak and trough.
(C)	**Correct**. The general equation for a wave in terms of position is $A\cos(2\pi x/\lambda)$, where λ is the wavelength of the wave. From the graph, it can be determined that the amplitude of the wave $5\ \text{V/m}$ and the wavelength is $10\ \text{m}$.
(D)	Incorrect. In this choice the amplitude of the wave is correct, but the wavelength is incorrect.

Question 4

Science Practice	Learning Objective	Topic
1.1|1.4|6.4|3.2|5.3	4.E.3.3|4.E.3.5	Charge Distribution - Friction, Conduction, and Induction

(A)	Incorrect. The sphere is metal, so any net charge will be distributed uniformly across the surface. Therefore, the same effect will be observed regardless of which side of the sphere the rod is on.
(B)	**Correct**. If the sphere is negatively charged and attracted to a positively charged rod, a negatively charged rod will repel the sphere. If the sphere was uncharged, it would be attracted to both the positively and negatively charged rods because of charge polarization.
(C)	Incorrect. Regardless of whether the sphere is charged, the force exerted by the rod on the sphere will decrease with increasing distance.
(D)	Incorrect. The force between the sphere and the rod would be stronger if the rod's charge was doubled, regardless of whether the sphere was charged or uncharged.

Question 5

Science Practice	Learning Objective	Topic
6.4	4.C.3.1	Heat and Energy Transfer

(A)	**Correct**. Container X contains atoms with a higher average kinetic energy, and hence temperature, than those in container Y, so the net energy transfer is from container X to container Y.
(B)	Incorrect. The type of atoms in each container does not influence the direction of energy transfer between the containers. Only the average kinetic energy of the atoms, which is equivalent to temperature, determines how the energy is transferred.
(C)	Incorrect. By reaching equilibrium, the atoms in both containers reach the same temperature and therefore have the same average kinetic energy.
(D)	Incorrect. The statement that all atoms in the system will behave one way or another is inaccurate. As a result of the interactions between the containers, some of the atoms in container X may speed up and some in Y may slow down. The average kinetic energy of the atoms in container X will decrease, while the average kinetic energy of the atoms in container Y will increase.

Question 6

Science Practice	Learning Objective	Topic
6.2	6.A.1.3	Waves

(A)	Incorrect. If the polarizing lenses are in the same orientation, then the second lens will have no effect because the light coming through the first lens will already be polarized in the same orientation.
(B)	**Correct**. Since both lens A and lens B are polarized in the same orientation, overlapping them perpendicularly will block most of the light from passing through. The light passing through the first lens will be polarized perpendicular to the orientation of the second lens.
(C)	Incorrect. Since lens C is not polarized, overlapping lens A or lens B with lens C in any orientation will do nothing to block the light from passing through.
(D)	Incorrect. If lens C was polarized like lens A and lens B, this orientation would work to block light from passing through. Since lens C is not polarized, overlapping it with either of the other lenses in any orientation will do nothing to block the light from passing through.

Question 7

Science Practice	Learning Objective	Topic
6.4|7.2	2.E.2.2	Isolines and Electric Fields

(A)	Incorrect. The observations about the topographical map are correct in this choice, but the electric potential interpretations are incorrect. The arrows move away from the region in the upper left and toward the region in the lower right, indicating that a positive charge exists in the upper left and a negative charge exists in the lower right.
(B)	**Correct**. In the upper left, the arrows are moving away from the region. This indicates a peak, since the arrows are directed from high elevation to low elevation. Similarly, this also represents a positive charge because the arrows point from high to low potentials. In the lower right, the arrows are pointed toward the region, indicating that either a valley or a negative charge could exist, depending on the subject of the figure.
(C)	Incorrect. This choice has the given sign convention backward, because both the topographical and the electric potential interpretations of the figure are incorrect.
(D)	Incorrect. The electric potential interpretations of the figure are correct; however, the topographical interpretations of the figure are incorrect. The arrows move away from the region in the upper left and toward the region in the lower right, indicating that a peak exists in the upper left and a valley exists in the lower right.

Question 8

Science Practice	Learning Objective	Topic
1.1|1.4	3.B.2.1	Fluids and Free-Body Diagrams

(A)	Incorrect. This choice suggests that the buoyant force is proportional to the exposed upward-facing surface area of the prism. However, the buoyant force does not depend on any surface areas in contact with the external liquid.
(B)	Incorrect. This choice suggests that the buoyant force is proportional to the surface area of the side of the prism in contact with the bottom of the container. However, in this case there is no relevant force that depends on that area.
(C)	Incorrect. This choice suggests that orientation Z has a larger buoyant force because it is taller than both orientation X and orientation Y. However, the maximum height of the prism does not affect the buoyant force; only the volume affects the force.
(D)	**Correct**. Since all the orientations use the same prism, the volume stays the same in each orientation. The buoyant force is proportional to the volume, so it is the same for all three orientations.

Question 9

Science Practice	Learning Objective	Topic
6.4	6.E.3.3	Refraction, Reflection and Absorption

(A)	Incorrect. While the diagram correctly shows both rays refracting toward the normal, the blue light has a higher index of refraction than the red light does, so the blue light should refract more than the red light does.
(B)	**Correct**. The hollow prism can be assumed to have an index of refraction of 1.0, so the liquid has a higher index of refraction for both blue light and red light. Therefore, the beams will refract toward the normal, with the blue light refracting more than the red light because the blue light has a higher index of refraction.
(C)	Incorrect. The beams would refract toward the normal, not away from the normal, because the indices of refraction in the liquid are greater than in the prism. Furthermore, the blue light would refract more than the red light because it has a larger index of refraction.
(D)	Incorrect. The indices of refraction of the liquid are greater than that of the air in the prism. This means that the beams would refract toward the normal, as shown in this choice.

Question 10

Science Practice	Learning Objective	Topic
2.2	2.D.1.1	Magnetic Fields and Forces

(A)	Incorrect. The magnetic field is pointed toward the top of the page, and the magnetic force on a moving charged object is perpendicular to the magnetic field.
(B)	Incorrect. This would be the case if the particle were an electron, in which case the resulting motion would be opposite that found by using the right-hand rule.
(C)	**Correct**. According to the right-hand rule and the equation $\vec{F} = q\vec{v} \times \vec{B}$, taking the vector product of the velocity with the magnetic field results in the force being in the direction out of the page.
(D)	Incorrect. Magnetic fields exert forces on moving charged objects.

Question 11

Science Practice	Learning Objective	Topic
5.1	7.A.3.3	Pressure, Thermal Equilibrium, and the Ideal Gas Law

(A)	Incorrect. In this choice, the temperature in state B is found by multiplying the temperature in state A by $\frac{V_A}{V_B}$ instead of $\frac{V_B}{V_A}$. This violates the ideal gas law because increasing the volume at a constant pressure corresponds to an increase in temperature.
(B)	Incorrect. This choice suggests that because the pressure is constant the temperature will remain constant. However, the ideal gas law predicts that increasing the volume at a constant pressure corresponds to an increase in temperature.
(C)	Incorrect. This choice suggests that the volume increases by a factor of 2, but it increases by a factor of 5.
(D)	**Correct**. For an enclosed gas, the ideal law states that $PV \propto T$. Applying this relationship to states A and B yields $\frac{P_B T_B}{P_A T_A} = \frac{T_B}{T_A}$. This can be rearranged to find T_B as follows: $T_B = \left(\frac{P_B V_B}{P_A V_A}\right) T_A$. The pressures in states A and B are the same, so the temperature in state B can be found by substituting in the volumes and the temperature in state A. $T_B = \left(\frac{1.00\ \text{m}^3}{0.2\ \text{m}^3}\right)(190\ \text{K}) = 950\ \text{K}$

Question 12

Science Practice	Learning Objective	Topic
6.4	5.B.9.5	Kirchhoff's Loop Rule

(A)	Incorrect. This circuit has two capacitors in series, which are in parallel with a third capacitor. Since two of the capacitors are in series, the circuit will not be able to store as much charge as if the capacitors were all in parallel.
(B)	Incorrect. All three capacitors are in series with each other, so this circuit will store the least charge.
(C)	**Correct**. When capacitors are placed in parallel, the total capacitance of the circuit is the sum of the individual capacitances. The stored charge is given by $\Delta V = QC$, resulting in the circuit with three capacitors in parallel having the largest stored charge.
(D)	Incorrect. Since all three circuits have different configurations of capacitors in series or in parallel, they will each store different amounts of charge.

