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.

From the 2019 Administration

AP® CollegeBoard

AP® Physics 1: Algebra-Based

Practice Exam

NOTE: This is a modified version of the 2019 AP Physics 1: Algebra-Based Exam.

This exam may not be posted on school or personal websites, nor electronically redistributed for any reason. This Released Exam is provided by the College Board for AP Exam preparation. Teachers are permitted to download the materials and make copies to use with their students in a classroom setting only. To maintain the security of this exam, teachers should collect all materials after their administration and keep them in a secure location.

Further distribution of these materials outside of the secure College Board site disadvantages teachers who rely on uncirculated questions for classroom testing. Any additional distribution is in violation of the College Board's copyright policies and may result in the termination of Practice Exam access for your school as well as the removal of access to other online services such as the AP Teacher Community and Online Score Reports.

Contents

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.

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 <u>two</u>

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 1: 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 1: 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

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AP® PHYSICS 1 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	Coulomb's law constant, $k = 1/4\pi\varepsilon_0 = 9.0 \times 10^{9}\ \text{N}\cdot\text{m}^2/\text{C}^2$
Electron mass, $m_e = 9.11 \times 10^{-31}$ kg	Universal gravitational constant, $G = 6.67 \times 10^{-11}\ \text{m}^3/\text{kg}\cdot\text{s}^2$
Speed of light, $c = 3.00 \times 10^{8}$ m/s	Acceleration due to gravity at Earth's surface, $g = 9.8\ \text{m/s}^2$

UNIT SYMBOLS								
	meter,	m	kelvin,	K	watt,	W	degree Celsius,	°C
	kilogram,	kg	hertz,	Hz	coulomb,	C		
	second,	s	newton,	N	volt,	V		
	ampere,	A	joule,	J	ohm,	Ω		

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. Assume air resistance is negligible unless otherwise stated.
III. In all situations, positive work is defined as work done <u>on</u> a system.
IV. The direction of current is conventional current: the direction in which positive charge would drift.
V. Assume all batteries and meters are ideal unless otherwise stated.

AP® PHYSICS 1 EQUATIONS

MECHANICS

$v_x = v_{x0} + a_x t$

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

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

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

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

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

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

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

$K = \frac{1}{2}mv^2$

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

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

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

$\omega = \omega_0 + \alpha t$

$x = A\cos(2\pi ft)$

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

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

$L = I\omega$

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

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

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

$U_s = \frac{1}{2}kx^2$

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

a = acceleration
A = amplitude
d = distance
E = energy
f = frequency
F = force
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 = volume
v = speed
W = work done on a system
x = position
y = height
α = angular acceleration
μ = coefficient of friction
θ = angle
ρ = density
τ = torque
ω = angular speed

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

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

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

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

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

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

$U_G = -\frac{Gm_1 m_2}{r}$

ELECTRICITY

$\left|\vec{F}_E\right| = k\left|\frac{q_1 q_2}{r^2}\right|$

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

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

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

$P = I\,\Delta V$

$R_s = \sum_i R_i$

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

A = area
F = force
I = current
ℓ = length
P = power
q = charge
R = resistance
r = separation
t = time
V = electric potential
ρ = resistivity

WAVES

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

f = frequency
v = speed
λ = wavelength

GEOMETRY AND TRIGONOMETRY

Rectangle
$A = bh$

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

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

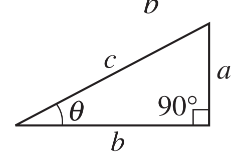
Rectangular solid
$V = \ell wh$

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 1

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. A 4 kg object moving to the left collides with and sticks to a 3 kg object moving to the right. Which of the following is true of the motion of the combined objects immediately after the collision?

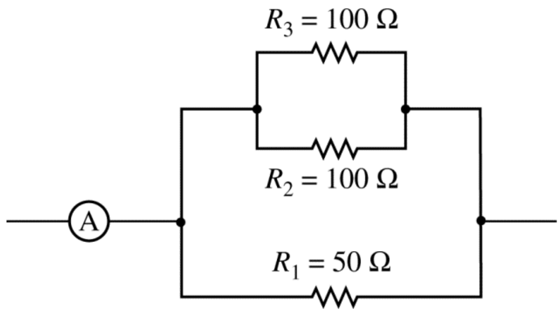
   (A) They must be moving to the left.
   (B) They must be moving to the right.
   (C) They must be at rest.
   (D) The motion cannot be determined without knowing the speeds of the objects before the collision.

2. A brother and sister are standing next to each other at rest on a surface of frictionless ice. The brother's mass is exactly twice that of his sister's. The sister suddenly pushes her brother. As a result, the sister moves with kinetic energy K. What is the resulting kinetic energy of the brother?

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

3. At time $t = 0$, a cart is at $x = 10\text{ m}$ and has a velocity of 3 m/s in the $-x$-direction. The cart has a constant acceleration in the $+x$-direction with magnitude $3\text{ m/s}^2 < a < 6\text{ m/s}^2$. Which of the following gives the possible range of the position of the cart at $t = 1\text{ s}$?

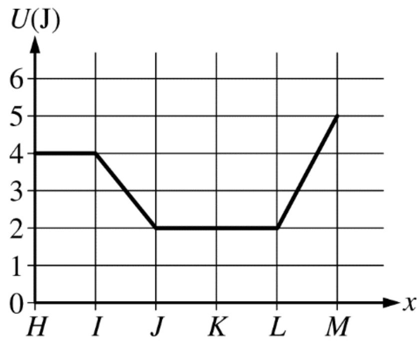
(A) $4\text{ m} < x < 5.5\text{ m}$
(B) $8.5\text{ m} < x < 10\text{ m}$
(C) $11.5\text{ m} < x < 13\text{ m}$
(D) $14.5\text{ m} < x < 16\text{ m}$



4. The figure above shows part of a circuit containing three resistors and an ammeter. A steady current flows through the ammeter. Resistors R_1, R_2, and R_3 have currents I_1, I_2, and I_3, respectively. Which of the following expressions correctly relates the three currents?

(A) $I_1 > (I_2 = I_3)$
(B) $(I_2 = I_3) > I_1$
(C) $I_1 = I_2 = I_3$
(D) The relationship cannot be determined without information about the rest of the circuit.

Questions 5-7 refer to the following material.



The graph above shows the potential energy U of a system as one object in the system moves along the x-axis and the rest of the system does not move. Six evenly-spaced points along the x-axis are labeled. At point H, the object is moving in the positive x-direction and the mechanical energy of the system is 5.0 J. As the object moves, no energy enters or leaves the system.

5. In which segment does the net force exerted on the object have the greatest magnitude?

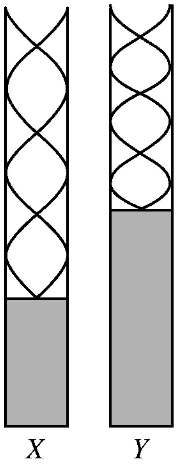
   (A) *HI*
   (B) *IJ*
   (C) *JL*
   (D) *LM*

6. What is the kinetic energy of the object at point K ?

   (A) 5 J
   (B) 4 J
   (C) 3 J
   (D) 2 J

7. Which of the following describes the magnitude of the momentum of the object in the first two straight-line segments shown in the graph as the object moves from point H to point J ?

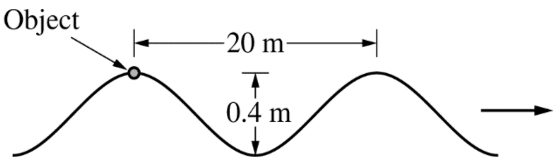
	HI	*IJ*
(A)	Zero	Increasing
(B)	Zero	Decreasing
(C)	Constant but nonzero	Increasing
(D)	Constant but nonzero	Decreasing



8. The figure above represents standing wave patterns in two identical tubes. The tubes contain different amounts of water, and the standing waves are produced by holding a vibrating tuning fork near the top of each tube. Is the frequency of the tuning fork the same for tubes X and Y, and why or why not?

(A) No, because one frequency cannot create multiple standing wave patterns of different total lengths.
(B) No, because the wavelengths of the patterns are different, so the frequencies must be different.
(C) Yes, because the patterns have the same number of nodes and antinodes.
(D) Yes, because the tubes are identical, so the same frequency can produce a standing wave in both.

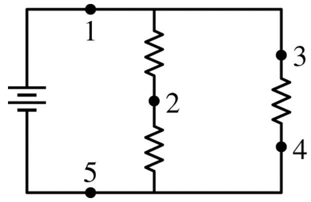
Item 9 was not scored.



Note: Figure not drawn to scale.

10. The figure above shows a water wave traveling to the right. The horizontal distance between two adjacent crests of the wave is 20 m. At the instant shown, an object floating on the surface of the water is at its maximum height. At a time 2 s later, the floating object has moved a vertical distance of 0.4 m to its lowest position. The speed of the wave is most nearly

(A) 0.1 m/s
(B) 0.2 m/s
(C) 5 m/s
(D) 10 m/s

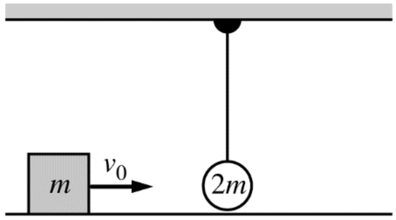


11. To test the hypothesis that all electrons entering a resistor also leave the resistor, ammeters could be placed in the above circuit at points

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

12. A toy doll and a toy robot are standing on a frictionless surface facing each other. The doll has a mass of 0.20 kg, and the robot has a mass of 0.30 kg. The robot pushes on the doll with a force of 0.30 N. The magnitude of the acceleration of the robot is

(A) zero
(B) 0.60 m/s^2
(C) 1.0 m/s^2
(D) 1.5 m/s^2



13. A block of mass m travels with speed v_0 to the right on a horizontal surface with negligible friction toward a sphere of mass $2m$ hanging at rest from a light cord, as shown above. The block collides elastically with the sphere. Which of the following correctly describes the speed and direction of the block and the speed of the sphere a short time after the collision?

	Speed and Direction of Block	Speed of Sphere
(A)	$v_0/3$ to the left	Slightly less than $2v_0/3$
(B)	$v_0/3$ to the right	Slightly less than $2v_0/3$
(C)	Zero	Slightly less than v_0
(D)	v_0 to the left	Zero

14. A block of mass m slides along a frictionless surface with kinetic energy K_i. It collides with a block of mass $3m$ that is initially at rest, and the two blocks stick together and slide with total kinetic energy K_f. What is the ratio $K_f : K_i$?

(A) 1 : 1
(B) 1 : 2
(C) 1 : 3
(D) 1 : 4

Questions 15-16 refer to the following material.

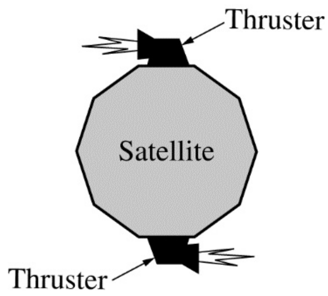
A meteoroid is in a circular orbit 600 km above the surface of a distant planet. The planet has the same mass as Earth but has a radius that is 90% of Earth's (where Earth's radius is approximately 6370 km).

15. The acceleration of the meteoroid due to the gravitational force exerted by the planet is most nearly

(A) $9\ \text{m/s}^2$ toward the center of the planet
(B) $9\ \text{m/s}^2$ in the direction of the meteoroid's motion
(C) $10\ \text{m/s}^2$ toward the center of the planet
(D) $10\ \text{m/s}^2$ in the direction of the meteoroid's motion

16. Does the planet exert a torque on the meteoroid with respect to the center of mass of the planet? Why or why not?

(A) Yes, because the planet exerts a centripetal force on the meteoroid.
(B) Yes, because the meteoroid's direction of motion is constantly changing.
(C) No, because the force exerted by the planet on the meteoroid has a negligible magnitude.
(D) No, because the planet exerts a force on the meteoroid parallel to its position vector relative to the center of mass of the planet.



17. A satellite in a circular orbit around Earth is initially not rotating with respect to its center of mass. Two identical thrusters on opposite sides of the satellite fire in opposite directions over the same 10-minute time interval, as shown above, and then turn off. How does the firing of the thrusters affect the mechanical energy of the satellite-Earth system and the shape of the satellite's orbit, if at all?

	Mechanical Energy of Satellite-Earth System	Shape of Orbit
(A)	No effect	No effect
(B)	No effect	Would change
(C)	Increases	No effect
(D)	Increases	Would change

18. A point charge of magnitude $2q$ exerts an electrostatic force of magnitude F on a point charge of magnitude q that is a distance R away. What is the magnitude of the force that the $2q$ point charge exerts on a point charge of magnitude $3q$ that is a distance $R/5$ away?

(A) $15F$
(B) $30F$
(C) $75F$
(D) $150F$

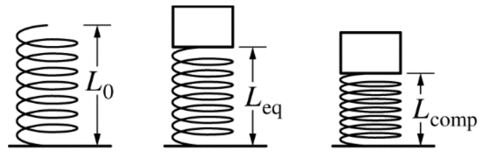


Figure 1 Figure 2 Figure 3

19. A vertical spring has unstretched length L_0, as shown in Figure 1. A block is attached to the top of the spring and slowly lowered until it is at rest and the spring has length L_{eq}, as shown in Figure 2. The block is then pushed down until the spring is compressed to length L_{comp}, as shown in Figure 3, and then released. After release, at what height will the kinetic energy of the block be maximum?

(A) L_0
(B) L_{eq}
(C) L_{comp}
(D) $\left(L_{eq} + L_{comp}\right)/2$

Cart Mass (kg)	Applied Force (N)	Time Force is Exerted (s)	Final Momentum (kg•m/s)	Final Kinetic Energy (J)
1	5	2	10	50
2	5	2	10	

20. Two frictionless lab carts start from rest and are pushed along a level surface by a constant force. Students measure the magnitude and duration of the force on each cart, as shown in the partially completed data table above, and calculate final kinetic energy and momentum. Which cart has a greater kinetic energy at the end of the push?

(A) The 1 kg cart
(B) The 2 kg cart
(C) Both carts have the same amount of kinetic energy.
(D) The relationship cannot be determined without knowing the distance each cart moved as the force was being applied.

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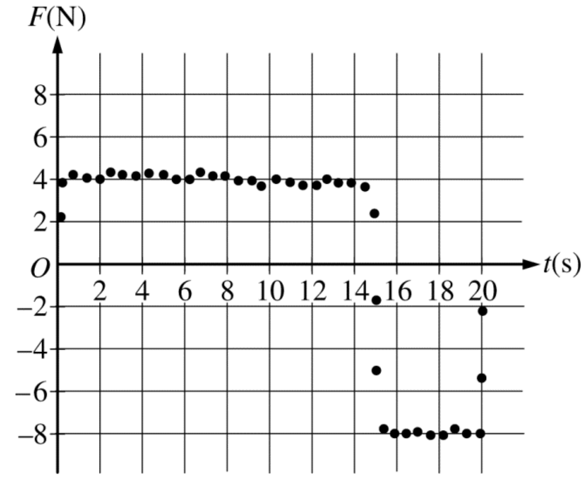
21. A simple pendulum consists of a sphere tied to the end of a string of negligible mass. The sphere is pulled back until the string is horizontal and then released from rest. Assume gravitational potential energy is zero when the sphere is at its lowest point. What angle will the string make with the horizontal when the kinetic energy and the potential energy of the sphere-Earth system are equal?

(A) Greater than $45°$
(B) Equal to $45°$
(C) Less than $45°$
(D) It cannot be determined without knowing the mass of the sphere.



22. A stationary cart attached to a force gauge is on a straight, horizontal, frictionless track. A student uses the force gauge to move the cart, and the gauge produces the graph of force as a function of time shown above. How does the momentum of the cart change during the time interval 0 s to 20 s?

(A) The momentum increases in magnitude during the entire time interval.
(B) The momentum decreases in magnitude during the entire time interval.
(C) The momentum increases in magnitude at first, then decreases and reverses direction.
(D) The momentum increases in magnitude at first, then decreases without reversing direction.

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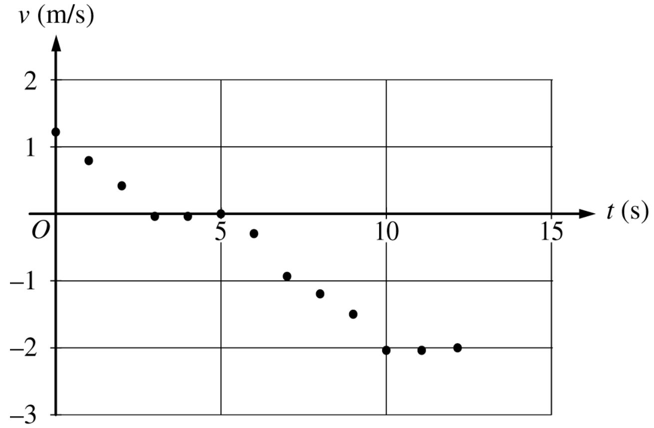


23. An engineer measures the velocity v of a remote-controlled cart on a straight track at regular time intervals. The data are shown in the graph above. During which of the following time intervals did the cart return to its position at time $t = 0$ s?

(A) $3 \text{ s} \le t < 5 \text{ s}$
(B) $5 \text{ s} \le t < 7 \text{ s}$
(C) $7 \text{ s} \le t < 10 \text{ s}$
(D) $10 \text{ s} \le t < 12 \text{ s}$

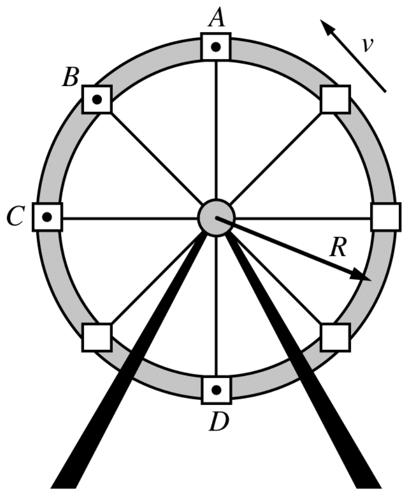
24. A guitar string with length 0.80 m resonates at a fundamental frequency of 320 Hz. A person presses on the string so that its effective length is reduced to 0.65 m, but the tension in the string does not change. The fundamental frequency of the 0.65 m string is most nearly

(A) 260 Hz
(B) 320 Hz
(C) 390 Hz
(D) 530 Hz

25. A student produces several standing waves on a string by adjusting the frequency of vibration at one end of the string. The student measures the wavelength λ and frequency f for each standing wave produced. Which of the following procedures and calculations will allow the student to determine the wave speed on the string?

(A) Graph λ as a function of $1/f$. The slope of the line is equal to the wave speed.
(B) Graph λ as a function of f. The slope of the line is equal to the wave speed.
(C) Graph λ as a function of $1/f$. The area under the line is equal to the wave speed.
(D) Graph λ as a function of f. The area under the line is equal to the wave speed.

Questions 26-28 refer to the following material.