Question 13

Science Practice	Learning Objective	Topic
6.4|7.2|7.1	7.A.1.1|7.A.2.1	Pressure, Thermal Equilibrium, and the Ideal Gas Law

(A)	Incorrect. This choice includes the incorrect assumption that every gas molecule will behave in the same way. However, some molecules may speed up and some may slow down. It is only on average that the molecules will slow down when the temperature decreases.
(B)	**Correct**. As the temperature decreases, the average kinetic energy of the gas molecules decreases, resulting in a decreased average speed of each molecule. Since their average speed is decreased, the average momentum of each molecule is lower, and the average force exerted by each molecule on the container during collisions decreases. This causes an overall decrease in pressure of the gas.
(C)	Incorrect. The average speed of all the molecules will decrease, not just of those with higher speeds.
(D)	Incorrect. By decreasing the temperature of the gas, the average speed among all of the molecules decreases. If the speeds were more evenly distributed, that might mean that there would be more molecules with high speeds and more with low speeds, but statistically that should not change the average speed among all of the molecules in the gas.

Question 14

Science Practice	Learning Objective	Topic
6.4	2.E.2.1	Isolines and Electric Fields

(A)	**Correct**. Even though point A lies near where the electric potential is zero, it is the point with the highest electric field because the electric field is highest at points where the separation between equipotential lines is lowest.
(B)	Incorrect. This point lies near the highest electric potential, but it does not lie at the highest electric field because the separation between equipotential lines is greater than at point A.
(C)	Incorrect. This point lies in the region where the separation between equipotential lines is greatest, meaning that the electric field at this point is lowest.
(D)	Incorrect. This point lies at the lowest electric potential, but it does not lie in a high electric field because the separation between the equipotential lines is greater than at point A.

Question 15

Science Practice	Learning Objective	Topic
1.1	2.D.2.1	Magnetic Fields and Forces

(A)	**Correct**. According to the right-hand rule, if the current in the wire is directed downward, then the direction of the magnetic field at the right wire is out of the page.
(B)	Incorrect. This would be the correct result if the current in the wire were directed toward the top of the page instead of toward the bottom of the page.
(C)	Incorrect. According to the right-hand rule, the only two possibilities for the direction of the magnetic field at the location of the right wire are into or out of the page.
(D)	Incorrect. This choice represents the direction of the magnetic force, not the field, produced by the current flowing through the left wire.

Question 16

Science Practice	Learning Objective	Topic
6.4|6.4|7.2|6.4	2.C.1.1|3.B.1.4|3.C.2.1	Electric Charges and Fields, Electric Forces and Free Body Diagrams, Describing Electric Force

(A)	Incorrect. According to Newton's third law, the magnitude of the force exerted on the proton by the electron and the magnitude of the force exerted on the electron by the proton are equal to each other.
(B)	**Correct**. The magnitude of the electric force exerted by the proton on the electron and exerted by the electron on the proton are equal. Thus, according to Newton's second law, the acceleration of the less massive body, the electron, will be larger than the acceleration of the proton.
(C)	Incorrect. The proton and the electron are particles and do not have potential energies associated with them. The proton-electron system has a potential energy that is characterized by the charges and separations of the particles.
(D)	Incorrect. Since the accelerations of the proton and electron are not equal, each particle will experience a different change in speed after moving the same distance.

Question 17

Science Practice	Learning Objective	Topic
1.1|2.2|2.2|6.4	3.B.2.1|3.C.2.1	Electric Forces and Free Body Diagrams, Describing Electric Force

(A)	**Correct**. Particle N is equidistant from particles L and M. It is negatively charged, so it is attracted to particle L and repelled by particle M. Therefore, the force exerted by particle L is up and to the left, and the force exerted by particle M is up and to the right. The charge of particle M has a greater magnitude than that of particle L and so exerts a larger force on particle N. Adding the force vectors results in a force up and to the right, with a larger component up than to the right.
(B)	Incorrect. This vector represents a situation in which particle M is closer to the origin than indicated, resulting in a larger horizontal component of the force exerted on particle N.
(C)	Incorrect. This vector represents the motion of particle N, where the signs of the charges of particles L and M are reversed.
(D)	Incorrect. This vector represents a scenario in which the attractive force exerted by particle L on particle N is much greater than the repulsive force exerted by particle M.

Question 18

Science Practice		Learning Objective	Topic
1.4|2.2		5.B.7.3	Heat and Energy Transfer
(A)	Incorrect. There is a nonzero area under the curve between states X and Y, so there is work done.		
(B)	Incorrect. Work is done only between states X and Y, and the pressure during that process is $2P_0$, not P_0.		
(C)	**Correct**. The work done by the processes is equal to the area under the curve. Therefore, the total work done on the gas occurs between states X and Y: $W = -P\Delta V = -2P_0(2V_0 - V_0) = -2P_0V_0$.		
(D)	Incorrect. This choice uses the initial pressure at state W in the calculation for work done on the gas, instead of the pressure during the process from state X to state Y.		

Question 19

Science Practice		Learning Objective	Topic
6.4		5.B.7.1	Heat and Energy Transfer
(A)	Incorrect. In state W, the temperature is twice as high as in state X, meaning that the internal energy in state W is greater than in state X.		
(B)	Incorrect. In state Y, the temperature (according to the ideal gas law) is twice as great as in state X. Therefore, the internal energy in state Y is greater than the internal energy in state X.		
(C)	**Correct**. In states X and Z, the temperature is the same, according to the ideal gas law, which states that $T \propto PV$. Thus, the internal energy is the same in both of these states.		
(D)	Incorrect. Since states X and Z have the same temperature, their internal energies are also the same.		

Question 20

Science Practice	Learning Objective	Topic
1.1	5.B.7.2	Heat and Energy Transfer

(A)	Incorrect. This process results in an increase in temperature, but it is not isovolumetric because the volume of the gas changes.
(B)	Incorrect. This process causes the volume of the gas to increase, likely due to a decrease in temperature, and cannot be considered isovolumetric because the volume changes.
(C)	Incorrect. This process is isovolumetric, but it represents a decrease in temperature, not an increase in temperature.
(D)	**Correct**. Isovolumetric means that the volume of the gas is kept constant. This means that the line from state Z to state M must be vertical on the graph. In order for the temperature to increase, the pressure must increase, meaning that the line should be directed upward.

Question 21

Science Practice	Learning Objective	Topic
2.2|6.4	4.E.5.1|5.B.9.5	Resistance and Capacitance, Kirchhoff's Loop Rule

(A)	Incorrect. This choice would be the effective resistance of the two resistors if the voltage across the $1000\ \Omega$ resistor is used when calculating the current in the battery.
(B)	Incorrect. This choice is the effective resistance of the two resistors in parallel, not the resistance of the variable resistor.
(C)	**Correct**. Using Kirchhoff's loop rule, the voltage across the variable resistor is $5\ \text{V}$, and the battery voltage is $25\ \text{V}$, so the voltage across the $2000\ \Omega$ resistor must be $20\ \text{V}$. Using Ohm's law, it can be seen that the current in the $2000\ \Omega$ resistor (and thus the battery current) is $\frac{20\ \text{V}}{2000\ \Omega} = 10\ \text{mA}$. Therefore, applying Ohm's law to the resistors in parallel shows that the effective resistance of the two resistors is $\frac{5\ \text{V}}{10\ \text{mA}} = 500\ \Omega$. The effective resistance for resistors in parallel is given by $\frac{1}{R_{\text{eff}}} = \frac{1}{R} + \frac{1}{1000\ \Omega}$, therefore $R = 1000\ \Omega$.
(D)	Incorrect. This choice results from a misapplication of Ohm's law in which the voltage across the variable resistor is multiplied by the resistance of the $1000\ \Omega$ resistor.

Question 22

Science Practice	Learning Objective	Topic
2.2	5.B.10.1	Conservation of Energy in Fluid Flow

(A)	Incorrect. The pressures cannot be the same because the water has different speeds at the two points.
(B)	Incorrect. This choice uses the difference between the speeds in the application of Bernoulli's equation instead of the difference between the squares of the speeds.
(C)	Incorrect. This choice uses the square of the difference between the speeds in the application of Bernoulli's equation instead of the difference between the squares of the speeds.
(D)	**Correct**. Applying Bernoulli's equation with no change in height yields $P_X + \frac{1}{2}\rho v_X^2 = P_Y + \frac{1}{2}\rho v_Y^2 P_X - P_Y = \frac{1}{2}\rho v_Y^2 - \frac{1}{2}\rho v_X^2 = \frac{1}{2}\rho\left(v_Y^2 - v_X^2\right)$. Plugging in values yields $6000\ \text{Pa}$.