An amusement park ride consists of a large vertical wheel of radius R that rotates counterclockwise on a horizontal axis through its center, as shown above. The cars on the wheel move at a constant speed v. Points A and D represent the position of a car at the highest and lowest point of the ride, respectively. A person of weight F_g sits upright on a seat in one of the cars. As the seat passes point A, the seat exerts a normal force with magnitude $0.8F_g$ on the person. While passing point A, the person releases a small rock of mass m, which falls to the ground without hitting anything.

26. Which of the following best describes the passenger's linear and angular velocity while passing point A ?

	Linear velocity	Angular velocity
(A)	Constant	Changing
(B)	Constant	Constant
(C)	Changing	Changing
(D)	Changing	Constant

27. What is the normal force exerted on the rider when passing point D ?

(A) $0.2F_g$

(B) $0.8F_g$

(C) $1.0F_g$

(D) $1.2F_g$

28. The kinetic energy of the rock when it is at the same height as point D is most nearly

(A) $\frac{1}{2}mv^2$

(B) $\frac{1}{2}2mgR$

(C) $\frac{1}{2}4mgR$

(D) $\frac{1}{2}m\left(v^2 + 4gR\right)$

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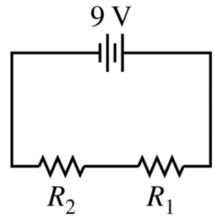
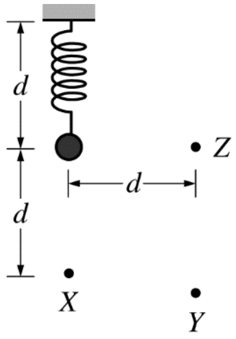
29. A negatively charged rod is placed in a small container filled with air that is electrically neutral. The container is then sealed. Fifteen seconds later, measurements reveal that the air inside the container has a net negative charge. What is the primary reason that the air becomes negatively charged?

(A) The extra electrons on the rod repel each other and therefore move away from the rod into the air.
(B) When air molecules bounce off the rod, negative charge transfers from the rod to some of those molecules.
(C) The electric force of the rod induces the air molecules near the rod to become negative, even if those molecules never touch the rod.
(D) When air molecules bounce off the rod, the rod's charge stays the same, but the rod exerts a force on the molecules that causes some of them to become negative.



30. The circuit shown above consists of a 9 V battery connected in series to two resistors. The potential difference across resistor R_1 is measured to be 3 V. Which of the following indicates the potential difference across resistor R_2 and explains why it has that value?

(A) 3 V, because the current through both resistors is the same
(B) 3 V, because the potential difference across resistors in series is always the same
(C) 6 V, because each coulomb of charge passing through the resistors loses 9 J of potential energy
(D) 6 V, because one-third of the current is used up in R_1, leaving two-thirds of the current to travel through R_2



31. An object hangs in equilibrium from a spring, as shown above. The object is then displaced to one of the labeled points X, Y, or Z. Which of the following correctly ranks the elastic potential energy U stored in the spring when the object is at each of the three positions?

(A) $U_Z > (U_X = U_Y)$
(B) $U_Y > (U_X = U_Z)$
(C) $U_Y > U_X > U_Z$
(D) $U_Y > U_Z > U_X$

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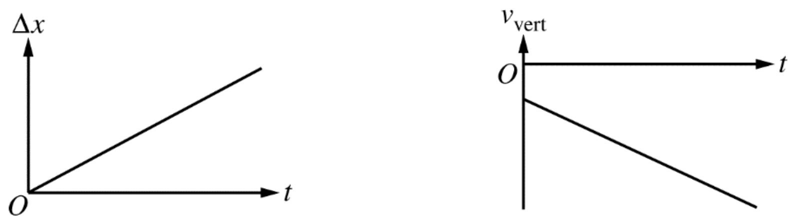
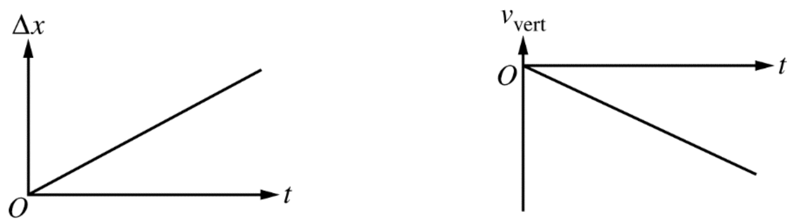
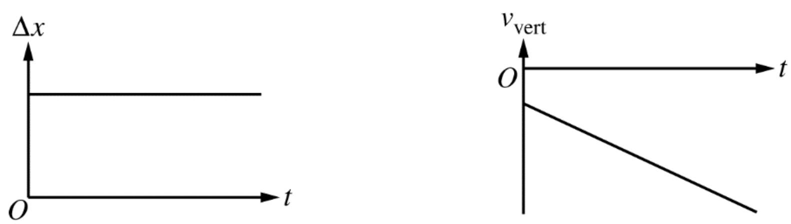
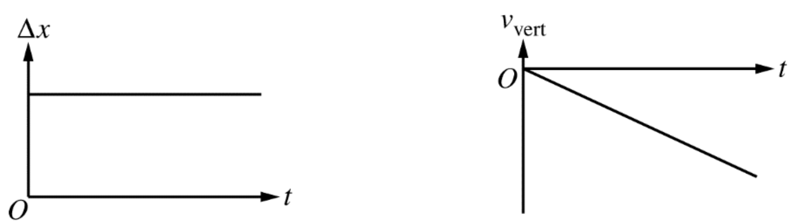
32. At time $t = 0$, a projectile is launched from the top of a cliff at an angle of 30 degrees below the horizontal. Which of the following pairs of graphs best represents the horizontal displacement Δx and the vertical velocity component v_{vert} of the projectile as a function of time t ?

Horizontal Displacement	Vertical Velocity Component

(A) 

(B) 

(C) 

(D) 

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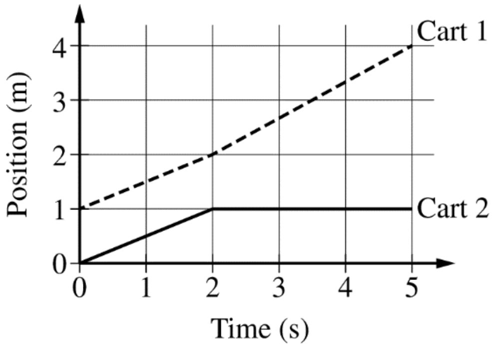


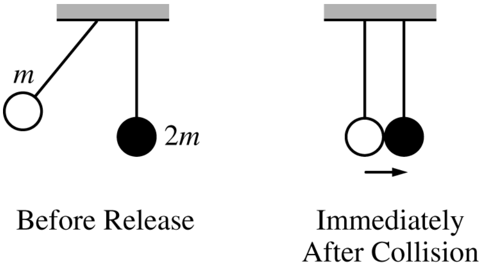
33. The graph above represents the position of two identical carts on a straight horizontal track as a function of time. Which of the following statements about the magnitude of the momentum of the two-cart system's center of mass, p_{com}, is true?

(A) p_{com} is constant from $t = 0$ s to $t = 5$ s.

(B) p_{com} is smaller after $t = 2$ s than it is before $t = 2$ s.

(C) p_{com} is larger after $t = 2$ s than it is before $t = 2$ s.

(D) p_{com} increases at a constant rate from $t = 0$ s to $t = 5$ s.

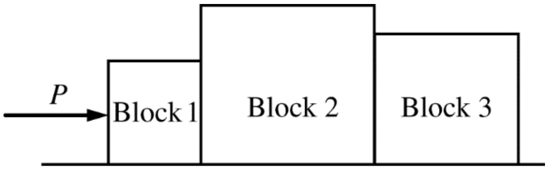


34. Sphere 1 of mass m and sphere 2 of mass $2m$ hang from light strings. Sphere 1 is pulled back, as shown above, and released from rest. Sphere 1 has kinetic energy K_i immediately before colliding with sphere 2. The two spheres stick together and move horizontally for an instant after the collision. During the collision, what is the change in the kinetic energy ΔK of the two-sphere system?

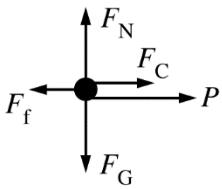
(A) 0
(B) $-K_i/3$
(C) $-K_i/2$
(D) $-2K_i/3$

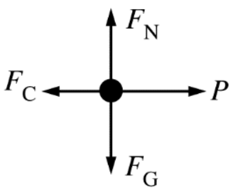
35. A wheel with radius 0.33 m and rotational inertia $2.0\ \text{kg}\bullet\text{m}^2$ spins on an axle with an initial angular speed of $3.0\ \text{rad/s}$. Friction in the axle exerts a torque on the wheel, causing the wheel to stop after 6.0 s. The average torque exerted on the wheel as it slows down has magnitude

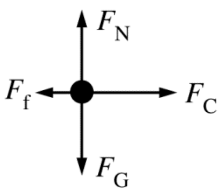
(A) 0.50 N•m
(B) 1.0 N•m
(C) 2.0 N•m
(D) 3.0 N•m

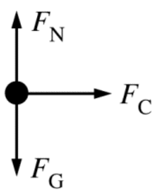


36. Three blocks are pushed along a rough surface by a force with magnitude P, as shown above. F_C is the magnitude of the contact force between blocks 2 and 3, and F_f, F_N, and F_G are the magnitudes of the friction, normal, and gravitational forces on block 3, respectively. Which of the following is a correct free-body diagram for block 3 ?

(A) 

(B) 

(C) 

(D) 

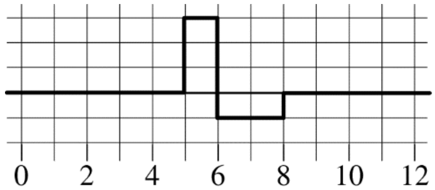
Directions: For each of the questions or incomplete statements below, two of the suggested answers will be correct. For each of these questions, you must select both correct choices to earn credit. No partial credit will be earned if only one correct choice is selected. Select the two that are best in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

131. A block slides down an inclined plane in a classroom. Which of the following pieces of information are needed to determine whether the velocity of the block will be constant? Select two answers.

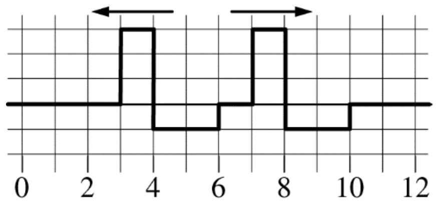
(A) The mass of the block
(B) The angle of the inclined plane
(C) The acceleration due to gravity in the classroom
(D) The coefficient of kinetic friction between the block and the inclined plane

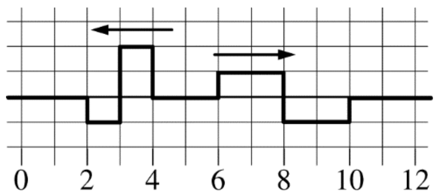
132. A test car and its driver, with a combined mass of 600 kg, are moving along a straight, horizontal track when a malfunction causes the tires to stop rotating. The car skids to a halt with constant acceleration, leaving skid marks on the road during the whole time it skids. Which two of the following measurements, taken together, would allow engineers to find the total mechanical energy dissipated during the skid? Select two answers.

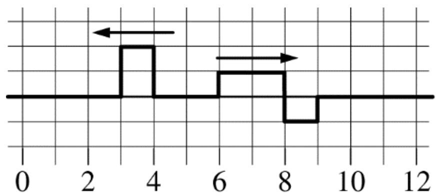
(A) The length of the skid marks
(B) The contact area of each tire with the track
(C) The coefficient of static friction between the tires and the track
(D) The coefficient of kinetic friction between the tires and the track

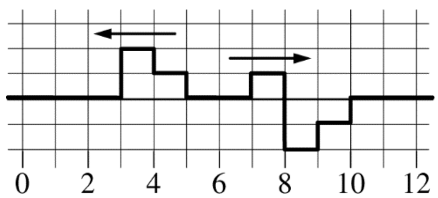


133. The figure above shows the result when two rectangular wave pulses overlap. If the pulses are moving at a rate of 1 tick mark per second, which of the following are possible graphs of the waves 2 s later? Select two answers.

(A)


(B)


(C)


(D)


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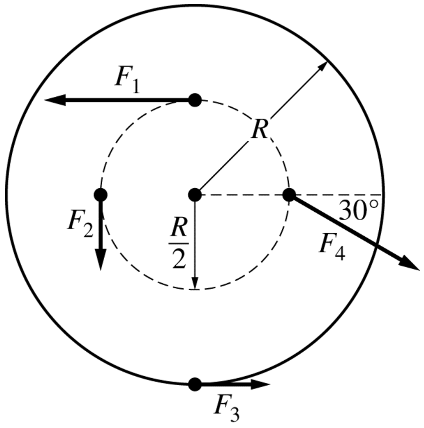

134. Four forces are exerted on a disk of radius R that is free to spin about its center, as shown above. The magnitudes are proportional to the length of the force vectors, where $F_1 = F_4$, $F_2 = F_3$, and $F_1 = 2F_2$. Which two forces combine to exert zero net torque on the disk? Select two answers.

(A) F_1
(B) F_2
(C) F_3
(D) F_4

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 1: 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
5
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 13 minutes each for questions 1, 4, and 5
Weight
Approximate weights:
Questions 2 and 3: 26% each
Questions 1, 4, and 5: 16% 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.

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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

83

AP® PHYSICS 1 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	Coulomb's law constant, $k = 1/4\pi\varepsilon_0 = 9.0 \times 10^{9}\ \text{N}\cdot\text{m}^2/\text{C}^2$
Electron mass, $m_e = 9.11 \times 10^{-31}$ kg	Universal gravitational constant, $G = 6.67 \times 10^{-11}\ \text{m}^3/\text{kg}\cdot\text{s}^2$
Speed of light, $c = 3.00 \times 10^{8}$ m/s	Acceleration due to gravity at Earth's surface, $g = 9.8\ \text{m/s}^2$

UNIT SYMBOLS								
	meter,	m	kelvin,	K	watt,	W	degree Celsius,	°C
	kilogram,	kg	hertz,	Hz	coulomb,	C		
	second,	s	newton,	N	volt,	V		
	ampere,	A	joule,	J	ohm,	Ω		

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. Assume air resistance is negligible unless otherwise stated.
III. In all situations, positive work is defined as work done <u>on</u> a system.
IV. The direction of current is conventional current: the direction in which positive charge would drift.
V. Assume all batteries and meters are ideal unless otherwise stated.

AP® PHYSICS 1 EQUATIONS

MECHANICS

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$L = I\omega$$

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

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

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

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

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

a = acceleration
A = amplitude
d = distance
E = energy
f = frequency
F = force
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 = volume
v = speed
W = work done on a system
x = position
y = height
α = angular acceleration
μ = coefficient of friction
θ = angle
ρ = density
τ = torque
ω = angular speed

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

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

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

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

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

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

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

ELECTRICITY

$$\left|\vec{F}_E\right| = k\left|\frac{q_1 q_2}{r^2}\right|$$

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

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

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

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

$$R_s = \sum_i R_i$$

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

A = area
F = force
I = current
ℓ = length
P = power
q = charge
R = resistance
r = separation
t = time
V = electric potential
ρ = resistivity

WAVES

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

f = frequency
v = speed
λ = wavelength

GEOMETRY AND TRIGONOMETRY

Rectangle
$A = bh$

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

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

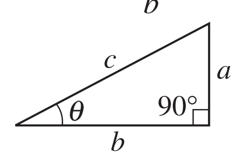
Rectangular solid
$V = \ell w h$

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

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

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

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



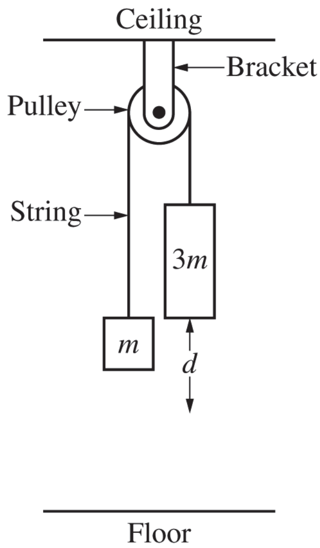
PHYSICS 1

Section II

Time—1 hour and 30 minutes

5 Questions

Directions: Questions 1, 4, and 5 are short free-response questions that require about 13 minutes each to answer and are worth 7 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. (7 points, suggested time 13 minutes)

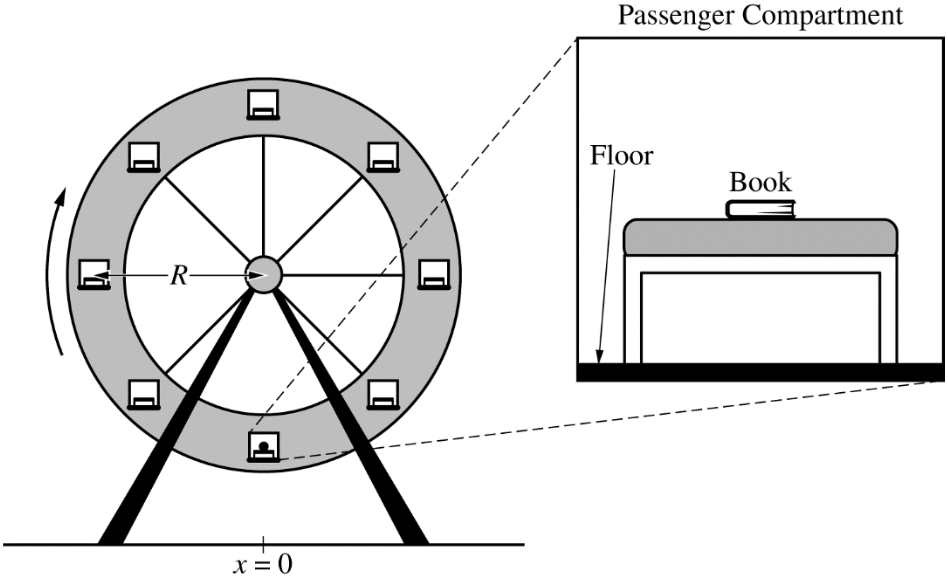
   Two blocks, with masses m and $3m$, are attached to the ends of a string with negligible mass that passes over a pulley, as shown above. The pulley has negligible mass and friction and is attached to the ceiling by a bracket. The blocks are simultaneously released from rest.

   (a) Derive an equation for the speed v of the block of mass $3m$ after it falls a distance d in terms of m, d, and physical constants, as appropriate.

(b) Determine the work done by the string on the two-block system as each block moves a distance *d*.

(c) The acceleration of the center of mass of the blocks-string-pulley system has magnitude a_{COM}. Briefly explain, in terms of any external forces acting on the system, why a_{COM} is less than *g*.

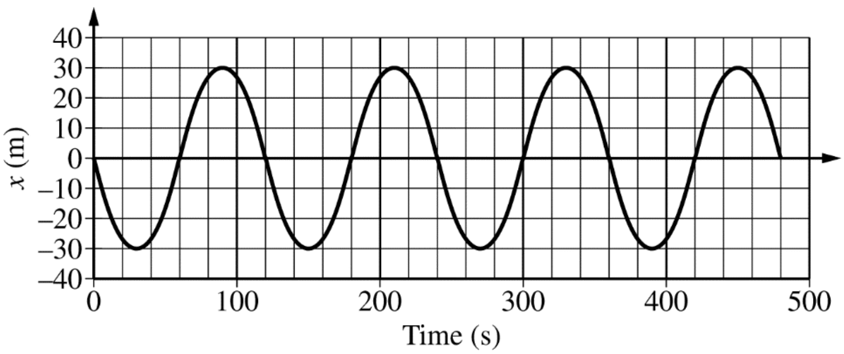
GO ON TO THE NEXT PAGE.