Question 23

Science Practice	Learning Objective	Topic
1.2|7.2|6.4|1.2	5.B.8.1|6.F.1.1|7.C.4.1	Energy in Modern Physics (Energy in Radioactive Decay and $E = mc^2$), Photoelectric Effect, Wave Functions and Probability

(A)	**Correct**. When an atom absorbs a photon, its energy level increases. Red light has less energy per photon than blue light, and this transition is the lowest energy absorption on the diagram.
(B)	Incorrect. It is correct that the energy level of the atom will increase if it absorbs red light; however, this choice likely represents the absorption of blue light because blue light has more energy per photon than red light.
(C)	Incorrect. When an atom absorbs a photon, its energy level increases, which is the opposite of what is represented by this choice. Likely, this choice represents the atom emitting a higher-energy photon, which would be the blue photon.
(D)	Incorrect. This choice shows the energy level decreasing, which indicates that a photon is emitted, not absorbed.

Question 24

Science Practice	Learning Objective	Topic
1.4|6.4|6.4	4.E.3.4|5.C.2.1	Charge Distribution - Friction, Conduction, and Induction, Conservation of Electric Charge

(A)	Incorrect. This would describe the charges on spheres B and C if sphere A was negatively charged instead of positively charged.
(B)	Incorrect. The spheres are initially isolated and uncharged, so the net charge of the two spheres must be zero.
(C)	**Correct**. When sphere A. is brought near the uncharged spheres, it induces charge separation and sphere B becomes negatively charged and sphere C becomes positively charged.
(D)	Incorrect. Sphere A would induce negative charges to move to sphere B. Also, the spheres are initially isolated and uncharged, so the net charge of the two spheres must be zero.

Question 25

Science Practice	Learning Objective	Topic
6.4|1.4|2.2	3.B.1.4|3.B.2.1|5.B.10.2	Fluids and Free-Body Diagrams, Conservation of Energy in Fluid Flow

(A)	Incorrect. In this case, the Newton's third law pair would be between the buoyant force of the fluid pushing up on the object and the force of the object pushing down on the fluid.
(B)	Incorrect. While the overall force exerted by the fluid is upward, the pressure is normal to the surface of the object, so some fluid pressure is directed upward and some is directed downward.
(C)	**Correct**. The force points upward because the pressure of the fluid increases as the depth of the fluid increases, and therefore the upward pressure on the bottom of the object is greater than the downward pressure on the top of the object.
(D)	Incorrect. The restive force would only apply to a moving object, and it would be opposite the motion of the object.

Question 26

Science Practice	Learning Objective	Topic
5.1	6.E.3.2	Refraction, Reflection and Absorption

(A)	Incorrect. Snell's law shows that the ratio of the indices of refraction is directly proportional to the ratio of the sines of the angles. A graph of the angles themselves will not produce a best-fit line equal to the index of refraction of the unknown medium.
(B)	Incorrect. A graph of the incident angle versus the refracted angle does not produce a best-fit line equal to the index of refraction of the refracted medium. Instead, the sine of the incident angle should be plotted versus the sine of the refracted angle.
(C)	Incorrect. This choice will produce a best-fit line equal to the inverse of the index of refraction of the refracted medium.
(D)	**Correct**. Since the incident medium is air, a best-fit line equal to the index of refraction of the unknown medium is produced by plotting the sine of the incident angle versus the sine of the refracted angle, according to Snell's law.

Question 27

Science Practice	Learning Objective	Topic
1.4	5.C.3.7	Kirchhoff's Junction Rule and the Conservation of Electric Charge

(A)	Incorrect. This choice represents the misconception that the voltage splits evenly between each branch.
(B)	Incorrect. This would be the resistance if the current from the battery is split evenly between the loops and the capacitor is treated like a resistor.
(C)	Incorrect. This choice represents the misconception that the total resistance in each loop must be equal, but the resistance of the branch with the capacitor is unknown.
(D)	**Correct**. After the switch is closed for a long time, the capacitor becomes fully charged and there is no current in the branch with the capacitor. Thus, it is not possible to determine the resistance of the resistor because the potential difference across it is zero.

Question 28

Science Practice	Learning Objective	Topic
1.4	6.E.5.1	Images from Lenses and Mirrors

(A)	Incorrect. This choice cannot produce a real image on the opposite side of the lens because diverging lenses always produce virtual images.
(B)	Incorrect. Diverging lenses always produce virtual images, but the student's observation describes a real image.
(C)	**Correct**. Converging lenses create real magnified images when the object is placed at a point between the focal length and twice the focal length.
(D)	Incorrect. Converging lenses create virtual magnified images when the object is placed inside the focal point.

Question 29

Science Practice	Learning Objective	Topic
6.3|7.1	1.D.3.1	Properties of Waves and Particles

(A)	**Correct**. Time intervals are different when measured in reference frames moving relative to one another. The muons' behavior is governed by the time intervals in their rest frame, so they decay with a half-life of 2.2×10^{-6} s in that frame. Since the muons are moving with respect to Earth, their clocks will run slower than those on Earth. So what the muons measure as a half-life in their frame is longer in Earth's frame, and more muons will reach Earth before decaying than would be expected without relativistic effects.
(B)	Incorrect. It is true that distances are not the same when measured in reference frames moving relative to one another. However, the muons are so small compared to the distances they are traveling that any effect on their size has a negligible effect on their travel times.
(C)	Incorrect. It is true that one can view relativistic effects as increasing the mass of the muons. This would result in an increase in the gravitational force on the muons. However, the muons' acceleration is the force divided by the mass, so there would be no change in their acceleration due to gravity.
(D)	Incorrect. It is true that energies may not be the same when measured in reference frames moving relative to one another. However, that will not affect the observed interactions. For example, if an observer in the rest frame of a muon sees it collide with and bounce off a molecule, leaving the molecule intact, an observer in Earth's frame will not see the molecule split into separate atoms.

Question 30

Science Practice	Learning Objective	Topic
6.4|6.4	5.C.1.1|5.G.1.1	Radioactive Decay

(A)	Incorrect. A positron has a positive charge that is equal in magnitude to the electron charge, so this decay would not conserve charge.
(B)	Incorrect. A neutron is a nucleon, and this decay would not conserve nucleon number.
(C)	Incorrect. A proton is a nucleon, and this decay would not conserve nucleon number.
(D)	**Correct**. The properties of the neutrino and antineutrino cancel. Since the electron has similar properties as the muon except for its mass, this decay can occur with the mass difference converted to energy.

Question 31

Science Practice	Learning Objective	Topic
7.2	4.C.4.1	Mass-Energy Equivalence

(A)	Incorrect. It is true that mass is converted to energy. However, that energy cannot directly become potential energy. A change in potential energy requires a change in the position of objects relative to each other. The products must first gain kinetic energy and move away from each other if their potential energy is to change.
(B)	**Correct**. When the muon decays, some mass is converted to energy. This energy becomes kinetic energy of the products.
(C)	Incorrect. Relativistic effects may cause observers in different reference frames to measure different energies. However, conservation of energy applies in every reference frame. Measurements will not show that energy is conserved in one frame but not another.
(D)	Incorrect. Relativistic effects can be viewed as causing an object to have a greater mass when it is in motion than when it is at rest. These effects do not cause the mass to appear slower.

Question 32

Science Practice	Learning Objective	Topic
6.4|6.4|1.4	3.B.1.4|4.E.2.1|5.B.4.2	Forces Review, Magnetic Flux, Kirchhoff's Loop Rule

(A)	Incorrect. A current is induced in the circuit, so the bulb lights up and dissipates energy as light and heat.
(B)	Incorrect. The gravitational potential energy of the system is determined by the height of the bar above Earth. The height decreases so the gravitational potential energy decreases.
(C)	Incorrect. The forces are not in the same direction. When the direction of the induced current in the bar is determined and the right-hand rule for the magnetic force is applied, it can be seen that the magnetic force is directed up the rails. The component of gravity parallel to the rails is directed down the rails.
(D)	**Correct**. The current induced in the circuit creates a field in the same direction as the given field, to oppose the decrease in flux as the bar moves. That current is counterclockwise in the top view. The right-hand rule applied to the current in the bar and the given field yields a magnetic force directed up the rails. The component of gravity parallel to the rails is directed down the rails.

Question 33

Science Practice	Learning Objective	Topic
6.4|7.2	6.C.4.1	Interference and Diffraction

(A)	Incorrect. Diffraction occurs when waves are incident on an object and is not dependent on the type of radiation an object emits.
(B)	Incorrect. It is true that visible light has higher energy than microwaves. However, the amount of diffraction depends on how close the wavelength is to the size of the object.
(C)	Incorrect. Diffraction does not depend on how easy it is to generate a particular type of radiation. Exhibiting wave or particle characteristics depends on the situation, and no type of radiation preferentially behaves like waves or particles.
(D)	**Correct**. The closer the wavelength of the waves is to the dimension of an object, the more the waves will be diffracted. $10^{-2}\ \text{m}$ is closer to the size of everyday objects than $10^{-6}\ \text{m}$, so microwaves will exhibit more diffraction.