2. (12 points, suggested time 25 minutes)

A passenger compartment of a rotating amusement park ride contains a bench on which a book of mass m_b is placed, as indicated by the dot in the left figure above. The compartment moves with a constant angular speed about the center of the ride along a circular path of radius R. The bench remains horizontal throughout the compartment's motion. The right figure above shows a magnified view of the compartment.

The graph below shows the horizontal (x) component of the book's position as a function of time, where the $+x$-direction is to the right.



(a)

i. Determine the period of revolution of the book.

ii. Calculate the tangential speed v_b (<u>not</u> the angular speed) of the book.

(b)

i. On the dot below, which represents the book, draw and label the forces (not components) that act on the book at the lowest point of its circular path. Each force must be represented by a distinct arrow starting on, and pointing away from, the dot.

ii. At the lowest point of the circular path, the book is moving only in the horizontal direction. In what direction, if any, is the net vertical force on the book?

____ Up ____ Down ____ No direction, since the net vertical force is equal to zero

Without deriving any equations, briefly explain your reasoning in terms of the book's motion.

(c) Derive an algebraic equation for the vertical force that the bench exerts on the book at the lowest point of the circular path in terms of the book's mass m_b, tangential speed v_b, radius R of the path, and physical constants, as appropriate. Do <u>not</u> substitute any numerical values for variables or physical constants.

(d) At the lowest point of the circular path, is the force that the bench exerts on the book greater than, less than, or equal to the weight of the book?

____ Greater than ____ Less than ____ Equal to

Briefly explain how your answers in (b)ii and (c) support your selection.

GO ON TO THE NEXT PAGE.

3. (12 points, suggested time 25 minutes)

A company selling a type of spring makes the following claim: “The elastic potential energy that the spring is capable of storing for a given compression distance does not decrease, even after the spring compresses and/or stretches hundreds of times.” The students in a physics class have decided to test the company’s claim.

(a)

i. State a basic physics principle or law the students could use in designing an experiment to test the company’s claim.

ii. Using the principle or law stated in part (a)i, determine an equation for the elastic potential energy stored in the spring in terms of quantities that can be obtained from measurements made with equipment usually found in a school physics laboratory.

(b) Design an experimental procedure the students could use to collect the data needed to test the company’s claim. Assume equipment usually found in a school physics laboratory is available.

In the table below, list the quantities and associated symbols that would be measured in your experiment and the equipment used to measure them. Also list the equipment that would be used to measure each quantity. You do not need to fill in every row. If you need additional rows, you may add them to the space just below the table.

Quantity to Be Measured	Symbol for Quantity	Equipment for Measurement

(b) Continued

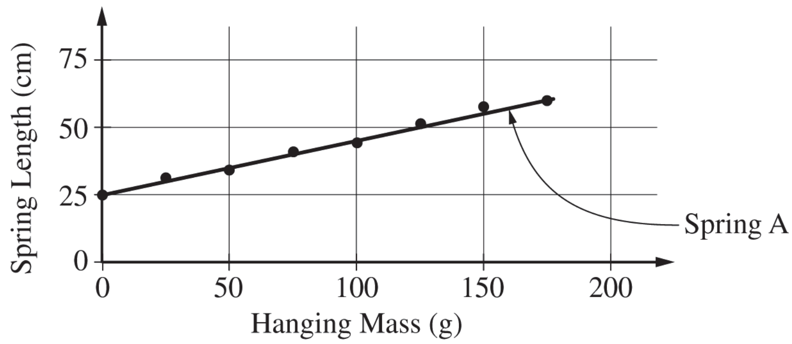
Describe the overall procedure to be used, referring to the table. Provide enough detail so another student could replicate the experiment, including any steps necessary to reduce experimental uncertainty. As needed, use the symbols defined in the table and/or include a simple diagram of the setup.

(c) Explain how the students should analyze the data to determine whether the company's claim is true, i.e., whether the energy stored by the spring for a given compression distance does not decrease after the spring has compressed and/or stretched hundreds of times.

Question 3 continues on the next page.

GO ON TO THE NEXT PAGE.

(d) The students also investigate two springs, spring A and spring B, made by another company. The students hang spring A vertically, attaching blocks of various known masses from the bottom end of the spring and measuring the total length of the spring for each block. The students graph the spring length as a function of hanging mass and draw the line of best fit, as shown below.



i. The students follow the same procedure using spring B, which has the same equilibrium length as spring A but stores more energy than spring A for a given displacement. On the graph above, sketch what the line of best fit could look like for the data obtained using spring B.

ii. The students attach a 100 g block to spring B and let it hang at rest. The students pull the block down by 1 cm, release it, and measure the time interval Δt for one oscillation. The students then repeat the procedure, but pull the block down by 2 cm instead of 1 cm. For which initial displacement, if either, is Δt greater?

____ Δt is greater for the 1 cm displacement.   ____ Δt is greater for the 2 cm displacement.   ____ Δt is the same in both cases.

Briefly explain your reasoning.

THIS PAGE MAY BE USED FOR SCRATCH WORK

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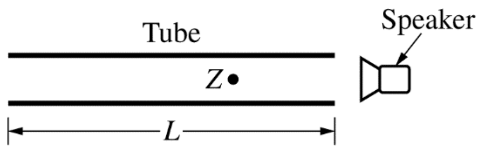


Note: Figure not drawn to scale.

4. (7 points, suggested time 13 minutes)

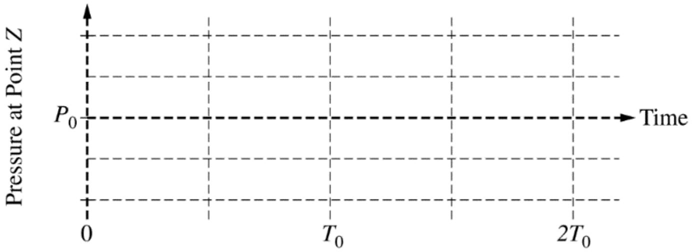
A speaker is placed near a narrow tube of length $L = 0.30$ m, open at both ends, as shown above. The speaker emits a sound of known frequency, which can be varied. A student slowly increases the frequency of the emitted sound waves, without changing the amplitude, until the fundamental frequency f_0 inside the tube is reached and standing waves are produced (fundamental resonance). The speed of sound in air is $340\ \text{m/s}$.

(a)

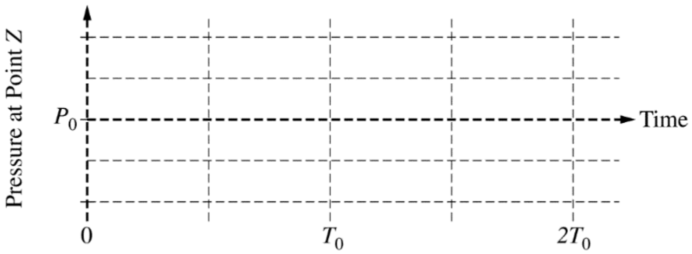
i. Calculate the period T_0 of the sound waves at the fundamental resonance.

ii. For the fundamental resonance, consider the air pressure at point Z inside the tube. On the axes below, sketch the air pressure at point Z as a function of time. At time $t = 0$, the pressure at point Z is P_0, which is the atmospheric pressure.

Note: Do any scratch (practice) work on the grid at the bottom of the page. Only the sketch made on the grid immediately below will be graded.



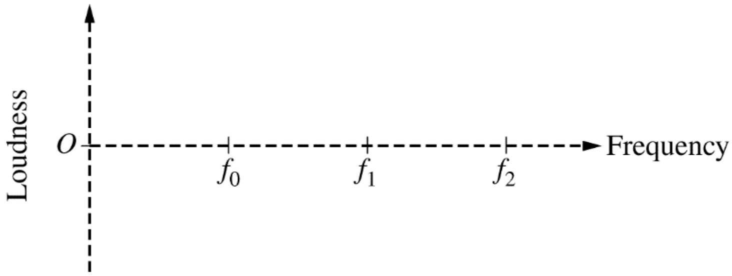
The grid below is provided for scratch work only. Sketches made below will not be graded.



GO ON TO THE NEXT PAGE.

(b) The student continues to slowly increase the frequency of the sound waves emitted by the speaker without making any other changes to the setup. The student hears additional resonances at two higher frequencies, f_1 and f_2.

On the axes below, sketch the loudness of the sound (sound volume) heard by the student as a function of the frequency generated by the speaker for the range of frequencies shown on the horizontal axis. The fundamental frequency is f_0.



(c) The temperature of the air in the tube is increased. As the temperature increases, the speed of sound in the air increases. (Assume the size of the tube does not change). Does the tube's fundamental frequency increase, decrease, or stay the same?

____ Increase ____ Decrease ____ Stay the same

Briefly explain your reasoning.

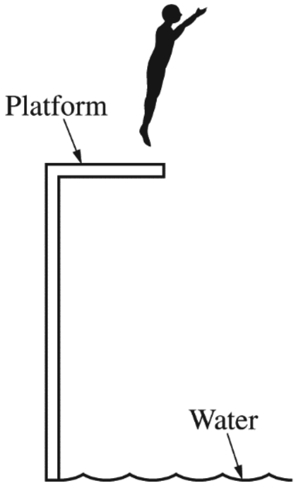


Figure 1

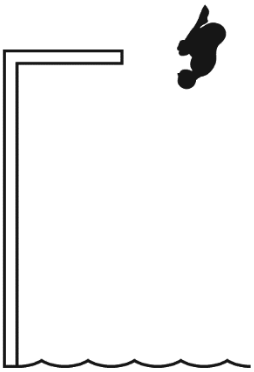


Figure 2

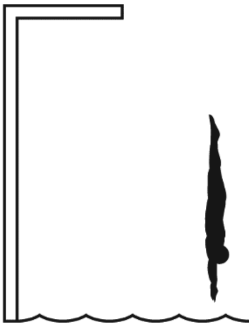


Figure 3

5. (7 points, suggested time 13 minutes)

The figures above show three stages of a dive performed by an athlete. During the dive, the athlete completes several rotations in midair while traveling from the platform to the surface of the water. Figure 1 shows the athlete just after jumping off the platform. Figure 2 shows the athlete rotating in midair. Figure 3 shows the athlete about to enter the water.

(a) In a clear, coherent paragraph-length response that may also contain figures and/or equations, explain why the athlete's angular speed increases between Figure 1 and Figure 2 but decreases between Figure 2 and Figure 3.

(b) Is the <u>rotational</u> kinetic energy $K_{2,\text{rot}}$ of the athlete in Figure 2 greater than, less than, or equal to the <u>rotational</u> kinetic energy $K_{1,\text{rot}}$ of the athlete in Figure 1 ?

____ $K_{2,\text{rot}} > K_{1,\text{rot}}$ ____ $K_{2,\text{rot}} < K_{1,\text{rot}}$ ____ $K_{2,\text{rot}} = K_{1,\text{rot}}$

Briefly explain your answer.

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 1: Algebra-Based
Practice Exam, Section I

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

*Item was not scored.

Multiple-Choice Section for Physics 1
2019 Course Framework Alignment and Rationales

Question 1

Science Practice	Learning Objective	Topic
2.2	5.D.2.5	Conservation of Linear Momentum

(A)	Incorrect. The objects could also be moving to the right or be at rest.
(B)	Incorrect. The objects could also be moving to the left or be at rest.
(C)	Incorrect. The objects could also be moving to the left or right.
(D)	**Correct**. The total momentum of the two-object system is the same immediately before and immediately after the collision. However, the initial speeds of the objects and therefore their initial momenta are not known. Therefore, the total momentum of the two-object system cannot be determined. After the collision, the objects move together in the direction of the unknown momentum of the system, or could remain at rest if the momentum is zero.

Question 2

Science Practice	Learning Objective	Topic
7.2	5.D.2.3	Conservation of Linear Momentum

(A)	Incorrect. This would be the sister's kinetic energy if K referred to the brother's kinetic energy, and it was also assumed that she had the same mass as (incorrect) and twice the speed of the brother when calculating her kinetic energy.
(B)	Incorrect. This would be the sister's kinetic energy if K referred to the brother's kinetic energy. Alternatively, it could also result from the assumption that the brother has the same speed (incorrect) as and twice the mass of the sister when calculating his kinetic energy.
(C)	**Correct**. Since the brother and sister are initially at rest, the total momentum of the brother-sister system is zero. After they push away from each other, the brother and sister will have momenta of equal magnitude but in opposite directions so that the vector sum of their momenta remains zero. In order for the momentum $p = mv$ to have the same magnitude, the brother's speed must be half of the sister's speed since he has twice the mass. Therefore the brother's kinetic energy $K = \frac{1}{2}mv^2$ will be $\frac{1}{2}(2m_{\text{sister}})\left(\frac{v_{\text{sister}}}{2}\right)^2 = \frac{1}{2}(m_{\text{sister}})(v_{\text{sister}})^2\left(2 \times \frac{1}{4}\right), = \frac{1}{2}(m_{\text{sister}})(v_{\text{sister}})^2\left(\frac{1}{2}\right) = \frac{K}{2}$ which is half of the sister's kinetic energy.
(D)	Incorrect. This option is based on the assumption that the brother has the same mass as (incorrect) and half the speed of the sister when calculating his kinetic energy.

Question 3

Science Practice	Learning Objective	Topic
1.5	3.A.1.1	Position, Velocity, and Acceleration

(A)	Incorrect. The acceleration of the cart is in the $+x$ -direction rather than the $-x$ -direction. This choice is based on the assumption that the acceleration range of the cart is entirely in the $-x$ -direction.
(B)	**Correct**. The range of constant acceleration values in the $+x$ -direction may be used to determine the possible range of final positions at $t = 1\text{s}$. The kinematics equation $x = x_0 + v_{x0}t + \frac{1}{2}a_x t^2$ can be solved separately for accelerations of $3\ \text{m/s}^2$ as well as $6\ \text{m/s}^2$, with $x_0 = 10\text{m}$, $v_{x0} = -3\ \text{m/s}$, and $t = 1\text{s}$. For an acceleration of $a_x = 3\ \text{m/s}^2$, the position at $t = 1\text{s}$ would be $x = (10\ \text{m}) + (-3\ \text{m/s})(1\text{s}) + \frac{1}{2}\left(3\ \text{m/s}^2\right)(1\text{s})^2 = (10 - 3 + 1.5)\ \text{m} = 8.5\ \text{m}$. For an acceleration of $a_x = 6\ \text{m/s}^2$, , the position at $t = 1\ \text{s}$ would be $x = (10\text{m}) + (-3\text{m/s})(1\text{s}) + \frac{1}{2}\left(6\text{m/s}^2\right)(1\text{s})^2 = (10 - 3 + 3)\text{m} = 10\text{m}$. Therefore, the position at $t = 1\text{s}$ must be between 8.5m and 10m.
(C)	Incorrect. The cart has an initial velocity of $3\text{m} / \text{s}$ in the $-x$ -direction. This choice is based on the assumption that the cart does not have an initial velocity.
(D)	Incorrect. The cart has an initial velocity of $3\ \text{m/s}$ in the $-x$ -direction. This choice is based on the assumption that the cart has an initial velocity of $3\ \text{m/s}$ in the $+x$ -direction.

Question 4

Science Practice	Learning Objective	Topic
1.4	5.C.3.3	Kirchhoff's Junction Rule, Ohm's Law (Resistors in Series and Parallel)

(A)	**Correct**. Applying the loop rule to any two of the resistors shows that any two, and therefore all three, resistors must have the same potential difference (voltage drop). From Ohm's law, the currents $I = \frac{V}{R}$ are then inversely related to the resistances (V is the same for each resistor). Since the ranking of the resistors is $(R_2 = R_3) > R_1$, the currents will have the reverse ranking and $I_1 > (I_2 = I_3)$. Alternatively, resistors R_2 and R_3 can be combined in parallel for a single equivalent resistance of $R_p = 50\Omega$, which is equal to R_1. Resistor R_1 therefore has the same current as the equivalent resistor R_p, which is twice the current in either R_2 or R_3.
(B)	Incorrect. This choice erroneously gives the currents the same ranking as the resistances of the resistors.
(C)	Incorrect. This choice erroneously gives the currents the same ranking as the potential differences across the resistors.
(D)	Incorrect. Although the current through the ammeter is not known, the relative amounts of the currents through the resistors can be determined.

Question 5

Science Practice		Learning Objective	Topic
6.4		4.C.2.1	Work and Mechanical Energy
(A)	Incorrect. This is the segment with the highest average potential energy for the system, but it is not where the net force on the object has the greatest magnitude.		
(B)	Incorrect. This is the only segment where the net force increases the object's kinetic energy as the object moves in the positive x-direction, but it is not where the net force is greatest in magnitude.		
(C)	Incorrect. This is the segment where the object's kinetic energy is greatest, but the net force on the object is actually zero.		
(D)	**Correct.** The change in the kinetic energy of the object is directly proportional to the net force exerted on the object, and equal in magnitude to the change in potential energy U of the system. ($\Delta E = F_{\|\|}d$, and the distance d is the same for any pair of adjacent points.) Therefore, the greatest net force occurs between adjacent points with the greatest magnitude of change in U. This interval is segment LM, where U changes by $3\,\mathrm{J}$.		

Question 6

Science Practice		Learning Objective	Topic
2.2		4.C.1.1	Work and Mechanical Energy
(A)	Incorrect. This value represents the total mechanical energy of the system.		
(B)	Incorrect. This value represents the potential energy of the system at point H.		
(C)	**Correct**. The total mechanical energy of the system, which is $5\ \mathrm{J}$,, is the sum of the system's potential energy and the kinetic energies of all objects in the system. Since the object that moves along the x-axis is the only moving object in the system, it is the only contributor to the system's kinetic energy. According to the graph, the system's potential energy is $2\,\mathrm{J}$ at point K and so the object must have a kinetic energy of $3\,\mathrm{J}$, for a total system mechanical energy of $5\ \mathrm{J}$.		
(D)	Incorrect. This value represents either the potential energy of the system at point K or the change in the object's kinetic energy between points H and K.		

Question 7

Science Practice	Learning Objective	Topic
1.4	4.B.1.1	Representations of Changes in Momentum

(A)	Incorrect. On segment HI, while the change is zero for the object's kinetic energy, speed, and magnitude of momentum, these quantities themselves are nonzero.
(B)	Incorrect. On segment HI, while the change is zero for the object's kinetic energy, speed, and magnitude of momentum, these quantities themselves are nonzero. On segment IJ, while the system's potential energy is decreasing, there will be an increase in the object's kinetic energy, speed, and magnitude of momentum.
(C)	**Correct**. The total mechanical energy of the system is 5 J for all locations, and equals the sum of the system's potential energy and the object's kinetic energy. (Everything else in the system is not moving and does not contribute to the total kinetic energy.) On segment HI, the system's potential energy is a constant 4 J, so the object's kinetic energy is a constant 1 J in order for the total mechanical energy to remain at 5 J. Since the object's kinetic energy is a positive constant, its speed and also the magnitude of its momentum must be positive constants as well. On segment IJ, the system's potential energy is decreasing, so the object's kinetic energy must be increasing for the total mechanical energy to remain at 5 J. Since the object's kinetic energy is increasing, its speed and also the magnitude of its momentum must be increasing as well.
(D)	Incorrect. On segment IJ, while the system's potential energy is decreasing, there will be an increase in the object's kinetic energy, speed, and magnitude of momentum.

Question 8

Science Practice	Learning Objective	Topic
6.4	6.D.3.2	Interference and Superposition (Waves in Tubes and on Strings)

(A)	Incorrect. A tube that is open at one end and closed at another end will have an antinode at the open end (with respect to the maximum displacement of the particles in the air) and a node at the closed end. The distance between a node and an antinode for a standing wave is $\frac{\lambda}{4}$. The second standing wave is established in the case where $L_0 = \frac{\lambda}{4} + \frac{\lambda}{2} = \frac{3\lambda}{4}$. The third standing wave is established in the case where $L_0 = \frac{3\lambda}{4} + \frac{\lambda}{2} = \frac{5\lambda}{4}$.
(B)	**Correct**. The wavelength of a wave is related to the velocity of the wave as it travels through the medium and the frequency of the wave is given by the equation $\lambda = \frac{v}{f}$, or $v = \lambda f$. The medium that a mechanical wave travels through determines the speed of the wave, which means that a change in the frequency of the wave will only change the wavelength of the wave. In both tubes, the fourth possible standing wave above the first harmonic is shown. The wavelength of the sound wave produced in tube X is different from the wavelength of the sound wave produced in tube Y. Therefore, if the speed of the sound waves are the same for both tubes, then the frequency of the tuning forces used to produce the sound waves in both tubes must be different for each tube.
(C)	Incorrect. Since the standing wave produced in tube X has the same number of nodes and antinodes (with respect to the maximum displacement of the particles in the air) as the standing wave produced in tube Y, the length of the tube in which sound waves can be produced is different. A tube that is open at one end and closed at another end will have an antinode at the open end (with respect to the maximum displacement of the particles in the air) and a node at the closed end. The distance between a node and an antinode for a standing wave is $\frac{\lambda}{4}$. The first harmonic is established in the case where $L = \frac{\lambda}{4}$ where n is a positive, odd, whole number starting with $n = 1$. Therefore, the wavelength of a standing wave for a given tube length will be $\lambda = \frac{4L}{n}$. The length of the tube affects the wavelength of the standing wave for a given value of n.
(D)	Incorrect. Although the tubes are identical, the length of the tube that allows for the production of standing waves of sound is different for each tube.

Question 9 was not used in scoring.

Question 10

<table>
<tr><th colspan="2">Science Practice</th><th>Learning Objective</th><th>Topic</th></tr>
<tr><td colspan="2">7.2</td><td>6.B.4.1</td><td>Periodic Waves</td></tr>
<tr><td>(A)</td><td colspan="3">Incorrect. This solution is based on the assumption that the wave speed is equal to the amplitude of the wave divided by time in which the object vertically travels from the crest of a wave to the next trough.</td></tr>
<tr><td>(B)</td><td colspan="3">Incorrect. This solution is based on the assumption that the average vertical speed of the floating object is equal to the speed of the water wave.</td></tr>
<tr><td>(C)</td><td colspan="3">Correct. The wavelength of the water wave is $\lambda = 20\,\text{m}$, the distance between two adjacent crests of the wave. In a time of $2\,\text{s}$, the object vertically travels from a crest of a wave to the next trough as the wave propagates through the water. This means that the wave has moved one-half of a wavelength. Therefore, the wave has traveled a distance of $\frac{\lambda}{2} = \frac{20\,\text{m}}{2} = 10\,\text{m}$ in a time of $2\,\text{s}$, and its speed is $\frac{10\,\text{m}}{2\,\text{s}} = 5\,\frac{\text{m}}{\text{s}}$.</td></tr>
<tr><td>(D)</td><td colspan="3">Incorrect. This solution is based on the assumption that the wave has moved a full wavelength in the stated $2\,\text{s}$ time interval.</td></tr>
</table>

Question 11

Science Practice	Learning Objective	Topic
5.1	5.C.3.2	Kirchhoff’s Junction Rule, Ohm’s Law (Resistors in Series and Parallel)

(A)	Incorrect. Point 1 is located at a position before the current splits at the top-center junction. Point 2 is located at a position after the current has split at the junction. The currents measured at these points do not correspond to the electrons that enter and leave the same resistor or resistor combination.
(B)	**Correct**. To test the hypothesis, current measurements must be made that correspond to the electrons that enter and leave the same resistor or resistor combination. If all electrons that enter each resistor in the circuit also leave each resistor, then ammeters placed at points 1 and 5 will register equal currents. The hypothesis could also be tested for just the rightmost resistor by placing ammeters at points 3 and 4, but this option was not provided.
(C)	Incorrect. Points 2 and 4 are located in different branches of the circuit, so the currents at these points do not correspond to the electrons that enter and leave the same resistor or resistor combination.
(D)	Incorrect. Point 3 is located at a position before the current recombines at the bottom-center junction. Point 5 is located at a position after the current has recombined at the junction. The currents measured at these points do not correspond to the electrons that enter and leave the same resistor or resistor combination.

Question 12

Science Practice	Learning Objective	Topic
7.2	3.A.4.2	Newton's Third Law and Free-Body Diagram

(A)	Incorrect. This solution is based on the assumption that the doll does not exert a force on the robot when the robot exerts a force on the doll. However, Newton's third law of motion should be considered when analyzing the situation.
(B)	Incorrect. This solution is based on the assumption that an external force of $0.3\,\text{N}$ is exerted on the doll-robot system, which has a mass of $0.5\,\text{kg}$. The value of $0.60\ \text{m/s}^2$ would then represent the acceleration of the system.
(C)	**Correct**. According to Newton's third law of motion, if object A exerts a force on object B, then object B exerts a force of equal magnitude but opposite direction on object A. Therefore, if the robot pushes the doll with a force of $0.3\,\text{N}$, the doll exerts a force on the robot of $0.3\,\text{N}$. Newton's second law of motion can then be used to calculate the robot's acceleration. $\vec{a} = \frac{\Sigma\vec{F}}{m}$ $a_{\text{robot}} = \frac{F_{\text{doll}}}{m_{\text{robot}}}$ $a_{\text{robot}} = \frac{0.3\,\text{N}}{0.3\,\text{kg}}$ $a_{\text{robot}} = 1\ \text{m/s}^2$
(D)	Incorrect. This value represents the acceleration of the doll.

Question 13

Science Practice	Learning Objective	Topic
2.2	5.D.1.5	Conservation of Linear Momentum

(A)	**Correct**. This is the only choice in which both the total momentum and the total kinetic energy of the block-sphere system do not change as a result of the collision. This is the only physically plausible outcome for an elastic collision. Assume that the speed of the sphere immediately after the collision is $\frac{2v_0}{3}$; a short time later it will be slightly less due to its upward swing on the cord. The initial momentum of the system is due to the block and is mv_0 toward the right, which can be taken as the positive direction. The sphere is initially at rest and has a rightward force exerted on it by the block, so the sphere must be moving toward the right after collision. If the velocities of the block and sphere immediately after the collision are $-\frac{v_0}{3}$ and $+\frac{2v_0}{3}$, respectively, then the total momentum immediately after the collision is $p = -m\frac{v_0}{3} + 2m\frac{2v_0}{3} = \left(-\frac{1}{3} + \frac{4}{3}\right)mv_0 = mv_0$, which equals the initial momentum. The initial kinetic energy of the system is due to the block and is $\frac{1}{2}mv_0^2$. For the speeds given in this choice, the total kinetic energy immediately after the collision is $K = \frac{1}{2}m\left(\frac{v_0}{3}\right)^2 + \frac{1}{2}2m\left(\frac{2v_0}{3}\right)^2 = \frac{1}{2}mv_0^2\left(\frac{1}{9} + 2 \times \frac{4}{9}\right) = \frac{1}{2}mv_0^2$, which equals the initial kinetic energy.
(B)	Incorrect. For this choice to be true, the total momentum of the block-sphere system would have to change from its initial value of mv_0 to a value of $p = m\frac{v_0}{3} + 2m\frac{2v_0}{3} = \left(\frac{1}{3} + \frac{4}{3}\right)mv_0 > mv_0$ as a result of the collision. This is not physically plausible.
(C)	Incorrect. For this choice to be true, the total momentum of the block-sphere system would have to change from its initial value of mv_0 to a value of $2mv_0$ as a result of the collision. This is not physically plausible.
(D)	Incorrect. For this choice to be true, the total momentum of the block-sphere system would have to change from its initial rightward direction to a leftward direction as a result of the collision. This is not physically plausible.

Question 14

Science Practice	**Learning Objective**	**Topic**
6.4	5.D.2.3	Conservation of Linear Momentum

(A)	Incorrect. This choice is based on the assumption that the collision is elastic and that kinetic energy remains the same immediately before, during, and immediately after the collision.
(B)	Incorrect. The combined mass of the blocks immediately after the collision is $4m$ instead of $2m$. The combined mass of the blocks immediately after the collision is not equal to the average of the blocks' masses.
(C)	Incorrect. The ratio $K_f : K_i$ is not equal to the ratio of the masses of the blocks.

(D)	**Correct**. The final kinetic energy of the two-block system must be divided by the initial kinetic energy of the two-block system. This ratio can be determined by applying the law of conservation of momentum. A net external force is not exerted on the two-block system, which means that the total momentum of the system remains the same from immediately before the collision to immediately after the collision. The block of mass m is treated as block X, and the block of mass $3m$ is treated as block Y. Determine the final speed of the system. $\Sigma\overrightarrow{p_0} = \Sigma\overrightarrow{p_f}$ $p_{X0} + p_{Y0} = p_{X0} + p_{Y0}$ $m_X v_{X0} + m_Y v_{Y0} = m_X v_{Xf} + m_Y v_{Yf}$ $mv_{X0} + (3m)(0) = (m + 3m)v_f$ $v_{X0} = 4v_f$ $v_f = \dfrac{v_{X0}}{4}$ Determine the initial kinetic energy of the system immediately before the collision. $K = \dfrac{1}{2}mv^2$ $K_i = \dfrac{1}{2}mv_X^2$ Determine the final kinetic energy of the system immediately after the collision. $K = \dfrac{1}{2}mv^2$ $K_f = \dfrac{1}{2}(m + 3m)\left(\dfrac{v_X}{4}\right)^2$ $K_f = \dfrac{1}{2}(4m)\dfrac{v_X^2}{16}$ $K_f = \left(\dfrac{4}{16}\right)\dfrac{1}{2}mv_X^2$ $K_f = \left(\dfrac{4}{16}\right)\dfrac{1}{2}mv_X^2$ $K_f = \dfrac{K_i}{4}$ Determine the ratio $K_f : K_i$. $\dfrac{K_f}{K_i} = \left(\dfrac{K_i}{4}\right)\left(\dfrac{1}{K_i}\right) = \dfrac{1}{4}$

Question 15

Science Practice	Learning Objective	Topic
2.2	2.B.2.2	Gravitational Field / Acceleration Due to Gravity on Different Planets

(A)	Incorrect. Although the radius of the planet is 90% the radius of Earth, that does not mean that the acceleration of the meteoroid is 90% that of the gravitational acceleration at Earth's surface.
(B)	Incorrect. This is the wrong magnitude and direction for the meteoroid's acceleration.
(C)	**Correct**. The meteoroid's acceleration must be in the same direction as the net force exerted on the meteoroid. The net force is entirely due to the gravitational force exerted by the planet, which is toward the center of the planet. Newton’s law of universal gravitation can be used to determine the magnitude of the meteoroid's acceleration. First, note that the distance from the meteoroid to the planet's center is $(0.9 \times 6370 + 600)\text{km} = 6333\text{km}$, which is very nearly ($99.4\%$ of) the radius of Earth. The gravitational force on the meteoroid is then $F_g = G\dfrac{m_1 m_2}{r^2} \approx G\dfrac{m_{\text{Earth}} m_{\text{meteoroid}}}{r_{\text{Earth}}^2}$. Dividing by the mass of the meteoroid gives an acceleration for the meteoroid of $a_{\text{meteoroid}} = \dfrac{F_g}{m_{\text{meteoroid}}} \approx G\dfrac{m_{\text{Earth}}}{r_{\text{Earth}}^2} = g \approx 10\dfrac{\text{m}}{\text{s}^2}$.
(D)	Incorrect. The meteoroid's acceleration is not in the direction of the meteoroid's motion.

Question 16

Science Practice		Learning Objective	Topic
7.2		5.E.1.1	Conservation of Angular Momentum
(A)	Incorrect. Although the planet's gravitational force does provide a centripetal force on the meteoroid, a centripetal force cannot provide a torque about the center of the circular orbit where the planet's center of mass is located.		
(B)	Incorrect. Although the meteoroid's direction of motion is constantly changing, this only indicates that a force, not necessarily a torque, is exerted on the meteoroid.		
(C)	Incorrect. The force exerted by the planet on the meteoroid is not negligible, and is responsible for the meteoroid moving in a circular orbit rather than a straight line.		
(D)	**Correct**. The planet exerts a force toward the center of mass of the planet, which is parallel to the meteoroid's position vector relative to the planet's center of mass. The position vector therefore has no component perpendicular to the force, so the torque $\tau = r_{\perp}F$ is zero because $r_{\perp}$ is zero.		

Question 17

Science Practice		Learning Objective	Topic
1.4		5.B.3.3	Conservation of Energy, the Work-Energy Principle, and Power
(A)	Incorrect. The rotational kinetic energy of the satellite changes as a result of the firing of the thrusters.		
(B)	Incorrect. The rotational kinetic energy of the satellite changes as a result of the firing of the thrusters, but the satellite's orbital path does not.		
(C)	**Correct**. Each thruster exerts a clockwise torque on the satellite, causing the satellite to rotate. The rotational kinetic energy of the satellite changes from being initially zero to a positive value. Since the other contributions to the mechanical energy of the satellite-Earth system (translational kinetic energy, gravitational potential energy) do not change, the increase in rotational kinetic energy means that the overall mechanical energy increases. Note also that the forces (not the torques) exerted by the identical thrusters are in opposite directions, and so do not change the net force exerted on the satellite. The satellite therefore continues in the same orbital path it would have if the thrusters did not fire.		
(D)	Incorrect. The satellite's orbital path does not change.		

Question 18

Science Practice	Learning Objective	Topic
2.2	3.C.2.1	Electric Force

(A)	Incorrect. This solution is based on the assumption that $\left(\frac{R}{5}\right)^2 = \frac{R^2}{5}$ rather than $\frac{R^2}{25}$.
(B)	Incorrect. This solution is based on the assumption that $\left(\frac{R}{5}\right)^2 = \frac{R^2}{5}$ rather than $\frac{R^2}{25}$, and the assumption that $F = k\frac{q^2}{R^2}$ rather than $F = 2k\frac{q^2}{R^2}$.
(C)	**Correct**. An application of Coulomb's law in the case for two point charges should be applied in this situation. Determine the value of F in terms of known quantities. $\lvert F_E\rvert = k\left\lvert\frac{q_1q_2}{r^2}\right\rvert$ $\lvert F\rvert = k\left\lvert\frac{(2q)(q)}{R^2}\right\rvert$ $F = 2k\frac{q^2}{R^2}$ Determine the magnitude of force under consideration F_1 in terms of F. $\lvert F_E\rvert = k\left\lvert\frac{q_1q_2}{r^2}\right\rvert$ $\lvert F_1\rvert = k\left\lvert\frac{(2q)(3q)}{\left(\frac{R}{5}\right)^2}\right\rvert$ $F_1 = k\frac{6q^2}{R^2}\left(\frac{25}{1}\right)$ $F_1 = (150)k\frac{q^2}{R^2}$ $F_1 = (75)\left(2k\frac{q^2}{R^2}\right)$ $F_1 = (75)\left(2k\frac{q^2}{R^2}\right)$ $F_1 = 75F$
(D)	Incorrect. This solution is based on the assumption that $F = k\frac{q^2}{R^2}$ rather than $F = 2k\frac{q^2}{R^2}$.

Question 19

Science Practice	Learning Objective	Topic
6.4	5.B.4.1	Conservation of Energy, the Work-Energy Principle, and Power

(A)	Incorrect. While this height is where the potential energy of the spring is a minimum, the gravitational potential energy between the block and Earth must also be taken into account to determine where the potential energy is a minimum for the block-spring-Earth system.
(B)	**Correct**. Since the block can remain at rest on the spring after being slowly lowered to a height L_{eq}, this height represents a minimum in the potential energy of the block-spring-Earth system. For the total mechanical energy of the system to remain constant after the block is released, this height must also represent a maximum in kinetic energy for the block.
(C)	Incorrect. While this is the minimum height attained by the block, and therefore where the gravitational potential energy between the block and Earth is a minimum, the potential energy of the spring must also be taken into account to determine where the potential energy is a minimum for the block-spring-Earth system.
(D)	Incorrect. This height is the midpoint between where the block was brought to rest at an earlier time and where it was later released, and so it might be confused with the midpoint of the block's oscillations where there would be a minimum in potential energy. However, after being released the block will oscillate between two heights that have a midpoint at L_{eq}, not $\frac{L_{eq} + L_{comp}}{2}$.

Question 20

Science Practice	Learning Objective	Topic
6.4	4.C.2.1	Work and Mechanical Energy

(A)	**Correct**. Both carts have the same final momentum. But since the mass of the 1 kg cart is half that of the 2 kg cart, the final speed of the 1 kg cart 1 must be twice that of the 2 kg cart in order for the momentum $\vec{p} = m\vec{v}$ to be the same for both carts. Since kinetic energy $K = \frac{1}{2}mv^2$ is proportional to both mass and the square of the speed, the final kinetic energy of the 2 kg cart is half that of the 1 kg cart, or 25 J.
(B)	Incorrect. Although kinetic energy $K = \frac{1}{2}mv^2$ is proportional to mass, which is greater for the 2 kg cart, the different final speeds of the two carts must also be taken into account.
(C)	Incorrect. Although both carts have the same final momentum, they have a different final kinetic energy.
(D)	Incorrect. Although knowing the distance over which the 5 N force was exerted would allow determination of the work done on, and therefore the final kinetic energy of, the 2 kg cart, the 2 kg cart's final kinetic energy can be determined from other information given in the question.