Question 34

Science Practice	Learning Objective	Topic
1.4	7.A.1.2	Pressure, Thermal Equilibrium, and the Ideal Gas Law

(A)	Incorrect. This choice could be obtained by using an incorrect relationship between force and pressure, assuming that the force is pressure divided by area.
(B)	Incorrect. This choice could be obtained by making two errors: incorrectly assuming that the force is pressure divided by area and assuming that the area is proportional to the radius.
(C)	Incorrect. This choice could be obtained by using an incorrect expression for the area, assuming that the area is proportional to the radius.
(D)	**Correct**. The force is pressure times area. The area is proportional to the radius squared. So when the radius is $2R$, the force is $4F$.

Question 35

Science Practice	Learning Objective	Topic
5.1|5.3	5.B.9.7	Kirchhoff's Loop Rule

(A)	Incorrect. If the internal resistance of the battery was negligible, the battery would always supply the same potential difference and the voltmeter reading would not change. For an ohmic resistor, $\Delta V = IR$. To determine whether a resistor is ohmic, multiple data points are needed for the same resistor to see whether they show a linear behavior. So, one cannot conclude that the resistors are nonohmic.
(B)	Incorrect. It is correct that nothing can be said about the ohmic nature of the resistors. Given that $\Delta V = IR$ for an ohmic resistor, multiple data points are needed for the same resistor to see whether they show a linear behavior. If the internal resistance of the battery was negligible, the battery would always supply the same potential difference and the voltmeter reading would not change.
(C)	Incorrect. It is correct that the battery has internal resistance, since the voltmeter reading changes as different resistors are connected. One set of values can be used to calculate the internal resistance: $I = 9.9\ \text{V} / 100\ \Omega = 0.099\ \text{A}$, so $10\,\text{V} - (0.099\ \text{A})r = 9.9\ \text{V}$ and $r \approx 1\ \Omega$. For an ohmic resistor, $\Delta V = IR$. To determine whether a resistor is ohmic, multiple data points are needed for the same resistor to see whether they show a linear behavior. So, one cannot conclude that the resistors are nonohmic.
(D)	**Correct**. The voltmeter reading changes as different resistors are connected, which means that there is a potential difference across some additional resistance, namely the internal resistance of the battery. One set of values can be used to calculate the internal resistance: $I = 9.9\ \text{V} / 100\ \Omega = 0.099\ \text{A}$, so $10\,\text{V} - (0.099\ \text{A})r = 9.9\ \text{V}$ and $r \approx 1\ \Omega$. For an ohmic resistor, $\Delta V = IR$. To determine whether a resistor is ohmic, multiple data points are needed for the same resistor to see whether they show a linear behavior. So, nothing can be said about the ohmic nature of the resistors.

Question 36

Science Practice	Learning Objective	Topic
1.4|2.2	6.E.4.2	Images from Lenses and Mirrors

(A)	**Correct**. The focal length is half the radius of curvature and is negative for a convex mirror. So, the correct calculation is $\frac{1}{s_i} = -\frac{1}{15\text{ cm}} - \frac{1}{25\text{ cm}} = \frac{-5-3}{75\text{ cm}} = -\frac{8}{75\text{ cm}}$. Thus, $s_i = -\frac{75\text{ cm}}{8} = -9.38\text{ cm}$, with the negative indicating that the image is behind the mirror.
(B)	Incorrect. This choice results from incorrectly using 30 cm as the focal length, when it is actually half that number, but correctly substituting it as a negative number. This incorrect calculation gives $\frac{1}{s_i} = -\frac{1}{30\text{ cm}} - \frac{1}{25\text{ cm}} = \frac{-5-6}{150\text{ cm}} = -\frac{11}{150\text{ cm}}$, yielding $s_i = -\frac{150\text{ cm}}{11} = -13.6\text{ cm}$, with the negative indicating that the image is behind the mirror.
(C)	Incorrect. This choice results from using the correct number for the focal length but neglecting that the focal length is negative for a convex mirror. This incorrect calculation gives $\frac{1}{s_i} = \frac{1}{15\text{ cm}} - \frac{1}{25\text{ cm}} = \frac{5-3}{75\text{ cm}} = \frac{2}{75\text{ cm}}$, yielding $s_i = \frac{75\text{ cm}}{2} = 37.5\text{ cm}$, with the positive indicating that the image is in front of the mirror.
(D)	Incorrect. This choice results from incorrectly using 30 cm as the focal length, when it is actually half that number, but correctly substituting it as a negative number. Also, the term for the object distance is included with the wrong sign. This incorrect calculation gives $\frac{1}{s_i} = -\frac{1}{30\text{ cm}} + \frac{1}{25\text{ cm}} = \frac{-5+6}{150\text{ cm}} = \frac{1}{150\text{ cm}}$, yielding $s_i = 150\text{ cm}$, with the positive indicating that the image is in front of the mirror.

Question 131

Science Practice	Learning Objective	Topic
5.1	4.E.4.3	Resistance and Capacitance

(A)	**Correct**. The equation relating capacitance and the geometry of the capacitor is $C = \frac{\varepsilon_0 A}{d}$. If area A is constant and plate separation d increases, then capacitance C decreases.
(B)	Incorrect. If area A increases and plate separation d is constant, then capacitance C increases.
(C)	**Correct**. If both area A and plate separation d increase, then capacitance C can decrease if the separation increases by a larger factor than the area.
(D)	Incorrect. If area A increases and plate separation d decreases, then capacitance C increases.

Question 132

Science Practice	Learning Objective	Topic
6.4|1.4|6.4|7.2	2.C.1.1|5.B.4.2|5.B.5.4	Electric Charges and Fields, Conservation of Electric Energy

(A)	Incorrect. The electric potential energy of the test charge-field system is the value of the test charge times the electric potential at location P. This will change when the value of the test charge changes.
(B)	**Correct**. By definition, a test charge does not have a significant effect on any electrical properties of the entities in its vicinity. The electric potential is a property of the field, so a slight change in the value of the test charge will not change the electric potential at location P.
(C)	**Correct**. A test charge, by definition, is very small and does not have a significant effect on any electrical properties of the entities in its vicinity. A slight change in the value of the test charge will not change the electric field at location P.
(D)	Incorrect. The electric force exerted on the test charge is the value of the test charge times the electric field at location P. This will change when the value of the test charge changes.

Question 133

Science Practice	Learning Objective	Topic
6.4|6.4	5.C.1.1|5.G.1.1	Radioactive Decay

(A)	**Correct**. The neutron n and the neutrino ν are uncharged. The single positive charge of the proton p and the single negative charge of the electron e cancel. Thus both sides of the equation have zero net charge.
(B)	Incorrect. The gamma ray has no charge. $1 + 2 \neq 4$, so charge is not conserved.
(C)	**Correct**. The charges on the nuclei are denoted by the atomic number, the lower number in the equation. The number on the right equals the sum of the numbers on the left: $92 = 90 + 2$. Therefore, charge is conserved.
(D)	Incorrect. The neutrino has no charge. $90 \neq 89 - 1$, so charge is not conserved.

Question 134

Science Practice	Learning Objective	Topic
4.1	6.E.5.2	Images from Lenses and Mirrors

(A)	**Correct**. Given the object distance s_o and the image distance s_i, the lens equation $\frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f}$ can be used to calculate the focal length.
(B)	**Correct**. Given the object distance s_o and the magnification M, the equation $M = \left\|\frac{s_i}{s_o}\right\|$ can be used to determine the absolute value of the image distance s_i. The orientation of the image indicates whether the image should be a positive or a negative value when the lens equation $\frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f}$ is then used to calculate the focal length.
(C)	Incorrect. This is not enough information. The height of the image cannot be used to compare the object and image without also knowing the object height.
(D)	Incorrect. This is only information about the image. Some information about the object is needed to use the relevant equations for lenses.

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Question 1

10 points total **Distribution of points**

A group of students is asked to design a heater for an indoor swimming pool using an electrically insulated current-carrying wire. The energy from the wire heats the water. The heater should deliver 10 kW of power to the water in the pool.

(a) LO 4.E.4.1, SP 2.2
2 points

The students use wire that has a cross-sectional area of $1.3 \times 10^{-5}\ \text{m}^2$ and a resistivity of $3.0 \times 10^{-6}\ \Omega\text{•m}$. They have access to a 240 V power supply. Calculate the length of the wire needed to construct the heater.

For applying a complete set of relevant equations that allow the length ℓ to be calculated from the given quantities, and either combining them algebraically or sequentially substituting values		1 point
For correct substitutions of power, area, resistivity, and potential difference (all four values)		1 point
$\Delta V = IR$, $R = \rho\ell/A$, $P = I\Delta V$		
Combining equations method:		
$\ell = \Delta V^2 A/\rho P$		
$\ell = (240\ \text{V})^2\left(1.3 \times 10^{-5}\ \text{m}^2\right)/\left(3.0 \times 10^{-6}\ \Omega\text{•m}\right)\left(1.0 \times 10^{4}\ \text{W}\right)$		
$\ell = 25\ \text{m}$		
Sequential substitution method:		
$I = P/\Delta V = 1.0 \times 10^{4}\ \text{W}/240\ \text{V} = 42\ \text{A}$		
$R = V/I = 240\ \text{V}/42\ \text{A} = 5.7\ \Omega$		
$\ell = RA/\rho = (5.7\ \Omega)\left(1.3 \times 10^{-5}\ \text{m}^2\right)/3.0 \times 10^{-6}\ \Omega\text{•m}$		
$\ell = 25\ \text{m}$		

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Question 1 (continued)

Distribution of points

(b)

The wire is completely submerged in the water, and the heater is turned on. After a while, both the water and the air above it are noticeably warmer.

i) LO 5.B.6.1, 1.2
2 points

Identify and describe both the primary process that transfers energy through the wire's electrical insulation and the primary process that transfers energy through the water.

Electrical Insulation Water

For describing the process of conduction and indicating it is the primary process by which energy is transferred through the insulation		1 point
For describing the process of convection and indicating it is the primary process by which energy is transferred through the water		1 point
Example description: Energy is transferred through the insulation primarily by interaction between neighboring particles. Particles near the wire gain energy and vibrate more, interact with nearby particles via 'collisions' and can cause them to vibrate more, and so forth. In the water, the primary mode is through bulk motion of the water. Hot water is slightly less dense and rises, causing colder water to sink. This continually brings energy to the top of the water.		

ii) LO 5.B.7.1, 6.4, SP 7.2; LO 7.B.2.1, SP 7.1
2 points

The door to the pool area is open, and the air outside is colder than the air in the pool area. The heater must remain on to maintain a constant water temperature that is greater than the air temperature in the pool area. Explain how the first and second laws of thermodynamics can be applied to show that this must occur.

For correctly addressing the flow of equal amounts of energy into and out of the air or water		1 point
For correctly addressing the spontaneous flow of energy from hot to cold objects		1 point
Example explanation: The 2nd law of thermodynamics states that energy naturally moves from hotter to cooler objects, so the water transfers energy to the air. To keep the temperature of the water constant, the rate of energy transfer to the water must be the same as the rate at which energy leaves the water and goes into the air in order to satisfy the 1st law of thermodynamics		
Claim (given): The heater must remain on to maintain a constant water temperature that is greater than the air temperature in the pool area. Evidence 1: The 2nd law of thermodynamics states that energy naturally moves from hotter to cooler objects. Reasoning 1: The water transfers energy to the air. Evidence 2: The 1st law of thermodynamics must be satisfied when keeping the temperature of the water constant. Reasoning: The rate of energy transfer to the water must be the same as the rate at which energy leaves the water and goes into the air.		

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Question 1 (continued)

Distribution of points

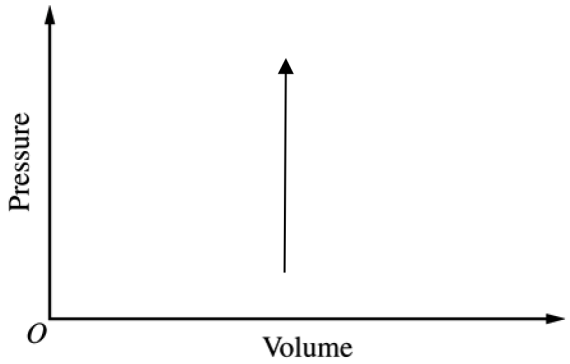
The door to the pool area is then closed so that energy transfer and air transfer into and out of the area are negligible. After some time the air in the pool area becomes warmer.

(c) LO 5.B.7.2, SP 1.1; LO 5.B.7.1, SP 6.4, 7.2)
2 points

On the graph below, sketch the thermodynamic process that the air in the pool area undergoes as it becomes warmer. Compare the amount Q of energy transferred to the air by heating to the change ΔU in the air's internal energy.

Sketch the Process

Compare Q and ΔU



For a vertical line that does not touch the horizontal axis, and either an arrowhead or labels that indicate the direction of the process		1 point
For a comparison consistent with the graph, or an incorrect graph but a correct comparison with an explanation that the work on the gas is zero		1 point
Correct comparison: $Q = \Delta U$		

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Question 1 (continued)

Distribution of points

(d) LO 7.A.1.1, SP 6.4
2 points

When the temperature of the room is 276 K, the air pressure is 1.0×10^5 Pa. Calculate the force exerted by the air in the room on a door that measures 2.0 m by 0.90 m when the temperature of the room is 310 K.

$PV = nRT$		
For obtaining a valid expression that can be used to calculate the pressure at 310 K		1 point
$P_{276\text{K}}/T_{276\text{K}} = P_{310\text{K}}/T_{310\text{K}}$		
$P_{310\text{K}} = \dfrac{P_{276\text{K}}T_{310\text{K}}}{T_{276\text{K}}} = \dfrac{(1 \times 10^5\ \text{Pa})(310\ \text{K})}{276\ \text{K}} = 1.1 \times 10^5\ \text{Pa}$		
For showing correct substitutions in the expression for the force and any numerical answer with correct units		1 point
$F = PA = (1.1 \times 10^5\ \text{Pa})(2.0\ \text{m})(0.9\ \text{m}) = 2.0 \times 10^5\ \text{N}$		

LO 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. **[SP 2.2, 6.4]**

LO 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. **[SP 1.2]**

LO 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. **[SP 6.4, 7.2]**

LO 5.B.7.2: The student is able to create a plot of pressure versus volume for a thermodynamic process from given data. **[SP 1.1]**

LO 7.A.1.1: The student is able to make claims about how the pressure of an ideal gas is connected to the force exerted by molecules on the walls of the container and how changes in pressure affect the thermal equilibrium of the system. **[SP 6.4, 7.2]**

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Question 2

12 points total **Distribution of points**

(a)

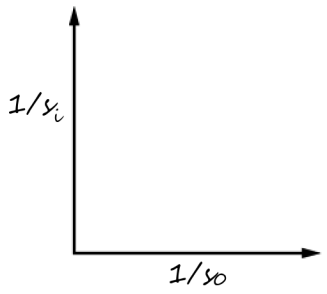
Students use a lightbulb, a screen, and a meterstick to determine the focal length of a concave mirror from a graph.

i) LO 6.E.4.1, SP 4.1; LO 6.E.4.2, SP 1.4
5 points

Describe a procedure that could be used to collect appropriate data and the measurements to be taken.

- Label the axes below with the quantities to be graphed.
- Draw a clearly labeled diagram of the experimental setup.
- Describe the procedure and indicate the quantities to be measured.

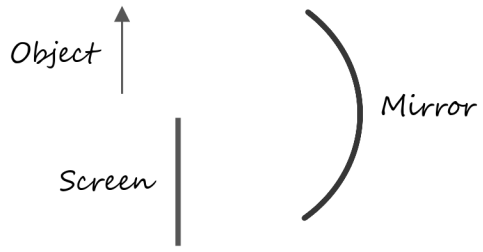
Label the Axes



Describe the Procedure

Place the object and screen in front of the mirror, as shown. Move the screen until a focused image is formed. Measure the distance of the object and the screen from the mirror. Move the object to a few other locations and repeat the screen adjustment and measurements.