Question 21

Science Practice	**Learning Objective**	**Topic**
1.4	5.B.4.2	Conservation of Energy, the Work-Energy Principle, and Power

(A)	Incorrect. The kinetic energy would be greater than the potential energy for all angles greater than $45°$.
(B)	Incorrect. The kinetic energy would be greater than the potential energy at an angle of $45°$, even though this is half of the $90°$ angle between the lowest point and the horizontal release point.
(C)	**Correct**. If the length of the string is L and the mass of the sphere is M , then the total mechanical energy of the sphere-Earth system is the initial gravitational potential energy MgL . The kinetic and potential energies always sum to MgL , and are equal when each is half of this amount or $0.5MgL$. This occurs when the sphere is at a vertical distance of $0.5L$ above the lowest point, which is also a vertical distance of $0.5L$ below the release point. It may be helpful to draw a figure with the string at an angle of $45°$. When the string angle is $45°$, the sphere is a vertical distance $\frac{L}{\sqrt{2}}$ or approximately $0.7L$ below the release point and approximately $0.3L$ above the lowest point. The potential energy is then approximately $0.3MgL$. The sphere must be higher in order for the potential energy to be the required $0.5MgL$, so the string angle must be closer to the horizontal release point – that is, at an angle smaller than $45°$.
(D)	Incorrect. While the potential and kinetic energies both depend on the mass of the sphere, a determination can be made as to when they are equal without knowing the sphere's mass.

Question 22

Science Practice	**Learning Objective**	**Topic**
6.4	3.D.2.2	Momentum and Impulse

(A)	Incorrect. From 15 s to 20 s, the impulse exerted on the cart is negative. Since the cart had a positive momentum at 15 s, the negative impulse after 15 s means that the cart's positive momentum will decrease in magnitude.
(B)	Incorrect. From 0 s to 15 s, the impulse exerted on the cart is positive. Since the cart was initially at rest, the positive impulse means that the cart's momentum increases steadily from zero between 0 s and 15 s.
(C)	Incorrect. While the magnitude of the cart's momentum does increase at first and later decrease, the cart neither stops nor reverses direction in the time interval shown.
(D)	**Correct**. The area bounded by the force curve and the horizontal axis for a specific interval of time represents the impulse exerted on the cart, and therefore the change in the cart's momentum during that time interval. From 0 s to approximately 15 s, the area bounded by the curve and the horizontal axis, and therefore the impulse exerted on the cart, is positive. Since the cart was initially at rest, the positive impulse means that the cart's momentum increases steadily from zero between 0 s and 15 s. The area of $4\text{ N} \times 15\text{ s} = 60\text{ N} \cdot \text{s}$ is the cart's momentum at 15 s. From 15 s to 20 s, the area bounded by the curve and the horizontal axis, and therefore the impulse exerted on the cart, is negative. Since the cart was initially traveling in the positive direction at 15 s, the negative impulse means that the momentum will start decreasing in magnitude after 15 s. The area of $-8\text{ N} \times 5\text{ s} = -40\text{ N} \cdot \text{s}$ means that, at 20 s, the cart's momentum will be $60\text{ N} \cdot \text{s} - 40\text{ N} \cdot \text{s} = +20\text{ N} \cdot \text{s}$. The cart's momentum is still in the positive direction at 20 s, so the cart does not reverse direction.

Question 23

Science Practice	Learning Objective	Topic
5.1	3.A.1.3	Position, Velocity, and Acceleration

(A)	Incorrect. When the area bound by the best-fit curve and the horizontal axis is negative and equal in magnitude to the positive area from 0s to approximately 3.0s, the remote-controlled car will return to its original position. During $3\text{s} \le t < 5\text{s}$, the remote-controlled car has only been displaced in the positive direction.
(B)	Incorrect. During $5\text{ s} \le t < 7\text{ s}$, the positive area bound by the best-fit curve and the horizontal axis will have a slightly greater magnitude than the negative area will have. This means that the remote-controlled car has been displaced in the positive direction during this time interval. Therefore, the remote-controlled car cannot be at its original position at time $t = 0\text{s}$.
(C)	**Correct**. When given a graph of a system's velocity as a function of time, the area bound between the curve and the horizontal axis is equal to the displacement of the object for the time interval under consideration. From 0s to approximately 3.0s, the area bound by the best-fit curve and the horizontal axis is positive. This means that the remote-controlled car has been displaced in the positive direction during this time interval. At approximately 3.0s, the speed of the remote-controlled car becomes zero. At approximately 5.0s, the car begins to increase its speed in the negative direction. Therefore, the remote-controlled car has reversed its direction. When the area bound by the best-fit curve and the horizontal axis is negative and equal in magnitude to the positive area from 0s to approximately 3.0s, the remote-controlled car will return to its original position. This will occur over the time range $7\text{ s} \le t < 10\text{s}$.
(D)	Incorrect. When the area bound by the best-fit curve and the horizontal axis is negative and equal in magnitude to the positive area from 0s to approximately 3.0s, the remote-controlled car will return to its original position. During $10\text{ s} \le t < 12\text{ s}$, the negative area will have a greater magnitude than the positive area will.

Question 24

Science Practice	Learning Objective	Topic
2.2	6.D.4.2	Interference and Superposition (Waves in Tubes and on Strings)

(A)	Incorrect. This frequency is calculated by incorrectly assuming that the fundamental frequency and the string length are proportional, when in fact they are inversely proportional.
(B)	Incorrect. This option is based on the incorrect assumption that the fundamental frequency does not depend on the length of the string.
(C)	**Correct**. At the fundamental frequency, the standing wave on a string of length L that is fixed at both ends has a wavelength $\lambda = 2L$. First, the wave speed can be determined from the equation $\lambda = \frac{v}{f}$ or $v = \lambda f = (2 \times 0.8\,\text{m})\left(320\,\text{s}^{-1}\right) = 512\ \text{m/s}$. Next, the fundamental frequency for the new string length of $0.65\,\text{m}$ can be determined from $f = \frac{v}{\lambda} = \frac{512\ \text{m/s}}{2 \times 0.65\ \text{m}} = 394\,\text{Hz} \approx 390\,\text{Hz}$. Note that fundamental frequency and string length are inversely proportional, since $v = \lambda f = 2Lf$. Thus, equating $L_1 f_1 = L_2 f_2$ for the two string lengths would also allow determination of the new fundamental frequency: $f_2 = \frac{L_1}{L_2} f_1 = \left(\frac{0.80\ \text{m}}{0.65\ \text{m}}\right) 320\,\text{Hz} = 394\,\text{Hz} \approx 390\,\text{Hz}$.
(D)	Incorrect. This option is based on two incorrect assumptions: first, that the standing wave for the $0.65\,\text{m}$ string length has a wavelength equal to the string length, and second, that the wave speed is equal to $343\ \text{m/s}$, a value typically used for the speed of sound in air.

Question 25

Science Practice	Learning Objective	Topic
5.1	6.B.4.1	Periodic Waves

(A)	**Correct**. This is a situation in which the student must linearize data to produce a graph that has a line of best fit. Data must be linearized so that the line of best fit has the form of $y = mx + b$. The student is plotting data that pertains to the wavelength λ and frequency f for each standing wave produced. The equation to use to determine the speed of the wave is $\lambda = \frac{v}{f}$. To linearize the data, the following quantities correspond to the equation for a line of best fit. $y = \lambda$ $x = \frac{1}{f}$ $b = 0$ Therefore, $m = v$. Graph λ as a function of $\frac{1}{f}$, and the slope of the line of best fit will be v.
(B)	Incorrect. If a graph of λ as a function of f is created, the curve will be that of an inverse function in which the slope always changes between two data points.
(C)	Incorrect. If a graph of λ as a function of $\frac{1}{f}$ is created, the area under the line between two points will not be the same with respect to two other points. Furthermore, the interval used on the horizontal axis to calculate the area would represent a $\Delta\left(\frac{1}{f}\right)$ and the unit for the area would be $\mathrm{m} \cdot \mathrm{s}$, which is not the unit for speed.
(D)	Incorrect. If a graph of λ as a function of f is created, the area under the curve between two points will not be the same with respect to two other points. Furthermore, the interval used on the horizontal axis to calculate the area would represent Δf, which is physically insignificant when determining the speed of a sound wave due to its wavelength and frequency.

Question 26

Science Practice	**Learning Objective**	**Topic**
1.5	3.A.1.1	Rotational Kinematics
(A)	Incorrect. Although the linear speed is constant, that does not mean the linear velocity is also constant. Although the wheel is rotating, that does not mean that the angular speed, which is the rate of rotation, is changing.	
(B)	Incorrect. Although the linear speed is constant, that does not mean the linear velocity is also constant.	
(C)	Incorrect. Although the wheel is rotating, that does not mean that the angular speed, which is the rate of rotation, is changing.	
(D)	**Correct**. The passenger is undergoing uniform circular motion. While the linear speed is constant, the linear velocity, a vector quantity, is changing direction and is therefore changing. Since the passenger's linear speed is constant, the wheel is turning at a constant rate and so the angular speed is constant.	

Question 27

Science Practice	**Learning Objective**	**Topic**
1.1	3.A.2.1	Applications of Circular Motion and Gravitation
(A)	Incorrect. This is the magnitude of the centripetal or net force exerted on the rider, not the normal force.	
(B)	Incorrect. While this is the normal force exerted on the rider at point A, the normal force at point D has a different value.	
(C)	Incorrect. This is the gravitational force. While the normal and gravitational forces are equal in magnitude for situations where an object is on a horizontal surface and not accelerating, the rider is undergoing uniform circular motion is therefore accelerating. As a result, it cannot be assumed that the normal and gravitational forces are equal in magnitude.	
(D)	**Correct**. Since the rider is undergoing uniform circular motion, the net force on the rider is a force of constant magnitude F_c that is always directed toward the center of the rider's circular path. At point A, taking the downward direction to be positive, F_c is found to be $F_c = \Sigma F = F_g - F_{nA} = F_g - 0.8F_g = 0.2F_g$. At point D, this time taking the upward direction to be positive, $F_c = \Sigma F = F_{nD} - F_g$. Solving this equation for the normal force at point D gives $F_{nD} = F_c + F_g = 0.2F_g + F_g = 1.2F_g$.	

Question 28

Science Practice	**Learning Objective**	**Topic**
1.4	5.B.4.2	Conservation of Energy, the Work-Energy Principle, and Power

(A)	Incorrect. This is the kinetic energy of the rock when it is first released with speed v at point A. After being released, the rock picks up speed and will have a greater kinetic energy when it is at the same height as point D.
(B)	Incorrect. This would be the kinetic energy if the block were dropped from rest and then fell a distance R. However, the rock is released with speed v and its change in height is $2R$.
(C)	Incorrect. This would be the kinetic energy if the block were dropped from rest. However, the rock is released with speed v.
(D)	**Correct**. The rock is released at point A and has the same speed v as the person when released. The kinetic energy will then increase by an amount equal to the decrease in potential energy of the rock-Earth system, $mg\Delta y = mg(2R)$ or $2mgR$. Adding this to the initial kinetic energy of $\frac{1}{2}mv^2$ gives a kinetic energy of $\frac{1}{2}mv^2 + 2mgR = \frac{1}{2}m\left(v^2 + 4mgR\right)$. Alternatively, the kinematics equation ${v_y}^2 = {v_{y0}}^2 + 2a_y(y - y_0)$ can be applied to the rock's vertical motion, with downward taken as the positive direction, to find ${v_y}^2 = 0 + 2g(2R) = 4gR$. Since $v_x = v$, the kinetic energy of the rock when it is at the same height as point D is $\frac{1}{2}m\left({v_x}^2 + {v_y}^2\right) = \frac{1}{2}m\left(v^2 + 4mgR\right)$.

Question 29

Science Practice	Learning Objective	Topic
1.1	1.A.5.1	Systems

(A)	Incorrect. Unless air molecules come into contact with the rod, the excess negative charge from the rod will not transfer to the surrounding air.
(B)	**Correct**. According to the law of conservation of charge, electrical charge can be neither created nor destroyed, but it may transfer from one object to another object and from one position to another position. When charge is transferred between two objects, the total net charge of the two objects remains constant. Therefore, if the air around the originally negatively charged rod has a negative charge, excess negative charge must have been transferred from the rod to the air. This transfer of charge took place because air molecules came into contact with the rod.
(C)	Incorrect. This option is based on the assumption that charge is created on the air molecules because of their proximity to the rod, without the molecules coming into contact with the rod.
(D)	Incorrect. This option is based on the assumption that the rod exerts a force that creates negative charge on the air molecules, rather than the negatively charged electrons initially in the rod exerting a repulsive force on each other.

Question 30

Science Practice	Learning Objective	Topic
6.4	5.B.9.3	Ohm’s Law, Kirchhoff’s Loop Rule (Resistors in Series and Parallel)

(A)	Incorrect. Although the current that passes through each resistor is the same, that does not mean that the potential difference across each resistor is the same.
(B)	Incorrect. The potential difference across resistors in series is the same only if each resistor has the same resistance. This is not necessarily true for the circuit shown.
(C)	**Correct.** An application of Kirchhoff’s loop rule can be applied to determine the potential difference across a circuit element or group of circuit elements. According to the rule, the sum of the potential difference values across each circuit element must be equal to the potential difference of the battery. $\Delta V_{\text{Battery}} = \Delta V_1 + \Delta V_2$ $\Delta V_2 = \Delta V_{\text{Battery}} - \Delta V$ $\Delta V_2 = (9\,\text{V}) - (3\,\text{V})$ $\Delta V_2 = 6\,\text{V}$ An equivalent statement of Kirchhoff's loop rule is that a coulomb of charge that passes through the resistors must lose the same $9\,\text{J}$ of energy that is provided by the battery. Since a coulomb of charge loses $3\,\text{J}$ of energy when passing through resistor R_1, it must lose an additional $6\,\text{J}$ of energy when passing through resistor R_2.
(D)	Incorrect. Although the potential difference across resistor R_2 is $6\,\text{V}$, it is incorrect to say that current is used up in either resistor. In fact, two resistors in series must have the same current, in accordance with Kirchhoff's junction rule.

Question 31

Science Practice	Learning Objective	Topic
1.4	5.B.3.3	Conservation of Energy, the Work-Energy Principle, and Power

(A)	Incorrect. While the gravitational potential energy of the object-Earth system is greatest at point Z, and might be incorrectly ranked as equal at points X and Y, the elastic potential energy of the spring has a different ranking than the gravitational potential energy of the object-Earth system.
(B)	Incorrect. While points X and Z are the same distance from where the object hangs in equilibrium, the amount that the spring is stretched is different for these two points. Therefore the potential energy stored in the spring is not equal at points X and Z.
(C)	**Correct.** Elastic potential energy of a spring is described by the equation $U_s = \frac{1}{2}kx^2$. Therefore, the elastic potential energy of the spring increases whenever there is an increase in x, the amount that the spring is stretched (or compressed) relative to its unstretched length. While we do not know what x is when the object is hanging from the spring in equilibrium, we do know that, for point Z, the spring will be stretched so that x has increased by an amount that is less than d. For point X, the spring is stretched so that x has increased by an amount equal to d. For point Y, the spring is stretched so that x has increased by an amount that is greater than d. Since $x_Y > x_X > x_Z$, it can be concluded that $U_Y > U_X > U_Z$.
(D)	Incorrect. While the gravitational potential energy of the object-Earth system is greater at point Z than at point X, the elastic potential energy is greater at point X than at point Z.

Question 32

Science Practice	**Learning Objective**	**Topic**
2.2	3.A.1.1	Position, Velocity, and Acceleration

(A)	**Correct.** The acceleration of the projectile is vertically downward. Therefore, the horizontal velocity component is constant and, in this case, nonzero. Since the horizontal velocity component is a nonzero constant, the graph of the horizontal displacement is a straight line with a nonzero slope, as depicted in the graph on the left. The downward acceleration means that the graph of the vertical velocity component is a straight line with a nonzero slope. Moreover, since the projectile is launched at a 30 degree angle below the horizontal, v_{vert} is initially nonzero, as depicted in the graph on the right.
(B)	Incorrect. The initial vertical velocity of the projectile is nonzero and downward, which means that the graph of v_{vert} should not start at the origin.
(C)	Incorrect. The graph on the left is the horizontal velocity component, not the horizontal displacement.
(D)	Incorrect. The graph on the left is the horizontal velocity component, not the horizontal displacement. The initial vertical velocity of the projectile is nonzero and downward, which means that the graph of v_{vert} should not start at the origin.

Question 33

Science Practice	Learning Objective	Topic
1.4	4.B.1.1	Representations of Changes in Momentum

(A)	Incorrect. The momentum of the system actually changes at $t = 2$ s.
(B)	**Correct.** The velocity of each cart is given by the slope of the corresponding graph, and each cart's momentum is its mass M_c times that slope. Before $t = 2$ s each graph has a slope of $\frac{1\text{m}}{2\text{s}} = \frac{1}{2}\text{m / s}$, so $p_{\text{com}} = \left(M_c \times \frac{1}{2}\text{m / s}\right) + \left(M_c \times \frac{1}{2}\text{m / s}\right) = M_c \times 1\text{m / s}$. After $t = 2$ s, the graphs for carts 1 and 2 have slopes of $\frac{2\text{m}}{3\text{s}} = \frac{2}{3}\text{m / s}$ and zero, respectively. We then have $p_{\text{com}} = \left(M_c \times \frac{2}{3}\text{m / s}\right) + (0) = M_c \times \frac{2}{3}\text{m / s}$, which is smaller than it was before $t = 2$ s.
(C)	Incorrect. Although the speed, and therefore the momentum, for Cart 1 is larger after $t = 2$ s, p_{com} is smaller after $t = 2$ s.
(D)	Incorrect. Although the speed, and therefore the momentum, for Cart 1 increases, it only does so at $t = 2$ s and does not increase at a constant rate for the entire time interval shown. Moreover, p_{com} actually decreases at $t = 2$ s and is constant for the time intervals before and after $t = 2$ s.

Question 34

Science Practice	Learning Objective	Topic
6.4	5.D.2.3	Conservation of Linear Momentum

(A)	Incorrect. This option is based on the assumption that the collision is elastic. However, since the spheres stick together immediately after the collision, the collision is completely inelastic and there is a loss of kinetic energy for the two-sphere system. Alternatively, this option could result from simplifying the expression $\frac{1}{2}(3m)\left(\frac{1}{3}v_i\right)^2$ incorrectly as $\frac{3}{3} \times \frac{1}{2}mv_i^2 = K_i$ instead of the correct $\frac{3}{9} \times \frac{1}{2}mv_i^2 = \frac{1}{3}K_i$.
(B)	Incorrect. This option is the negative of the final kinetic energy $\frac{1}{3}K_i$ of the two-sphere system, not the change in kinetic energy of the system.
(C)	Incorrect. This option is based on using an incorrect mass of $2m$ rather than $3m$ when finding the speed of the two-sphere system immediately after the collision.
(D)	**Correct.** This question can be solved by applying conservation of momentum to the collision between the spheres. Let the speed of sphere 1 immediately before the collision be v_i. In terms of v_i, the kinetic energy and momentum of the two-sphere system immediately before the collision are then $K_i = \frac{1}{2}mv_i^2$ and $p = mv_i$, respectively. Since the momentum of the system does not change during the collision, the common speed v_f of the two spheres immediately after the collision can be found by equating expressions for the momentum of the system immediately before and after the collision: $p = mv_i = (3m)v_f$. Solving for v_f gives $v_f = \frac{1}{3}v_i$. As a result, the kinetic energy of the system immediately after the collision is $K_f = \frac{1}{2}(3m)v_f^2 = \frac{1}{2}(3m)\left(\frac{1}{3}v_i\right)^2 = \frac{3}{9} \times \frac{1}{2}mv_i^2$, which is $\frac{1}{3}K_i$. During the collision, then, the kinetic energy changes by an amount $\Delta K = K_f - K_i = \frac{1}{3}K_i - K_i = -\frac{2}{3}K_i$.

Question 35

Science Practice	Learning Objective	Topic
2.2	4.D.3.1	Angular Momentum and Torque

(A)	Incorrect. The net torque exerted on the wheel is not proportional to the square of the average angular acceleration of the wheel.
(B)	**Correct.** The average angular acceleration must first be determined by applying the correct angular kinematic equation. $\omega = \omega_0 + \alpha t$ $\alpha t = \omega - \omega_0$ $\alpha = \frac{\omega - \omega_0}{t}$ $\alpha = \frac{(0.0 \text{ rad/s}) - (3.0 \text{ rad/s})}{(6.0\text{s})}$ $\alpha = \frac{-3.0 \text{ rad/s}}{6.0 \text{ s}}$ $\alpha = -0.5 \text{ rad/s}^2$ Newton's second law in the context of rotational motion may now be applied to this situation. $\Sigma\tau = I\alpha$ $\Sigma\tau = (2.0 \text{ kg}\cdot\text{m}^2)(0.5 \text{ rad/s}^2)$ $\Sigma\tau = 1.0 \text{ N}\cdot\text{m}$
(C)	Incorrect. The net torque exerted on the wheel is not inversely proportional to the average angular acceleration of the wheel.
(D)	Incorrect. This option corresponds to the average net force exerted on the wheel rather than the average net torque exerted on the wheel.

Question 36

Science Practice	Learning Objective	Topic
1.1	3.A.2.1	Newton's Third Law and Free-Body Diagram

(A)	Incorrect. The force of magnitude P is exerted on block 1 only, not on block $3,$ and should not be in the diagram. The only rightward force on block 3 is from block 2 pushing on block 3 by exerting the contact force of magnitude F_C.
(B)	Incorrect. Block 2 pushes on block 3 by exerting the contact force of magnitude F_C toward the right, so this force should be drawn pointing to the right instead of to the left. The force of magnitude P is exerted on block 1 only, not on block $3,$ and should not be in the diagram.
(C)	**Correct.** Block 2 pushes on block 3 by exerting the contact force of magnitude F_C toward the right. The friction force of magnitude F_f will then be in the opposite direction, or toward the left. The gravitational force F_G is exerted by Earth downward on block $3.$ To balance the downward gravitational force, the surface pushes upward on block 3 with a normal force of magnitude F_N.
(D)	Incorrect. The rough surface exerts a frictional force to the left on block $3.$ This force should be included in the diagram.

Question 131

Science Practice		Learning Objective	Topic
4.2		3.B.1.2	Newton's Second Law
(A)	Incorrect. The mass of the block does not affect the acceleration of the block down the inclined plane.		
(B)	**Correct.** To determine if the velocity of the block is constant, Newton's second law of motion can be applied to determine if the acceleration of the block is zero. Downward along the ramp is considered to be the positive x direction, and upward and perpendicular to the ramp is considered to be the positive y direction. First, determine the normal force exerted on the block by applying Newton's second law to the y direction, in which the acceleration a_y is zero. $\Sigma F_y = ma_y = 0$ $F_n - F_{gy} = 0$ $F_n = F_{gy} = mg\cos\theta$ Next, apply Newton's second law to the x direction, along which the block moves. $\Sigma F_x = ma_x$ $ma_x = \Sigma F_x = F_{gx} - F_f = mg\sin\theta - \mu_k F_n$ $ma_x = mg\sin\theta - \mu_k mg\cos\theta$ $a_x = g\sin\theta - \mu_k g\cos\theta = g(\sin\theta - \mu_k\cos\theta)$ To determine if the block's acceleration a_x is zero, it is necessary to evaluate the expression in parentheses. To do this, the angle θ of the inclined plane and the coefficient of kinetic friction μ_k are needed.		
(C)	Incorrect. Although the block's acceleration a_x is proportional to g, the value of g is not needed to determine whether a_x is zero.		

Question 131 (continued)

(D)	**Correct.** To determine if the velocity of the block is constant, Newton's second law of motion can be applied to determine if the acceleration of the block is zero. Downward along the ramp is considered to be the positive x direction, and upward and perpendicular to the ramp is considered to be the positive y direction. First, determine the normal force exerted on the block by applying Newton's second law to the y direction, in which the acceleration a_y is zero. $\Sigma F_y = ma_y = 0$ $F_n - F_{gy} = 0$ $F_n = F_{gy} = mg\cos\theta$ Next, apply Newton's second law to the x direction, along which the block moves. $\Sigma F_x = ma_x$ $ma_x = \Sigma F_x = F_{gx} - F_f = mg\sin\theta - \mu_k F_n$ $ma_x = mg\sin\theta - \mu_k mg\cos\theta$ $a_x = g\sin\theta - \mu_k g\cos\theta = g(\sin\theta - \mu_k\cos\theta)$ To determine if the block's acceleration a_x is zero, it is necessary to evaluate the expression in parentheses. To do this, the angle θ of the inclined plane and the coefficient of kinetic friction μ_k are needed.

Question 132

Science Practice	Learning Objective	Topic
7.2	3.E.1.1	Work and Mechanical Energy

(A)	**Correct.** The mechanical energy dissipated as the car skids and comes to rest is equal to the initial kinetic energy $K = \frac{1}{2}Mv_0^{\ 2}$, where $M = 600\ \text{kg}$ is the known mass of the car and driver, and v_0 is the unknown initial car speed. This can be shown to be equal to $F_f\Delta x$, where F_f is the frictional force exerted on the car and Δx is the distance the car travels as it skids, as follows. The kinematics relation $v_0^{\ 2} = 2a\Delta x$ and Newton's second law $a = \frac{F_{\text{net}}}{M} = \frac{F_f}{M}$ can be combined as $v_0^{\ 2} = 2\frac{F_f}{M}\Delta x$. Rearranging terms gives $\frac{1}{2}Mv_0^{\ 2} = F_f\Delta x$, as claimed. Since the car is skidding, F_f represents a force of kinetic, not static, friction. It is related to the normal force, which equals the weight of the car and driver, by $F_f = \mu_k F_n = \mu_k Mg$, so the amount of mechanical energy dissipated is $F_f\Delta x = \mu_k Mg\Delta x$. Knowing the coefficient of kinetic friction μ_k and the length Δx of the skid marks would allow the engineers to find the total mechanical energy dissipated during the skid.
(B)	Incorrect. The contact area between the tires and the road does not affect the magnitude of the force of kinetic friction exerted on the car as it skids across the road.
(C)	Incorrect. When a car skids, the frictional force exerted on the car is due to kinetic friction rather than static friction.

(D)	**Correct.** The mechanical energy dissipated as the car skids and comes to rest is equal to the initial kinetic energy $K = \frac{1}{2}Mv_0^2$, where $M = 600\text{ kg}$ is the known mass of the car and driver, and v_0 is the unknown initial car speed. This can be shown to be equal to $F_f\Delta x$, where F_f is the frictional force exerted on the car and Δx is the distance the car travels as it skids, as follows. The kinematics relation $v_0^2 = 2a\Delta x$ and Newton's second law $a = \frac{F_{\text{net}}}{M} = \frac{F_f}{M}$ can be combined as $v_0^2 = 2\frac{F_f}{M}\Delta x$. Rearranging terms gives $\frac{1}{2}Mv_0^2 = F_f\Delta x$, as claimed. Since the car is skidding, F_f represents a force of kinetic, not static, friction. It is related to the normal force, which equals the weight of the car and driver, by $F_f = \mu_k F_n = \mu_k Mg$, so the amount of mechanical energy dissipated is $F_f\Delta x = \mu_k Mg\Delta x$. Knowing the coefficient of kinetic friction μ_k and the length Δx of the skid marks would allow the engineers to find the total mechanical energy dissipated during the skid.

Question 133

Science Practice	Learning Objective	Topic
1.1	6.D.1.1	Interference and Superposition (Waves in Tubes and on Strings)

(A)	Incorrect. Between $5 \le x \le 6$ the two waves would constructively interfere so that the height of the resultant wave is 6 units tall above the horizontal axis. This is not what is shown in the figure. There are other instances in which the waves interfere that do not match what is shown in the figure.
(B)	**Correct.** At $2\ \mathrm{s}$ before this graph was created, the wave pulse traveling toward the left and the wave pulse traveling toward the right would destructively interfere between $4 \le x \le 5$ so that the two wave pulses completely cancel each other. Between $5 \le x \le 6$ the two waves would constructively interfere so that the height of the resultant wave is 3 units tall above the horizontal axis. Between $6 \le x \le 8$, the wave pulse traveling to right has a height of 1 unit below the horizontal axis.
(C)	Incorrect. Between $7 \le x \le 8$ the two waves would constructively interfere so that the height of the two wave pulses completely cancel each other. This is not what is shown in the figure. There are other instances in which the waves interfere that do not match what is shown in the figure.
(D)	**Correct.** At $2\ \mathrm{s}$ before this graph was created, the wave pulse traveling toward the left and the wave pulse traveling toward the right would constructively interfere between $5 \le x \le 6$ so that the height of the resultant wave is 3 units tall above the horizontal axis. Between $6 \le x \le 7$, the two waves would destructively interfere so that the height of the resultant wave is 1 unit tall below the horizontal axis. Between $7 \le x \le 8$, the wave pulse traveling to the right has a height of 1 unit below the horizontal axis.

Question 134

Science Practice	**Learning Objective**	**Topic**
6.4	3.F.2.1	Torque and Angular Acceleration

<table>
<tr><td>(A)</td><td>Incorrect. The torque produced by F_1 is $\frac{RF_1}{2}$ counterclockwise.
While the force F_3 is in the opposite direction of F_1, they produce torques in the same direction (both counterclockwise). Consequently, the torques exerted by F_1 and F_3, while of the same magnitude, do not combine to exert zero net torque.</td></tr>
<tr><td>(B)</td><td>Correct. The torque exerted on an object by a force F is $\tau = r_{\perp}F = rF\sin\theta$. Since F_1, F_2, and F_3 all exert torques in the same (counterclockwise) direction, no two of them can be combined to produce a net torque of zero. One of them must combine with the torque exerted by F_4, the only force that exerts a clockwise torque, in order to produce zero net torque.

The magnitude of the torque exerted by F_4 is

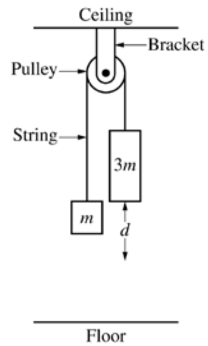
$$\tau_4 = rF\sin\theta = \frac{R}{2}F_4\sin(30°) = \frac{R}{2}F_4\frac{1}{2} = \frac{1}{4}RF_4.$$
This equals the magnitude of the torque exerted by F_2, which is

$$\tau_2 = rF\sin\theta = \frac{R}{2}F_2\sin(90°) = \frac{R}{2}\cdot\frac{F_1}{2} = \frac{R}{2}\cdot\frac{F_4}{2} = \frac{1}{4}RF_4 = \tau_4.$$
Since F_2 and F_4 exert torques of equal magnitude in opposite directions, they combine to exert zero net torque on the disk.</td></tr>
<tr><td>(C)</td><td>Incorrect. The torque produced by F_3 is $RF_3 = \frac{RF_1}{2}$ counterclockwise. While the force F_1 is in the opposite direction of F_3, they produce torques in the same direction (both counterclockwise). Consequently, the torques exerted by F_1 and F_3, while of the same magnitude, do not combine to exert zero net torque.</td></tr>
</table>

(D)	**Correct.** The torque exerted on an object by a force F is $\tau = r_{\perp}F = rF\sin\theta$. Since F_1, F_2, and F_3 all exert torques in the same (counterclockwise) direction, no two of them can be combined to produce a net torque of zero. One of them must combine with the torque exerted by F_4, the only force that exerts a clockwise torque, in order to produce zero net torque. The magnitude of the torque exerted by F_4 is $\tau_4 = rF\sin\theta = \frac{R}{2}F_4\sin(30°) = \frac{R}{2}F_4\frac{1}{2} = \frac{1}{4}RF_4.$ This equals the magnitude of the torque exerted by F_2, which is $\tau_2 = rF\sin\theta = \frac{R}{2}F_2\sin(90°) = \frac{R}{2}\cdot\frac{F_1}{2} = \frac{R}{2}\cdot\frac{F_4}{2} = \frac{1}{4}RF_4 = \tau_4.$ Since F_2 and F_4 exert torques of equal magnitude in opposite directions, they combine to exert zero net torque on the disk.

Question 1

7 points total **Distribution of points**



Two blocks, with masses m and $3m$, are attached to the ends of a string with negligible mass that passes over a pulley, as shown above. The pulley has negligible mass and friction and is attached to the ceiling by a bracket. The blocks are simultaneously released from rest.

<u>Note</u>: Quantities associated with the block of mass m are denoted by a subscript A (e.g. F_{gA}), and quantities associated with the block of mass $3m$ are denoted by a subscript B (e.g. F_{gB}).

(a) LO 3.A.1.1, SP 2.2; LO 4.A.2.3, SP 1.4, 2.2; LO 4.A.3.1, SP 2.2; LO 4.C.1.1, SP 1.4, 2.1, 2.2; LO 5.B.4.2, SP 1.4, 2.1, 2.2
4 points

Derive an equation for the speed v of the block of mass $3m$ after it falls a distance d in terms of m, d, and physical constants, as appropriate.

For using an appropriate equation for Newton's second law		1 point
$\Sigma\vec{F} = m\vec{a}$		
For using Newton's second law to find the magnitude of the common acceleration of the blocks		1 point
Let F_{gA} and F_{gB} be the gravitational forces exerted on the blocks of mass m and $3m$, respectively.		
Example 1: Apply Newton's second law to the two-block system along the path of motion		
$\Sigma\vec{F} = (3m + m)\vec{a}$ $F_{gB} - F_{gA} = (3m + m)a$ $3mg - mg = 4ma$ $2mg = 4ma$ $a = 2mg/4m = 2g/4 = g/2$		

Question 1 (continued)

Distribution of points

(a) (continued)

Example 2: Apply Newton's second law to each block separately, and eliminate the tension force F_T		
For block B: $\Sigma\vec{F} = 3m\vec{a}$ $F_{gB} - F_T = 3ma$ $3mg - F_T = 3ma$ $F_T = 3mg - 3ma$ For block A: $\Sigma\vec{F} = m\vec{a}$ $F_T - F_{gA} = ma$ $3mg - 3ma - mg = ma$ $4ma = 2mg$ $a = 2mg/4m = 2g/4 = g/2$		
For using correct kinematics equation(s) to find the speed of the block		1 point
Example 1: $v_y^2 = v_{y0}^2 + 2a_y(y - y_0)$		
Example 2: $y = y_0 + v_{y0}t + 1/2\,a_y t^2$ and $v_y = v_{y0} + a_y t$		
For a correct answer, or an answer consistent with the acceleration identified earlier, with supporting work		1 point
Example 1: $v_y^2 = v_{y0}^2 + 2a_y(y - y_0)$ $v_y^2 = (0)^2 - 2(\frac{g}{2})(0 - d) = (-g)(-d) = gd$ $v_y = \pm\sqrt{gd}$ $\lvert v_y \rvert = \sqrt{gd}$		
Example 2: First apply $y = y_0 + v_{y0}t + 1/2\,a_y t^2$ $0 = d + (0)(t) - (1/2)(g/2)t^2$ $-d = -(g/4)t^2$ $t^2 = 4d/g$, thus $t = \pm 2\sqrt{d/g}$ $\lvert t \rvert = 2\sqrt{d/g}$ Then apply $v_y = v_{y0} + a_y t$ $v_y = (0) - (g/2)(2\sqrt{d/g}) = -\sqrt{gd}$ $\lvert v_y \rvert = \sqrt{gd}$		

Question 1 (continued)

Distribution of points

(a) (continued)

Alternate solution (using conservation of energy)		*Alternate points*
For using an appropriate equation for conservation of energy		*1 point*
Example 1: $-\Delta U = \Delta K$		
Example 2: $U_{iB} + U_{iA} + K_{iB} + K_{iA} = U_{fB} + U_{fA} + K_{fB} + K_{fA}$		
For correctly relating the types of energy present (e.g., correct expressions are used for the gravitational potential energy of both mass-Earth systems and the kinetic energy of both masses)		*1 point*
For correct qualitative application for the upward motion of the block of mass M (i.e. - appropriate signs for gravitational potential energy terms for the two blocks)		*1 point*
For a correct answer with supporting work		*1 point*
Example 1: $-\Delta U = \Delta K$ $-(\Delta U_B + \Delta U_A) = K_B + K_A$ $3mgd - mgd = (1/2)(3m)v^2 + (1/2)(m)v^2$ $2mgd = 2mv^2$ $gd = v^2$ $v = \pm\sqrt{gd}$ $\lvert v \rvert = \sqrt{gd}$		
Example 2: $U_{iB} + U_{iA} + K_{iB} + K_{iA} = U_{fB} + U_{fA} + K_{fB} + K_{fA}$ $3mgd + mg(0) + (0) + (0) = 3mg(0) + mgd + (1/2)(3m)v^2 + (1/2)mv^2$ $3mgd = mgd + 2mv^2$ $3gd - gd = 2v^2$ $2gd = 2v^2$ $gd = v^2$ $v = \pm\sqrt{gd}$ $\lvert v \rvert = \sqrt{gd}$		

Question 1 (continued)

Distribution of points

(b) LO 5.B.5.5, SP 2.2, 6.4
1 point

Determine the work done by the string on the two-block system as each block moves a distance d.

For a correct answer of zero OR an algebraic expression (in terms of m, d, and/or g) that is equivalent to zero		1 point
<u>Note</u>: This point can be earned if an incorrect unit is written or if no unit is indicated.		
Example 1: 0 J		
Example 2: $W_T = F_T d + (-F_T d) = (3/2)mgd - (3/2)mgd = 0\text{ J}$		
Example 3: $W_S + W_g = \Delta K$ $W_S = \Delta K - W_g$ $= (1/2)(m+3m)v^2 - (3mgd - mgd)$ $= 2mv^2 - 2mgd = 2mgd - 2mgd = 0\text{ J}$		

(c) LO 4.A.2.3, SP 1.4, 2.2; LO 4.A.3.1, SP 2.2
2 points

The acceleration of the center of mass of the blocks-string-pulley system has magnitude a_{COM}. Briefly explain, in terms of any external forces acting on the system, why a_{COM} is less than g.