Draw a Diagram



For labeling axes with appropriate quantities: $1/s_o$ and $1/s_i$, or s_o and s_i		1 point
For a diagram with correct arrangement of all three items: object and screen on the same side of mirror, facing the concave surface		1 point
For getting a sharp image on the screen		1 point
For measuring object and image distance		1 point
For using several object distances		1 point

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Question 2 (continued)

Distribution of points

(a) (continued)

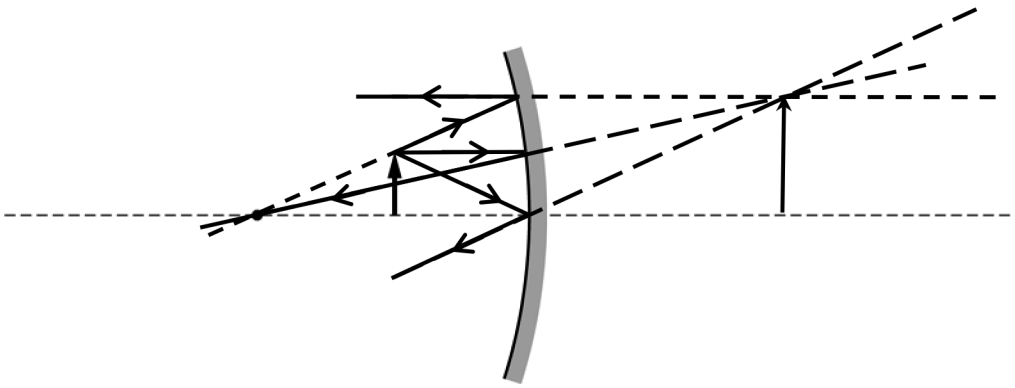
ii) LO 6.E.4.1, SP 5.1
1 point

Describe how the focal length can be determined from the graph.

For indicating how to determine the focal length given the axis labels in part (i)		1 point
Example: The inverse of the *x*- or *y*-intercept of a best-fit line to a plot of $1/s_o$ and $1/s_i$		
Example: The image distance at which there is an asymptote (vertical or horizontal) of a best-fit curve to a plot of s_o and s_i		

(b) LO 6.E.2.1, SP 6.4; LO 6.E.4.2, SP 1.4
3 points

The figure below represents one arrangement of a concave mirror and an object. The dot represents the focal point of the mirror and the arrow represents the object. Draw a ray diagram to illustrate the formation of the image that includes at least two rays and the resulting image.



For the first correct ray		1 point
For a second correct ray, with no incorrect rays		1 point
For correctly drawing an image that is consistent with the rays		1 point

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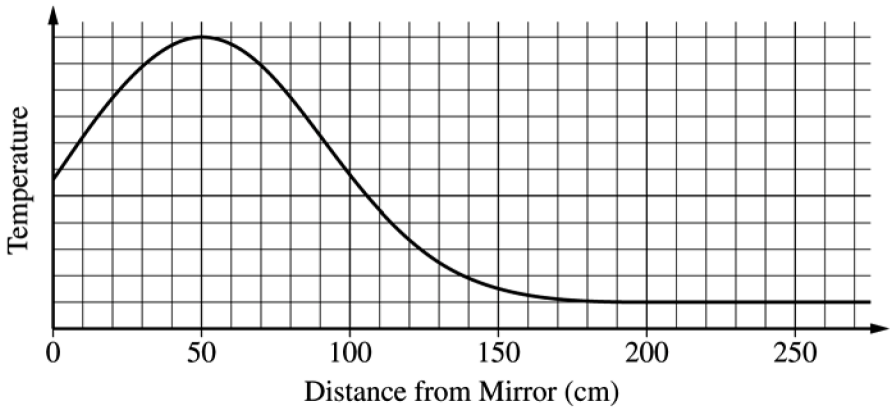
Question 2 (continued)

Distribution of points

(c)

Some students take the concave mirror outside and hold it with the concave side facing the Sun. The students want to locate the image of the Sun. They measure the temperature of the air in front of the mirror along the principal axis and graph the air temperature as a function of distance from the mirror. The graph below is their best-fit curve to the data.



i) LO 6.E.2.1, SP 6.4, 7.2; LO 6.E.4.1; SP 5.3; LO 6.E.4.2, SP 1.4
1 point

Based on the curve, at what distance from the mirror would you expect to find the image of the Sun?

For identifying the image distance as the position of the greatest temperature, i.e., 50 cm		1 point

ii) LO 6.E.2.1, SP 6.4, 7.2; LO 6.E.4.1; SP 5.3; LO 6.E.4.2, SP 1.4
2 points

Use a relevant equation to explain how your response to (c)(i) relates to the focal length of the mirror.

For recognizing that the object distance is effectively infinity		1 point
For using or referring to the mirror equation to show that the focal length is the same as the image distance		1 point
Claim: The focal length is the same as the distance of the image of the Sun. Evidence: $\frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f}$ Reasoning: The object distance is effectively infinity. This means $\frac{1}{s_o}$ is zero and thus $f = s_i$.		

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Question 2 (continued)

LO 6.E.2.1: The student is able to make predictions about the locations of object and image relative to the location of a reflecting surface. The prediction should be based on the model of specular reflection with all angles measured relative to the normal to the surface. **[SP 6.4, 7.2]**

LO 6.E.4.1: The student is able to plan data collection strategies and perform data analysis and evaluation of evidence about the formation of images due to reflection of light from curved spherical mirrors. **[SP 3.2, 4.1, 5.1, 5.2, 5.3]**

LO 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. **[SP 1.4, 2.2]**

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Question 3

12 points total **Distribution of points**

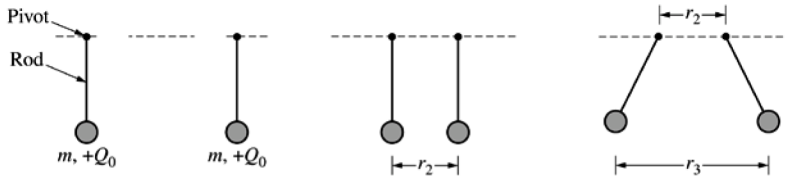

Figure 1 Figure 2 Figure 3

Note: Figure 1 not drawn to scale.

Two insulating spheres with mass m and charge $+Q_0$ are near Earth's surface, suspended vertically from identical light, stiff rods with pivots at the top, as shown in Figure 1. The spheres are initially far apart. The pivots are locked so the rods remain vertical while the spheres are moved together by external forces until the spheres are a distance r_2 from each other, as shown in Figure 2. Finally, the pivots are held a distance r_2 apart and unlocked, and the rods are allowed to swing out until the spheres momentarily come to rest a distance r_3 apart, as shown in Figure 3. The pivots are always at the same height.

(a)

Consider the system that includes only the two spheres, with Earth external to the system.

i) LO 5.B.4.1, SP 6.4
2 points

Write an expression for the work done moving the spheres horizontally from far apart to a separation of r_2. Express your answer in terms of Q_0, r_2, and physical constants, as appropriate.

For recognizing that the work equals the change in potential energy		1 point
$W = \Delta U$		
$W = q\Delta V = kqq/r$		
For a correct expression		1 point
$W = kQ_0^2/r_2$		

ii) LO 5.B.5.4, SP 6.4
2 points

The total energy of the two-sphere system (with Earth still external to the system) changes as the system goes from the configuration in Figure 2 to the configuration in Figure 3. Explain how the energy changes in terms of the forces exerted on the system.

For indicating that the total energy decreases with some attempt to explain		1 point
For any indication that an external force does negative work the system		1 point
Example explanation: The gravitational force exerted by Earth does negative work on the two-sphere system as the spheres rise, decreasing the energy of the system.		
Claim: The total energy decreases. Evidence: The spheres are at a higher position in Figure 3 than in Figure 2. Reasoning: The spheres move opposite to the direction of the external force of gravity, so Earth does negative work on them.		

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Question 3 (continued)

Distribution of points

(b) LO 5.B.4.2, SP 1.4; LO 5.B.5.4, SP 6.4
2 points

Now consider the system that contains both Earth and the two spheres. What is the work done on this new system for the changes in sphere position described in parts (a)(i) and (ii) ? Explain your reasoning.

Part (a)(i) Part (a)(ii)

For indicating that the work on this system resulting from the changes in position described in part (a)(i) is the same as for the system in part (a)(i) with a valid explanation, such as the same external forces are needed		1 point
For indicating that the work on this system resulting from the changes in position described in part (a)(ii) is zero because there are no external forces doing work		1 point
Example for part (a)(i): The work done on this system is the same as the work done on the system in part (a)(i) because the external forces moving the spheres apart have to overcome the same electric forces over the same distance. Claim: The work for this system resulting from the changes in position described in part (a)(i) is the same as for the system in part (a)(i). Evidence: The same amount of work is done by an external force to move the spheres horizontally the same distance away from each other. Reasoning: If the same objects move in the same way against the same force, the work done must be the same.		
Example for part (a)(ii): The work done on this system is zero because the only interactions that change the energy of the system are internal to the system, and thus no work is done on the system. Claim 2: The work for this system resulting from the changes in position described in part (a)(ii) is zero. Example evidence 2: All the objects are part of the system. Example reasoning 2: The system cannot do work on itself.		