For indicating that there is an upward force on the system		1 point
<u>Note</u>: String tension is NOT a force on the system because the string is part of the system		
For relating the net force to the acceleration of the center of mass to show that $a_{COM} < g$ OR for showing that F_{net} is less than the weight of the system		1 point
Example explanation: The force of gravity acts downward on the system, but there is an upward external force exerted on the pulley by the bracket attached to the ceiling, This makes the net force on the system less than the weight of the system. Thus, the acceleration of the system is less than g: $F_{net} = ma_{COM}$ and if $F_{net} < mg$ then $a_{COM} < g$.		
Claim (given): a_{COM} is less than g. Evidence: The system is supported at the pulley by the bracket (shown in earlier figure). Reasoning: The upward supporting force exerted by the bracket makes the net force on the system less than the weight of the system. Thus, the acceleration of the system is less than g.		

Question 1 (continued)

LOs

Learning Objective (3.A.1.1): The student is able to express the motion of an object using narrative, mathematical, and graphical representations. [**See Science Practices 1.5, 2.1, 2.2**]

Learning Objective (4.A.2.3): The student is able to create mathematical models and analyze graphical relationships for acceleration, velocity, and position of the center of mass of a system and use them to calculate properties of the motion of the center of mass of a system. [**See Science Practices 1.4 and 2.2**]

Learning Objective (4.A.3.1): The student is able to apply Newton's second law to systems to calculate the change in the center-of-mass velocity when an external force is exerted on the system. [**See Science Practice 2.2**]

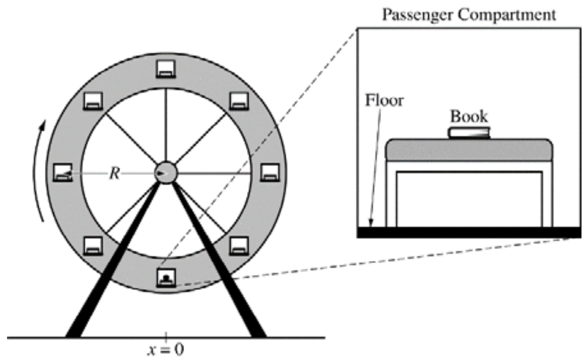
Learning Objective (4.C.1.1): The student is able to calculate the total energy of a system and justify the mathematical routines used in the calculation of component types of energy within the system whose sum is the total energy. [**See Science Practices 1.4, 2.1, and 2.2**]

Learning Objective (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. [**See Science Practices 1.4, 2.1, and 2.2**]

Learning Objective (5.B.5.5): The student is able to predict and calculate the energy transfer to (i.e., the work done on) an object or system from information about a force exerted on the object or system through a distance. [**See Science Practices 2.2 and 6.4**]

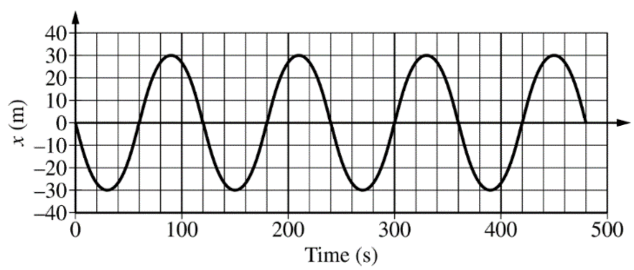
Question 2

12 points total **Distribution of points**



A passenger compartment of a rotating amusement park ride contains a bench on which a book of mass m_b is placed, as indicated by the dot in the left figure above. The compartment moves with a constant angular speed about the center of the ride along a circular path of radius R. The bench remains horizontal throughout the compartment's motion. The right figure above shows a magnified view of the compartment.

The graph below shows the horizontal (x) component of the book's position as a function of time, where the $+x$-direction is to the right.



(a) LO 3.A.1.1, SP 1.5, 2.1, 2.2

(i)
1 point

Determine the period of revolution of the book.

For indicating the correct period of 120 seconds, 2 minutes, OR the equivalent		1 point

(ii)
2 points

Calculate the tangential speed v_b (not the angular speed) of the book.

For using the correct radius of 30 m as found from the graph		1 point
For substitution of the period, consistent with the answer in (a)(i), into a correct expression		1 point
Speed $= d/T = 2\pi R/T = 2\pi(30\text{ m})/(120\text{ s}) = 1.6\text{ m/s}$		
Notes: $(\pi/2)\text{ m/s}$ is acceptable. $\pi R/(60\text{ s})$ or $(\pi R/60)\text{ m/s}$ can only earn 1 of the two points.		

Question 2 (continued)

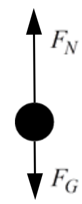
Distribution of points

(b) LO 3.A.2.1, SP 1.1; LO 3.A.3.1, SP 6.4, 7.2; LO 3.B.1.1, 6.4, 7.2

(i)

3 points

On the dot below, which represents the book, draw and label the forces (not components) that act on the book at the lowest point of its circular path. Each force must be represented by a distinct arrow starting on, and pointing away from, the dot.



For a correctly drawn and labeled normal force		1 point
For a correctly drawn and labeled gravitational force		1 point
For drawing no extraneous forces, given that at least one force is drawn		1 point

(ii)

1 point

At the lowest point of the circular path, the book is moving only in the horizontal direction. In what direction, if any, is the net vertical force on the book?

____ Up ____ Down ____ No direction, since the net vertical force is equal to zero

Without deriving any equations, briefly explain your reasoning in terms of the book's motion.

Correct answer: "Up"		
<u>Note</u>: Response cannot earn credit if incorrect selection is made.		
For an explicit or implicit assertion based on forces		1 point
Example explanation: Because there is a centripetal force		
Claim: The direction of the net vertical force on the book is <u>up</u>. Evidence: The book is at the lowest point of its circular path. (Given) For an object in uniform circular motion, the centripetal force is always directed toward the center of the circular path. Reasoning: The net force is the centripetal force on the book, which must be upward toward the center of the book's circular path.		

Question 2 (continued)

Distribution of points

(c) LO 3.B.1.3, SP 1.5, 2.2; LO 3.B.2.1, SP 1.1, 1.4, 2.2
3 points

Derive an algebraic equation for the vertical force that the bench exerts on the book at the lowest point of the circular path in terms of the book's mass m_b, tangential speed v_b, radius R of the path, and physical constants, as appropriate. Do not substitute any numerical values for variables or physical constants.

For using Newton's 2nd law correctly or consistent with the diagram in (b)(i)		1 point
$\Sigma\vec{F} = m\vec{a}$ (for the rotating system) $F_{net} = ma_c = mv^2/r$		
For a correct expression for the centripetal acceleration		1 point
$a_c = mv^2/r = m_b v_b^2/R$		
For a correct final expression with no numbers substituted for values		1 point
$F_{\text{net}} = m_b v_b^2/R = F_N - F_G$ $F_N = m_b v_b^2/R + F_G$ $= m_b\left(v_b^2/R + g\right)$		

(d) LO 3.A.3.1, SP 6.4, 7.2; LO 3.B.1.1, SP 6.4, 7.2; LO 3.B.2.1, SP 1.1, 1.4, 2.2
2 points

At the lowest point of the circular path, is the force that the bench exerts on the book greater than, less than, or equal to the weight of the book?
____ Greater than ____ Less than ____ Equal to
Briefly explain how your answers in (b)ii and (c) support your selection.

Correct Answer: "Greater than"		
For correct reasoning with a selection consistent with the answer from (b)(ii) and (c)		1 point
For explaining why the force from the bench is greater than the weight of the book.		1 point
Note: A response with an incorrect selection consistent with parts (b)(ii) and (c) can earn 2 points.		
Claim: At the lowest point of the circular path, the force that the bench exerts on the book is greater than the weight of the book. Evidence: The direction of the net vertical force on the book is up. (Part (b)(ii) answer) The book exerts a vertical force on the bench of magnitude $m_b\left(v_b^2/R + g\right)$. (Part (c) answer) Reasoning: The upward force exerted by the bench must be greater than the downward gravitational force, in order for the net force to be upward as stated in the answer to (b)(ii). The magnitude $m_b\left(v_b^2/R + g\right)$ of the force exerted by the bench derived in part (c) is greater than the book's weight $m_b g$.		

Question 2 (continued)

LOs

Learning Objective (3.A.1.1): The student is able to express the motion of an object using narrative, mathematical, and graphical representations. [**See Science Practices 1.5, 2.1, and 2.2**]
Learning Objective (3.A.2.1): The student is able to represent forces in diagrams or mathematically using appropriately labeled vectors with magnitude, direction, and units during the analysis of a situation. [**See Science Practice 1.1**]
Learning Objective (3.A.3.1): The student is able to analyze a scenario and make claims (develop arguments, justify assertions) about the forces exerted on an object by other objects for different types of forces or components of forces. [**See Science Practices 6.4 and 7.2**]
Learning Objective (3.B.1.1): The student is able to predict the motion of an object subject to forces exerted by several objects using an application of Newton's second law in a variety of physical situations with acceleration in one dimension. [**See Science Practices 6.4 and 7.2**]
Learning Objective (3.B.1.3): The student is able to reexpress a free-body diagram representation into a mathematical representation and solve the mathematical representation for the acceleration of the object. [**See Science Practices 1.5 and 2.2**]
Learning Objective (3.B.2.1): The student is able to create and use free-body diagrams to analyze physical situations to solve problems with motion qualitatively and quantitatively. [**See Science Practices 1.1, 1.4, and 2.2**]

Question 3

12 points total | **Distribution of points**

A company selling a type of spring makes the following claim: "The elastic potential energy that the spring is capable of storing for a given compression distance does not decrease, even after the spring compresses and/or stretches hundreds of times." The students in a physics class have decided to test the company's claim.

(a)(i and ii) LO 4.C.2.1, SP 6.4; LO 5.B.3.1, SP 6.4; LO 5.B.4.1, SP 6.4; LO 5.B.5.1, SP 4.2
1 point

(i) State a basic physics principle or law the students could use in designing an experiment to test the company's claim.

(ii) Using the principle or law stated in part (a)i, determine an equation for the elastic potential energy stored in the spring in terms of quantities that can be obtained from measurements made with equipment usually found in a school physics laboratory.

For a valid equation or valid equations in (a)ii that is/are consistent with (a)i AND that include(s) the elastic potential energy stored in the spring		1 point
Example: Conservation of Energy, Work-Energy Theorem $U_s = 1/2kx^2, U_s = 1/2mv_{\text{max}}^2$, OR $\Delta U_g = mg\Delta y$		

(b) LO 3.B.3.2, SP 4.1; LO 4.C.2.1, SP 6.4; LO 5.B.3.1, SP 6.4; LO 5.B.4.1, SP 6.4; LO 5.B.5.1, SP 4.2
5 points

Design an experimental procedure the students could use to collect the data needed to test the company's claim. Assume equipment usually found in a school physics laboratory is available.
In the table below, list the quantities and associated symbols that would be measured in your experiment and the equipment used to measure them. Also list the equipment that would be used to measure each quantity. You do not need to fill in every row. If you need additional rows, you may add them to the space just below the table.

Quantity to Be Measured	Symbol for Quantity	Equipment for Measurement

Describe the overall procedure to be used, referring to the table. Provide enough detail so another student could replicate the experiment, including any steps necessary to reduce experimental uncertainty. As needed, use the symbols defined in the table and/or include a simple diagram of the setup.

Question 3 (continued)

Distribution of points

(b) (continued)

Measurements and equipment		
For listing relevant/appropriate equipment that matches the measured quantities		1 point
Procedure		
For a plausible/practical way to directly or indirectly determine the stored energy in the spring or spring constant of the spring		1 point
For compressing and/or stretching the spring multiple (hundreds of) times in between the initial and final measurements		1 point
For including both initial and final measurements so that the stored energy can be compared		1 point
For attempting to reduce uncertainty (e.g. - multiple trials with either one spring or multiple springs)		1 point

Example Procedure 1:

Quantity to Be Measured	Symbol for Quantity	Equipment for Measurement
Spring Compression	D	Meterstick
Maximum Velocity	v_{max}	Motion Sensor

Attach the spring to a wall horizontally. Push a block into the spring, compressing the spring a displacement D. Measure the displacement, D, with a meterstick. Release the block and use the motion sensor to record the block's maximum velocity, v_{max}. Repeat the experiment to verify the maximum velocity. Compress the spring from equilibrium to distance D and back to equilibrium hundreds of times and then repeat the displacement and maximum velocity measurements.

Example Procedure 2:

Quantity to Be Measured	Symbol for Quantity	Equipment for Measurement
Spring Compression	D	Meterstick
Maximum Compression Force	F_{max}	Force Sensor

Attach the spring horizontally to a wall. Apply a force F_{max} to compress the spring a displacement D from equilibrium. Measure D with a meterstick and F_{max} with a force sensor. Relax the spring and repeat the experiment to confirm F_{max}. Compress the spring from equilibrium to the displacement D and back to equilibrium hundreds of times, then repeat the displacement and force measurements.

Question 3 (continued)

Distribution of points

(c) LO 3.B.3.3, SP 5.1; LO 3.E.1.1, SP 6.4, 7.2; LO 5.B.3.2, SP 2.2; LO 5.B.3.3, SP 2.2; LO 5.B.5.1, SP 5.1
2 points

Explain how the students should analyze the data to determine whether the company's claim is true, i.e., whether the energy stored by the spring for a given compression distance does not decrease after the spring has compressed and/or stretched hundreds of times.

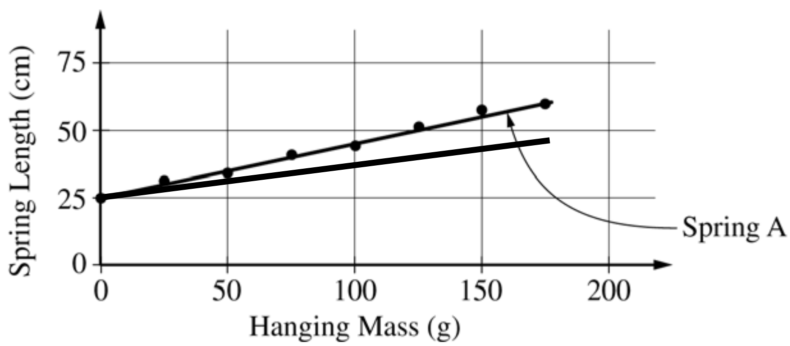
For explaining how to compare the initial elastic spring potential energy to the final spring potential energy after many trials (or a plausible alternative) to quantify if the energy stored by the spring for a given compression distance does not decrease after the spring has compressed and/or stretched hundreds of times		1 point
For indicating how the comparison would confirm or refute the hypothesis		1 point
Example Analysis 1: When the spring is compressed and comes back to equilibrium, all the stored elastic potential energy is transferred to kinetic energy of the block, causing the block to reach maximum velocity. If the maximum velocity v_{max} of the block before and after the hundreds of stretches is the same, then the stored elastic potential energy is the same, and the company's claim is true.		
Claim: If the maximum velocity v_{max} of the block before and after the hundreds of stretches is the same, then the stored elastic potential energy is the same, and the company's claim is true. Evidence: Energy is a conserved quantity. $U_S = \frac{1}{2}kx^2$ $K = \frac{1}{2}mv^2$ Reasoning: When the spring is compressed and comes back to equilibrium, all the stored elastic potential energy is transferred to kinetic energy of the block, causing the block to reach maximum velocity.		
Example Analysis 2: The work done on the spring is equal to average applied force $\left(\frac{1}{2}F_{max}\right)$ times the displacement from equilibrium. The work done is also equivalent to the elastic potential energy stored by the spring. If F_{max} remains the same for displacement D after several hundred stretches, then the elastic potential energy is the same, and the company's claim is true.		
Claim: If F_{max} remains the same for displacement D after several hundred stretches, then the elastic potential energy is the same, and the company's claim is true. Evidence: Energy is a conserved quantity. $U_S = \frac{1}{2}kx^2$ $\Delta E = W = F_{\parallel}d$ Reasoning: The work done on the spring is equal to average applied force $\left(\frac{1}{2}F_{max}\right)$ times the displacement from equilibrium. The work done is also equivalent to the elastic potential energy stored by the spring.		

Question 3 (continued)

Distribution of points

(d) LO 3.B.3.1, SP 6.4; LO 3.B.3.3, SP 5.1; LO 4.A.2.1, SP 6.4; SP 4.C.2.1, SP 6.4; LO 5.B.3.3, SP 1.4, 2.2; LO 5.B.5.2, SP 5.1

The students also investigate two springs, spring A and spring B, made by another company. The students hang spring A vertically, attaching blocks of various known masses from the bottom end of the spring and measuring the total length of the spring for each block. The students graph the spring length as a function of hanging mass and draw the line of best fit, as shown below.



(i)
3 points

The students follow the same procedure using spring B, which has the same equilibrium length as spring A but stores more energy than spring A for a given displacement. On the graph above, sketch what the line of best fit could look like for the data obtained using spring B.

For a curve starting at (0, 25)		1 point
For a straight line with positive slope		1 point
For a line with a smaller slope than the original best fit line, regardless of vertical-axis intercept.		1 point

Question 3 (continued)

Distribution of points

(d) (continued)

(ii)

1 point

The students attach a 100 g block to spring B and let it hang at rest. The students pull the block down by 1 cm, release it, and measure the time interval Δt for one oscillation. The students then repeat the procedure, but pull the block down by 2 cm instead of 1 cm. For which initial displacement, if either, is Δt greater?

____ Δt is greater for the 1 cm displacement. ____ Δt is greater for the 2 cm displacement. ____ Δt is the same in both cases.

Briefly explain your reasoning.

Correct answer: "Δt is the same in both cases"		
Note: Response cannot earn credit if incorrect selection is made.		
For indicating that the mathematical model $T = 2\pi\sqrt{\frac{m}{k}}$ only depends on the mass and the spring constant OR that the period does not depend on distance the spring is stretched		1 point
Claim: Δt is the same in both cases. Evidence: $T = 2\pi\sqrt{\frac{m}{k}}$ Reasoning: The period of an object oscillating on a spring depends on the mass and the spring constant, but not the amplitude.		

Question 3 (continued)

LOs

Learning Objective (3.B.3.1): The student is able to predict which properties determine the motion of a simple harmonic oscillator and what the dependence of the motion is on those properties. [**See Science Practices 6.4 and 7.2**]

Learning Objective (3.B.3.2): The student is able to design a plan and collect data in order to ascertain the characteristics of the motion of a system undergoing oscillatory motion caused by a restoring force. [**See Science Practice 4.2**]

Learning Objective (3.B.3.3): The student can analyze data to identify qualitative or quantitative relationships between given values and variables (i.e., force, displacement, acceleration, velocity, period of motion, frequency, spring constant, string length, mass) associated with objects in oscillatory motion to use that data to determine the value of an unknown. [**See Science Practices 2.2 and 5.1**]

Learning Objective (3.E.1.1): The student is able to make predictions about the changes in kinetic energy of an object based on considerations of the direction of the net force on the object as the object moves. [**See Science Practices 6.4 and 7.2**]

Learning Objective (4.A.2.1): The student is able to make predictions about the motion of a system based on the fact that acceleration is equal to the change in velocity per unit time, and velocity is equal to the change in position per unit time. [**See Science Practice 6.4**]

Learning Objective (4.C.2.1): The student is able to make predictions about the changes in the mechanical energy of a system when a component of an external force acts parallel or antiparallel to the direction of the displacement of the center of mass. [**See Science Practice 6.4**]

Learning Objective (5.B.3.1): The student is able to describe and make qualitative and/or quantitative predictions about everyday examples of systems with internal potential energy. [**See Science Practices 2.2, 6.4, and 7.2**]

Learning Objective (5.B.3.2): The student is able to make quantitative calculations of the internal potential energy of a system from a description or diagram of that system. [**See Science Practices 1.4 and 2.2**]

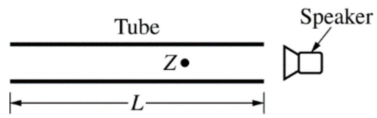
Learning Objective (5.B.3.3): The student is able to apply mathematical reasoning to create a description of the internal potential energy of a system from a description or diagram of the objects and interactions in that system. [**See Science Practices 1.4 and 2.2**]

Learning Objective (5.B.4.1): The student is able to describe and make predictions about the internal energy of systems. [**See Science Practices 6.4 and 7.2**]

Learning Objective (5.B.5.1): The student is able to design an experiment and analyze data to examine how a force exerted on an object or system does work on the object or system as it moves through a distance. [**See Science Practices 4.2 and 5.1**]

Question 4

7 points total **Distribution of points**



Note: Figure not drawn to scale.