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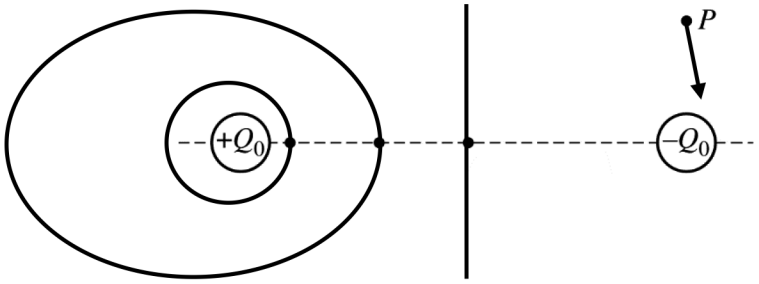
Question 3 (continued)

Distribution of points

(c) LO 2.C.2.1, SP 2.2, 6.4; LO 2.C.4.1, SP 2.2, 6.4; LO 2.C.4.2, SP 1.4, 2.2; LO 2.E.2.1, SP 6.4
3 points

The rods are now held fixed at the positions shown in Figure 3, and negative charge is added to the right sphere so its net charge is $-Q_0$. The circles in the figure below represent the spheres. On the figure, do the following.

- Draw a single vector originating on point *P* that represents the net electric field at that point.
- For each of the dots on the horizontal dashed line, draw an isoline of electric potential that goes through the dot.



For an electric field vector at point *P* pointing down and toward the right		1 point
For a vertical isoline through the center dot		1 point
For arcs or closed isolines through the other points, with the correct concavity, that will not obviously cross each other		1 point

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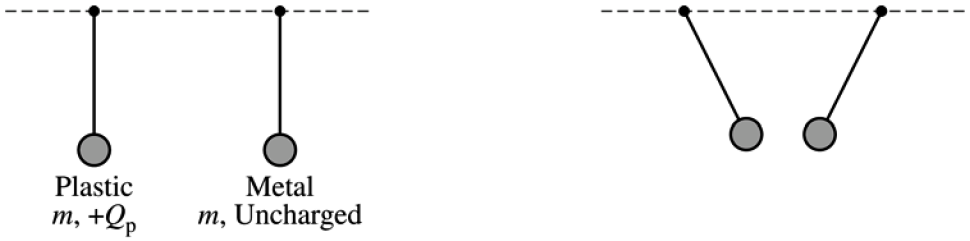
Question 3 (continued)

Distribution of points

(d) LO 4.E.3.1, SP 6.4; LO 4.E.3.2, SP 6.4; LO 4.E.3.5, SP 5.1; LO 4.E.3.4, SP 1.1, 1.4, 6.4; LO 3.C.2.1, SP 6.4)
3 points

In a new situation, the two spheres still have the same mass m, but the left sphere is made of plastic and has charge $+Q_p$ and the right sphere is made of metal and is uncharged. The spheres are brought near but do not touch, as shown below on the left. When the rods are allowed to pivot, the spheres move toward each other, as shown on the right. In terms of charge distributions, explain why the force between the spheres is attractive.



For indicating that the uncharged sphere becomes polarized, or that the charge on the sphere is redistributed		1 point
For indicating that the left side of the uncharged sphere is negative or the right side is positive		1 point
For indicating that the net force is attractive because that the negative induced charge is closer to the positively charged plastic sphere than the positive induced charge		1 point
Example: The positive charges in the plastic sphere cause the metal sphere to become polarized, with negative charges moving toward the left side of the sphere. The negative charges in the metal sphere are closer to the plastic sphere than the positive charges, so the attractive force between the spheres is larger than the repulsive force, and the net force is attractive. Claim: The force is attractive. Evidence: The negative charges in the metal sphere are closer to the plastic sphere than the positive charges. Reasoning: The negative charges exert a larger force on the plastic sphere than the positive charges.		

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Question 3 (continued)

LO 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. **[SP 2.2, 6.4]**

LO 2.C.4.1: The student is able to distinguish the characteristics that differ between monopole fields (gravitational field of spherical mass and electrical field due to single point charge) and dipole fields (electric dipole field and magnetic field) and make claims about the spatial behavior of the fields using qualitative or semi-quantitative arguments based on vector addition of fields due to each point source, including identifying the locations and signs of sources from a vector diagram of the field. **[SP 2.2, 6.4, 7.2]**

LO 2.C.4.2: The student is able to apply mathematical routines to determine the magnitude and direction of the electric field at specified points in the vicinity of a small set (two to four) of point charges and express the results in terms of magnitude and direction of the field in a visual representation by drawing field vectors of appropriate length and direction at the specified points. **[SP 1.4, 2.2]**

LO 2.E.2.1: The student is able to determine the structure of isolines of electric potential by constructing them in a given electric field. **[SP 6.4, 7.2]**

LO 3.C.2.1: The student is able to make predictions about the interaction between two electric point charges, using Coulomb's law qualitatively and quantitatively. **[SP 2.2, 6.4]**

LO 4.E.3.1: The student is able to make predictions about the redistribution of charge during charging by friction, conduction, and induction. **[SP 6.4]**

LO 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. **[SP 6.4, 7.2]**

LO 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**.** **[SP 1.1, 1.4, 6.4]**

LO 4.E.3.5: The student is able to plan 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. **[SP 3.2, 4.1, 4.2, 5.1, 5.3]**

LO 5.B.4.1: The student is able to describe and make predictions about the internal energy of systems. **[SP 6.4, 7.2]**

LO 5.B.4.2: The student is able to calculate changes in kinetic energy and potential energy of a system using information from representations of that system. **[SP 1.4, 2.1, 2.2]**

LO 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). **[SP 6.4, 7.2]**

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Question 4

10 points total **Distribution of points**

A uranium-231 nucleus can decay into an alpha particle and a thorium-227 nucleus.

(a) LO 7.C.3.1, SP 6.4
1 point

Nuclei in a 500 g sample of uranium-231 undergo this decay. The amount of uranium-231 remaining is measured at the same time every day for a period of eight days. The table below shows the data obtained.

Amount of uranium-231 (g)	500	424	359	305	258	219	186	157	134
Time (days)	0	1	2	3	4	5	6	7	8

According to the data, what is the approximate half-life of uranium-231 ?

1 point for a half-life between 4 and 4.5 days		1 point

(b)

One uranium-231 nucleus decays. The uranium nucleus has a mass of 3.835609×10^{-25} kg and is moving in the $-x$-direction with a kinetic energy of 2.5×10^{-13} J before the decay. The thorium nucleus has a mass of 3.769064×10^{-25} kg , and the alpha particle has a mass of 0.066447×10^{-25} kg .

i) LO 5.B.4.1, SP 6.4
2 points

Calculate the velocity of the center of mass of the two decay products immediately after the decay. Be sure to specify the direction of the velocity.

The velocity of the center of mass does not change because there are no external forces. Therefore, it is the same as the velocity of the original nucleus.		
$K = \frac{1}{2}mv^2$ so $v = \sqrt{2K/m}$		
For correct substitution of the given values for kinetic energy and mass		1 point
$v = \sqrt{2\left(2.5 \times 10^{-13}\ \text{J}\right)/\left(3.835609 \times 10^{-25}\ \text{kg}\right)}$		
For indicating that the velocity is in the negative x direction		1 point
$v = 1.14 \times 10^{6}$ m/s in the $-x$-direction		

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Question 4 (continued)

Distribution of points

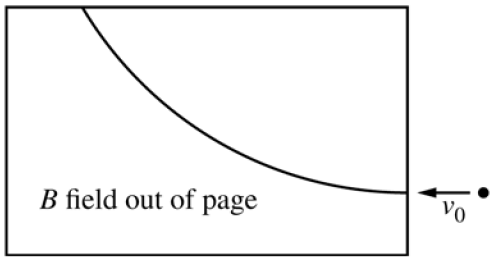
(b) (continued)

ii) LO 4.C.4.1, SP 2.2
2 points

Calculate the amount of energy released in the decay of the uranium-231 nucleus.

For correctly calculating the mass difference		1 point
$\Delta m = \left(3.835609 \times 10^{-25}\ \text{kg}\right) - \left(3.769064 \times 10^{-25}\ \text{kg}\right) - \left(0.066447 \times 10^{-25}\ \text{kg}\right)$		
$\Delta m = 9.8 \times 10^{-30}\ \text{kg}$		
For correctly substituting the calculated mass and the speed of light into a correct expression to calculate the energy $\Delta E = mc^2$		1 point
$\Delta E = \left(9.8 \times 10^{-30}\ \text{kg}\right)\left(3 \times 10^{8}\ \text{m/s}\right)^2$		
$\Delta E = 8.82 \times 10^{-13}\ \text{J}$		

(c) LO 2.D.1.1, SP 2.2; LO 3.C.3.1, SP 1.4; LO 3.C.3.2, SP 4.2, 5.1
5 points



An alpha particle is moving to the left with speed v_0 when it enters a region containing a uniform magnetic field of known magnitude B directed out of the page. The figure above shows the path of the alpha particle through the region. In a coherent paragraph-length response, explain how the charge-to-mass ratio and sign of the charge of the alpha particle can be verified by using the effect of the magnetic field on the path of the particle. Equations or diagrams that support your written description may be included.