A speaker is placed near a narrow tube of length $L = 0.30$ m, open at both ends, as shown above. The speaker emits a sound of known frequency, which can be varied. A student slowly increases the frequency of the emitted sound waves, without changing the amplitude, until the fundamental frequency f_0 inside the tube is reached and standing waves are produced (fundamental resonance). The speed of sound in air is $340\ \text{m/s}$.

(a) LO 6.D.3.2, SP 6.4; LO 6.D.3.4, SP 1.2; LO 6.D.4.2, SP 2.2

(i) 3 points

Calculate the period T_0 of the sound waves at the fundamental resonance.

For correctly (explicitly or implicitly) relating wavelength to the length of the pipe		1 point
$\lambda = 2L = 0.6$ m		
For using $f = v/\lambda$ or $T = \lambda/v$		1 point
$f_0 = v/2L$ or $T = (2L)/v$ earn 2 out of 3 points		
For an answer with units from having correctly used the relationship ($f = v/\lambda$ or $T = \lambda/v$) that is consistent with the wavelength used. Note: The wavelength need not be correct to earn this point. Correct answer: 0.0018 s		1 point

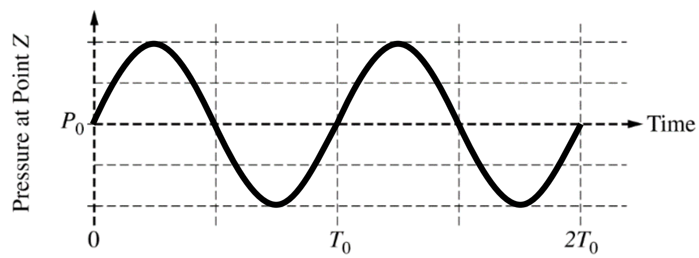
(ii) 2 points

For the fundamental resonance, consider the air pressure at point Z inside the tube. On the axes below, sketch the air pressure at point Z as a function of time. At time $t = 0$, the pressure at point Z is P_0, which is the atmospheric pressure.

Question 4 (continued)

Distribution of points

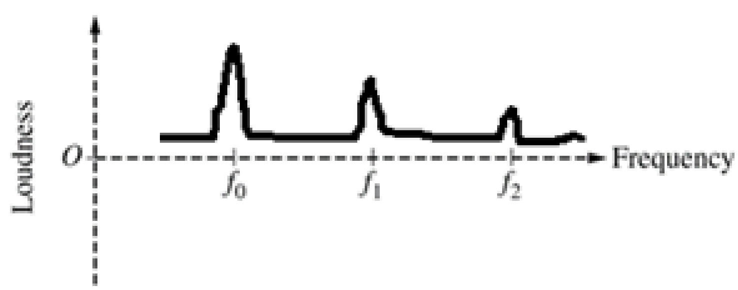
(a)(ii) (continued)



For drawing a periodic function with at least two cycles shown		1 point
For an approximate sinusoidal graph (with any phase) of period T_0 that is vertically centered on the horizontal axis		1 point
Notes: A graph with the incorrect phase can still earn full credit (i.e., the pressure at $t = 0$ may be any value). The response can earn 1 point for a drawing indicating a standing wave pattern if the period is T_0, but no credit is earned if the period is not T_0		

(b) LO 6.A.1.2, SP 1.2; LO 6.D.3.2, SP 6.4; LO 6.D.3.4, SP 1.2; LO 6.D.4.1, SP 1.5, 6.1
1 point

The student continues to slowly increase the frequency of the sound waves emitted by the speaker without making any other changes to the setup. The student hears additional resonances at two higher frequencies, f_1 and f_2.
On the axes below, sketch the loudness of the sound (sound volume) heard by the student as a function of the frequency generated by the speaker for the range of frequencies shown on the horizontal axis. The fundamental frequency is f_0.



For drawing a function with both of the following: • Peaks at f_0, f_1, and f_2, with no extraneous peaks • No negative values		1 point

Question 4 (continued)

Distribution of points

(c) LO 6.D.3.2, SP 6.4; LO 6.D.3.4, SP 1.2
1 point

The temperature of the air in the tube is increased. As the temperature increases, the speed of sound in the air increases. (Assume the size of the tube does not change). Does the tube's fundamental frequency increase, decrease, or stay the same?

____ Increase ____ Decrease ____ Stay the same

Briefly explain your reasoning.

Correct Answer: "Increase"		
Note: The response cannot earn credit if an incorrect selection is made.		
For using correct reasoning that explicitly or implicitly uses $v = f\lambda$		1 point
Example: $v = f\lambda$. Since λ is constant and v increases, f must increase.		
Claim: The tube's fundamental frequency increases. Evidence: $v = f\lambda$ Reasoning: Since λ is constant and v increases, f must increase.		

LOs

Learning Objective (6.A.1.2): The student is able to describe representations of transverse and longitudinal waves. [**See Science Practice 1.2**]

Learning Objective (6.D.3.2): The student is able to predict properties of standing waves that result from the addition of incident and reflected waves that are confined to a region and have nodes and antinodes. [**See Science Practice 6.4**]

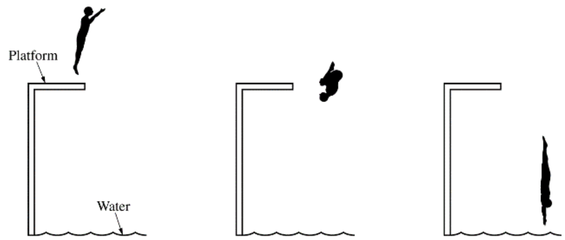
Learning Objective (6.D.3.4): The student is able to describe representations and models of situations in which standing waves result from the addition of incident and reflected waves confined to a region. [**See Science Practice 1.2**]

Learning Objective (6.D.4.1): The student is able to challenge with evidence the claim that the wavelengths of standing waves are determined by the frequency of the source regardless of the size of the region. [**See Science Practices 1.5 and 6.1**]

Learning Objective (6.D.4.2): The student is able to calculate wavelengths and frequencies (if given wave speed) of standing waves based on boundary conditions and length of region within which the wave is confined, and calculate numerical values of wavelengths and frequencies. Examples should include musical instruments. [**See Science Practice 2.2**]

Question 5

7 points total **Distribution of points**



The figures above show three stages of a dive performed by an athlete. During the dive, the athlete completes several rotations in midair while traveling from the platform to the surface of the water. Figure 1 shows the athlete just after jumping off the platform. Figure 2 shows the athlete rotating in midair. Figure 3 shows the athlete about to enter the water.

(a) LO 4.D.2.1, SP 1.2, 1.4; LO 5.E.1.1, SP 6.4
5 points

In a clear, coherent paragraph-length response that may also contain figures and/or equations, explain why the athlete's angular speed increases between Figure 1 and Figure 2 but decreases between Figure 2 and Figure 3.

For a statement that angular momentum is conserved (i.e. - statement that angular momentum stays the same while the athlete is in the air)		1 point
For reasoning in terms of mass distribution why rotational inertia is less in Figure 2 than in 1 and/or 3		1 point
For a correct indication that I and angular speed are inversely related. Note: The response can refer to "$L = I\omega$" or a similar word-based statement.		1 point
For explicitly addressing both intervals 1-2 and 2-3. Note: The response can simply refer to earlier reasoning without repeating it.		1 point
For a logical, relevant, and internally consistent argument that addresses the required argument, explanation or question asked, and follows the guidelines described in the published requirements for the paragraph-length response		1 point
Example paragraph response: The angular momentum of the athlete remains constant throughout the dive. In Figure 2 the athlete pulls in her arms and legs closer to the point of rotation, so the rotational inertia decreases. Since angular momentum is conserved, and $L = I\omega$, the angular velocity increases. In Figure 3 the athlete extends her arms and legs increasing the rotational inertia and decreasing the angular velocity.		
Claim (given): The athlete's angular speed increases between Figure 1 and Figure 2 but decreases between Figure 2 and Figure 3. Evidence: Angular momentum is a conserved quantity. Reasoning: In Figure 2 the athlete pulls in her arms and legs closer to the point of rotation, so the rotational inertia decreases. Since angular momentum is conserved, and $L = I\omega$, the angular velocity increases. In Figure 3 the athlete extends her arms and legs increasing the rotational inertia and decreasing the angular velocity.		

Question 5 (continued)

Distribution of points

(b) LO 5.B.3.1, SP 2.2, 6.4, 7.2
2 points

Is the rotational kinetic energy $K_{2,\text{rot}}$ of the athlete in Figure 2 greater than, less than, or equal to the rotational kinetic energy $K_{1,\text{rot}}$ of the athlete in Figure 1 ?

____ $K_{2,\text{rot}} > K_{1,\text{rot}}$ ____ $K_{2,\text{rot}} < K_{1,\text{rot}}$ ____ $K_{2,\text{rot}} = K_{1,\text{rot}}$

Briefly explain your answer.

Correct answer: $K_{2,\text{rot}} > K_{1,\text{rot}}$		
Note: the response can earn credit even if an incorrect selection is made.		
For reasoning that there is an increase in angular velocity and a decrease in rotational inertia		1 point
For reasoning qualitatively or quantitatively that the decrease in rotational inertia does not "compensate for" the increase in angular velocity		1 point
Claim: $K_{2,\text{rot}} > K_{1,\text{rot}}$ Evidence: $L = I\omega$ $K = \frac{1}{2}I\omega^2$ Reasoning: There is an increase in angular velocity and a decrease in rotational inertia. In terms of the rotational kinetic energy $K_{\text{rot}} = \frac{1}{2}I\omega^2 = \frac{1}{2}(I\omega)\omega = \frac{1}{2}L\omega$, the decrease in I does not "compensate for" the increase in ω.		

Alternate solution (using angular momentum and energy)		*Alternate points*
For reasoning that angular speed increases or rotational inertia decreases and angular momentum is constant		*1 point*
For reasoning qualitatively or quantitatively that kinetic energy depends on angular speed or rotational inertia		*1 point*
Claim: $K_{2,\text{rot}} > K_{1,\text{rot}}$ *Evidence:* $L = I\omega$ $K_{rot} = \frac{1}{2}L\omega = \frac{1}{2}L\left(\frac{L}{I}\right) = \frac{1}{2}\frac{L^2}{I}$ *Reasoning: There is an increase in angular velocity* ω *(or a decrease in rotational inertia I) and angular momentum is constant. In terms of rotational kinetic energy* $K_{\text{rot}} = \frac{1}{2}L\omega$ $\left(= \frac{1}{2}\frac{L^2}{I}\right)$*, a constant angular momentum means that* K_{rot} *must increase, so* $K_{2,\text{rot}} > K_{1,\text{rot}}$.		

Question 5 (continued)

Distribution of points

(b) (continued)

Alternate solution (using work and energy):		*Alternate points*
For reasoning that no work is done on the athlete by external torques		*1 point*
For reasoning that mechanical energy was increased by the work done by her muscles (and/or conversion of cellular chemical energy into mechanical energy)		*1 point*
Claim: $K_{2,\text{rot}} > K_{1,\text{rot}}$ *Evidence:* $\Delta E = W = F_{\|\|}d = Fd\cos\theta$ *Reasoning: The force exerted by the athlete's muscles on the arms and legs is inward, in the same direction that the arms and legs are moving between Figures 1 and 2, so positive work is done by the muscles. No other forces exert a torque on the athlete, so the positive work done by the muscles results in greater kinetic energy.*		

LOs

Learning Objective (4.D.2.1): The student is able to describe a model of a rotational system and use that model to analyze a situation in which angular momentum changes due to interaction with other objects or systems. [**See Science Practices 1.2 and 1.4**]
Learning Objective (5.B.3.1): The student is able to describe and make qualitative and/or quantitative predictions about everyday examples of systems with internal potential energy. [**See Science Practices 2.2, 6.4, and 7.2**]
Learning Objective (5.E.1.1): The student is able to make qualitative predictions about the angular momentum of a system for a situation in which there is no net external torque. [**See Science Practices 6.4 and 7.2**]

2019 AP Physics 1 Scoring Worksheet

Section I: Multiple Choice

________________ $\times$ 1.0256 = ________________________

Number Correct (out of 39*) — Weighted Section I Score (Do not round)

Section II: Free Response

Question 1 ____________ $\times$ 0.8888 = ____________
(out of 7) (Do not round)

Question 2 ____________ $\times$ 0.8888 = ____________
(out of 12) (Do not round)

Question 3 ____________ $\times$ 0.8888 = ____________
(out of 12) (Do not round)

Question 4 ____________ $\times$ 0.8888 = ____________
(out of 7) (Do not round)

Question 5 ____________ $\times$ 0.8888 = ____________
(out of 7) (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 1

Composite Score Range	AP Score
57-80	5
43-56	4
34-42	3
24-33	2
0-23	1

*Although 40 multiple-choice items were administered in Section I, item 9 was not used in scoring.

2019 AP Physics 1: Algebra-Based
Question Descriptors and Performance Data

Multiple-Choice Questions

Question	Science Practice	Learning Objective	Topic	Key	% Correct
1	2.2	5.D.2.5	Conservation of Linear Momentum	D	76
2	7.2	5.D.2.3	Conservation of Linear Momentum	C	50
3	1.5	3.A.1.1	Position, Velocity, and Acceleration	B	55
4	1.4	5.C.3.3	Kirchhoff's Junction Rule, Ohm's Law (Resistors in Series and Parallel)	A	66
5	6.4	4.C.2.1	Work and Mechanical Energy	D	71
6	2.2	4.C.1.1	Work and Mechanical Energy	C	63
7	1.4	4.B.1.1	Representations of Changes in Momentum	C	52
8	6.4	6.D.3.2	Interference and Superposition (Waves in Tubes and on Strings)	B	58
9	*	*	*	*	*
10	7.2	6.B.4.1	Periodic Waves	C	63
11	5.1	5.C.3.2	Kirchhoff's Junction Rule, Ohm's Law (Resistors in Series and Parallel)	B	73
12	7.2	3.A.4.2	Newton's Third Law and Free-Body Diagram	C	65
13	2.2	5.D.1.5	Conservation of Linear Momentum	A	52
14	6.4	5.D.2.3	Conservation of Linear Momentum	D	50
15	2.2	2.B.2.2	Gravitational Field / Acceleration Due to Gravity on Different Planets	C	50
16	7.2	5.E.1.1	Conservation of Angular Momentum	D	35
17	1.4	5.B.3.3	Conservation of Energy, the Work-Energy Principle, and Power	C	46
18	2.2	3.C.2.1	Electric Force	C	40
19	6.4	5.B.4.1	Conservation of Energy, the Work-Energy Principle, and Power	B	43
20	6.4	4.C.2.1	Work and Mechanical Energy	A	49
21	1.4	5.B.4.2	Conservation of Energy, the Work-Energy Principle, and Power	C	18
22	6.4	3.D.2.2	Momentum and Impulse	D	38
23	5.1	3.A.1.3	Position, Velocity, and Acceleration	C	45
24	2.2	6.D.4.2	Interference and Superposition (Waves in Tubes and on Strings)	C	50
25	5.1	6.B.4.1	Periodic Waves	A	42
26	1.5	3.A.1.1	Rotational Kinematics	D	42
27	1.1	3.A.2.1	Applications of Circular Motion and Gravitation	D	25
28	1.4	5.B.4.2	Conservation of Energy, the Work-Energy Principle, and Power	D	14
29	1.1	1.A.5.1	Systems	B	48
30	6.4	5.B.9.3	Ohm's Law, Kirchhoff's Loop Rule (Resistors in Series and Parallel)	C	25
31	1.4	5.B.3.3	Conservation of Energy, the Work-Energy Principle, and Power	C	58
32	2.2	3.A.1.1	Position, Velocity, and Acceleration	A	36
33	1.4	4.B.1.1	Representations of Changes in Momentum	B	41
34	6.4	5.D.2.3	Conservation of Linear Momentum	D	26
35	2.2	4.D.3.1	Angular Momentum and Torque	B	49
36	1.1	3.A.2.1	Newton's Third Law and Free-Body Diagram	C	56

*Item was not scored.

2019 AP Physics 1: Algebra-Based
Question Descriptors and Performance Data

Question	Science Practice	Learning Objective	Topic	Key	% Correct
131	4.2	3.B.1.2	Newton's Second Law	B,D	45
132	7.2	3.E.1.1	Work and Mechanical Energy	A,D	56
133	1.1	6.D.1.1	Interference and Superposition (Waves in Tubes and on Strings)	B,D	46
134	6.4	3.F.2.1	Torque and Angular Acceleration	B,D	25

Free-Response Questions

Question	Science Practice	Learning Objective	Topic	Mean Score
1	2.2|1.4|2.2|2.2|1.4|2.1|2.2|1.4|2.1|2.2|2.2|6.4	3.A.1.1|4.A.2.3|4.A.3.1|4.C.1.1|5.B.4.2|5.B.5.5	1.2|2.7|4.2|4.3	1.32
2	1.5|2.1|2.2|1.1|6.4|7.2|6.4|7.2|1.5|2.2|1.1|1.4|2.2	3.A.1.1|3.A.2.1|3.A.3.1|3.B.1.1|3.B.1.3|3.B.2.1	3.7|3.8	4.46
3	6.4|4.2|5.1|6.4|7.2|6.4|6.4|6.4|2.2|1.4|2.2|6.4|4.2|5.1	3.B.3.1|3.B.3.2|3.B.3.3|3.E.1.1|4.A.2.1|4.C.2.1|5.B.3.1|5.B.3.2|5.B.3.3|5.B.4.1|5.B.5.1|5.B.5.2	1.2|4.2|4.3|6.1|6.2	6.03
4	1.2|6.4|1.2|1.5|6.1|2.2	6.A.1.2|6.D.3.2|6.D.3.4|6.D.4.1|6.D.4.2	10.1|10.3	2.35
5	1.2|1.4|2.2|6.4|7.2|6.4|7.2	4.D.2.1|5.B.3.1|5.E.1.1	4.3|7.3|7.4	2.85