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Question 4 (continued)

		Distribution of points
For indicating that the direction of deflection indicates the sign of the particle's charge, i.e. showing understanding of the application of a hand rule for the direction of the magnetic force		1 point
For a clear indication that the magnetic force causes a centripetal acceleration		1 point
For indicating that the radius of the path would need to be measured		1 point
For an indication that the charge-to-mass ratio depends on v_0, B, and r, using either equations or words		1 point
For a logical, relevant, and internally consistent argument that addresses the question, has sufficient paragraph structure, and follows the guidelines described in the published requirements for the paragraph length response		1 point
Claim (given): The charge-to-mass ratio and sign of the charge of the alpha particle can be verified by using the effect of the magnetic field on the path of the particle. Evidence: The alpha particle moves in a curved path. Reasoning: The magnetic force is centripetal. The charge-to-mass ratio depends on v_0, B, and r. The radius of the path would need to be measured.		

LO 2.D.1.1: The student is able to apply mathematical routines to express the force exerted on a moving charged object by a magnetic field. **[SP 2.2]**

LO 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. **[SP 1.4]**

LO 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. **[SP 4.2, 5.1]**

LO 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. **[SP 2.2, 2.3, 7.2]**

LO 5.B.4.1 The student is able to describe and make predictions about the internal energy of systems. **[SP 6.4, 7.2]**

LO 7.C.3.1: The student is able to predict the number of radioactive nuclei remaining in a sample after a certain period of time, and also predict the missing species (alpha, beta, gamma) in a radioactive decay. [**SP 6.4]**

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2019 AP Physics 2 Scoring Worksheet

Section I: Multiple Choice

_____	× 1.0000 =	_____
Number Correct (out of 40)		Weighted Section I Score (Do not round)

Section II: Free Response

Question 1	_____ (out of 10)	× 0.9090 =	_____ (Do not round)
Question 2	_____ (out of 12)	× 0.9090 =	_____ (Do not round)
Question 3	_____ (out of 12)	× 0.9090 =	_____ (Do not round)
Question 4	_____ (out of 10)	× 0.9090 =	_____ (Do not round)

Sum = _____
Weighted Section II Score (Do not round)

Composite Score

_____	+	_____	=	_____
Weighted Section I Score		Weighted Section II Score		Composite Score (Round to nearest whole number)

AP Score Conversion Chart
Physics 2

Composite Score Range	AP Score
61-80	5
51-60	4
38-50	3
21-37	2
0-20	1

2019 AP Physics 2: Algebra-Based
Question Descriptors and Performance Data

Multiple-Choice Questions

Question	Science Practice	Learning Objective	Topic	Key	% Correct
1	6.4	7.C.3.1	Wave Functions and Probability	C	95
2	1.4	5.B.7.3	Internal Energy and Energy Transfer	B	80
3	1.5	6.B.3.1	Periodic Waves	C	84
4	1.1|1.4|6.4|3.2|5.3	4.E.3.3|4.E.3.5	Charge Distribution - Friction, Conduction, and Induction	B	82
5	6.4	4.C.3.1	Heat and Energy Transfer	A	78
6	6.2	6.A.1.3	Waves	B	72
7	6.4|7.2	2.E.2.2	Isolines and Electric Fields	B	76
8	1.1|1.4	3.B.2.1	Fluids and Free-Body Diagrams	D	80
9	6.4	6.E.3.3	Refraction, Reflection and Absorption	B	53
10	2.2	2.D.1.1	Magnetic Fields and Forces	C	79
11	5.1	7.A.3.3	Pressure, Thermal Equilibrium, and the Ideal Gas Law	D	70
12	6.4	5.B.9.5	Kirchhoff's Loop Rule	C	72
13	6.4|7.2|7.1	7.A.1.1|7.A.2.1	Pressure, Thermal Equilibrium, and the Ideal Gas Law	B	78
14	6.4	2.E.2.1	Isolines and Electric Fields	A	57
15	1.1	2.D.2.1	Magnetic Fields and Forces	A	66
16	6.4|6.4|7.2|6.4	2.C.1.1|3.B.1.4|3.C.2.1	Electric Charges and Fields, Electric Forces and Free Body Diagrams, Describing Electric Force	B	71
17	1.1|2.2|2.2|6.4	3.B.2.1|3.C.2.1	Electric Forces and Free Body Diagrams, Describing Electric Force	A	59
18	1.4|2.2	5.B.7.3	Heat and Energy Transfer	C	64
19	6.4	5.B.7.1	Heat and Energy Transfer	C	57
20	1.1	5.B.7.2	Heat and Energy Transfer	D	86
21	2.2|6.4	4.E.5.1|5.B.9.5	Resistance and Capacitance, Kirchhoff's Loop Rule	C	61
22	2.2	5.B.10.1	Conservation of Energy in Fluid Flow	D	58
23	1.2|7.2|6.4|1.2	5.B.8.1|6.F.1.1|7.C.4.1	Energy in Modern Physics (Energy in Radioactive Decay and $E = mc^2$), Photoelectric Effect, Wave Functions and Probability	A	57
24	1.4|6.4|6.4	4.E.3.4|5.C.2.1	Charge Distribution - Friction, Conduction, and Induction, Conservation of Electric Charge	D	73
25	6.4|1.4|2.2	3.B.1.4|3.B.2.1|5.B.10.2	Fluids and Free-Body Diagrams, Conservation of Energy in Fluid Flow	C	52
26	5.1	6.E.3.2	Refraction, Reflection and Absorption	D	58
27	1.4	5.C.3.7	Kirchhoff's Junction Rule and the Conservation of Electric Charge	D	59
28	1.4	6.E.5.1	Images from Lenses and Mirrors	C	43
29	6.3|7.1	1.D.3.1	Properties of Waves and Particles	A	63
30	6.4|6.4	5.C.1.1|5.G.1.1	Radioactive Decay	D	35
31	7.2	4.C.4.1	Mass-Energy Equivalence	B	56
32	6.4|6.4|1.4	3.B.1.4|4.E.2.1|5.B.4.2	Forces Review, Magnetic Flux, Kirchhoff's Loop Rule	D	40

2019 AP Physics 2: Algebra-Based
Question Descriptors and Performance Data

Question	Science Practice	Learning Objective	Topic	Key	% Correct
33	6.4|7.2	6.C.4.1	Interference and Diffraction	D	51
34	1.4	7.A.1.2	Pressure, Thermal Equilibrium, and the Ideal Gas Law	D	48
35	5.1|5.3	5.B.9.7	Kirchhoff's Loop Rule	D	27
36	1.4|2.2	6.E.4.2	Images from Lenses and Mirrors	A	25
131	5.1	4.E.4.3	Resistance and Capacitance	A,C	67
132	6.4|1.4|6.4|7.2	2.C.1.1|5.B.4.2|5.B.5.4	Electric Charges and Fields, Conservation of Electric Energy	B,C	49
133	6.4|6.4	5.C.1.1|5.G.1.1	Radioactive Decay	A,C	52
134	4.1	6.E.5.2	Images from Lenses and Mirrors	A,B	71

Free-Response Questions

Question	Science Practice	Learning Objective	Topic	Mean Score
1	2.2|1.2|6.4|7.2|1.1|6.4|7.1	4.E.4.1|5.B.6.1|5.B.7.1|5.B.7.2|7.A.1.1|7.B.2.1	4.3|2.7|2.2|2.11	5.13
2	6.4|7.2|4.1|5.1|5.3|1.4	6.E.2.1|6.E.4.1|6.E.4.2	6.4|6.5	6.42
3	2.2|6.4|2.2|6.4|1.4|2.2|6.4|6.4|6.4|6.4|1.1|1.4|6.4|5.1|6.4|1.4|6.4	2.C.2.1|2.C.4.1|2.C.4.2|2.E.2.1|3.C.2.1|4.E.3.1|4.E.3.2|4.E.3.4|4.E.3.5|5.B.4.1|5.B.4.2|5.B.5.4	3.11|3.12|3.8|3.4|3.13	4.30
4	2.2|1.4|4.2|5.1|2.2|6.4|6.4	2.D.1.1|3.C.3.1|3.C.3.2|4.C.4.1|5.B.4.1|7.C.3.1	5.5|5.6|7.4|7.3|7.7	4.53