

Answers to Multiple-Choice Questions

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

Free-Response Section

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

Information for Free-Response Question 1

Timing	The student should spend approximately 10–13 minutes on this question.
Essential Knowledge/ Big Ideas	3.A.1 An observer in a particular reference frame can describe the motion of an object using such quantities as position, displacement, distance, velocity, speed, and acceleration. 4.A.3 Forces that systems exert on each other are because of interactions between objects in the systems. If the interacting objects are parts of the same system, there will be no change in the center-of-mass velocity of that system. 4.B.1 The change in linear momentum for a constant-mass system is the product of the mass of the system and the change in velocity of the center of mass. 4.B.2 The change in linear momentum of the system is given by the product of the average force on that system and the time interval during which the force is exerted.
Science Practice	2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 5.1 The student can analyze data to identify patterns or relationships.
Learning Objective	3.A.1.3 The student is able to analyze experimental data describing the motion of an object and is able to express the results of the analysis using narrative, mathematical, and graphical representations. 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. 4.B.1.1 The student is able to calculate the change in linear momentum of a two-object system with constant mass in linear motion from a representation of the system (data, graphs, etc.). 4.B.2.1 The student is able to apply mathematical routines to calculate the change in momentum of a system by analyzing the average force exerted over a certain time on the system.
Characteristics of a STRONG Response	Part (a) The student is able to recognize and state that the measurements were NOT started at the time of release because the carts have non-zero momentum at $t = 0$. Part (b) The student is able to • Use the graph to calculate the change in momentum for each cart • Recognize that the “external force” is the sum of the two forces on the carts. Part (c) The student correctly states that there is no difference and recognizes that as long as the net mass of the system remains unchanged, the net effect on the system remains unchanged as well.

Characteristics of a GOOD Response	Part (a) The student implies the reason the measurements were not started at the time of release, instead of making an explicit statement. Part (b) The student is able to • Use the graph to calculate the change in momentum for each cart • Recognize that the “external force” is the sum of the two forces on the carts but fails to account that the forces are in opposite directions and/or performs a miscalculation. Part (c) The student is able to recognize that the answers would not be different, but has difficulty explaining why.
Characteristics of a WEAK Response	Part (a) The student states that the measurements were started at the same time. OR The student has difficulty in stating a correct reason why the measurements were not started upon release. Part (b) The student is able to calculate only the force on a single cart. Part (c) The student incorrectly states that the answers would be different. OR The student states the answers would not be different with no attempt at a justification.

Scoring Guidelines for Free-Response Question 1

Question 1		
7 points total		Distribution of points
(a) 1 point		
For a correct, justified response about the state of motion at time $t = 0$ For example: No. The carts have a non-zero momentum at $t = 0$, so this cannot be the instant they were released.		1 point
(b) 4 points		
For using the relationship between force and momentum, or Newton's second law and the definitions of acceleration and momentum $F = \Delta p / \Delta t$ or $F = ma$, $a = \Delta v / \Delta t$, and $p = mv$		1 point
For recognizing that the force causes a change in momentum or a change in velocity		1 point
For using reasonable values of momenta from the graph to calculate the momenta of the carts $F_5 = \Delta p / \Delta t = (1.25 \text{ kg}\cdot\text{m/s} - 0.25 \text{ kg}\cdot\text{m/s}) / 10 \text{ s} = 0.10 \text{ N}$ $F_1 = \Delta p / \Delta t = (-0.6 \text{ kg}\cdot\text{m/s} - -0.2 \text{ kg}\cdot\text{m/s}) / 10 \text{ s} = -0.04 \text{ N}$		1 point
For recognizing that the external force is the sum of the two forces on the cart $F_{\text{ext}} = F_5 + F_1 = 0.10 \text{ N} - 0.04 \text{ N} = 0.06 \text{ N}$		1 point
Calculating only the force on one of the carts earns a maximum of 1 point.		
<i>Alternate Solution:</i>		<i>Alternate Points</i>
For recognizing that the momentum of the system is the sum of the momenta of the two carts		1 point
For obtaining reasonable values of momenta from the graph and using them to calculate the system momenta $p_{\text{system initial}} = -\frac{0.5 \text{ kg}\cdot\text{m/s}}{3} + 0.25 \text{ kg}\cdot\text{m/s} = 0.08 \text{ kg}\cdot\text{m/s}$ $p_{\text{system final}} = -\left(\frac{6}{5}\right)(0.5 \text{ kg}\cdot\text{m/s}) + 1.25 \text{ kg}\cdot\text{m/s} = 0.65 \text{ kg}\cdot\text{m/s}$		1 point
For using the change in the system's momentum (final value minus initial value) $\Delta p_{\text{system}} = 0.65 \text{ kg}\cdot\text{m/s} - 0.08 \text{ kg}\cdot\text{m/s} = 0.57 \text{ kg}\cdot\text{m/s}$		1 point
For using the relationship between force and momentum to determine the external force $F = \Delta p / \Delta t = 0.57 \text{ kg}\cdot\text{m/s} / 10 \text{ s} = 0.057 \text{ N}$		1 point

Question 1 (continued)

**Distribution
of points**

(c) 2 points

2 points

For a correct, justified response about the effect of changing the masses of the carts

For example:

No. The calculations in part (b) account for the effect of the external force on the motion of the entire system. The changes in individual masses do not change the total mass of the system, so the net effect on the system remains the same.

In the absence of other correct reasoning, recognizing that the mass is the same for both situations earned 1 point.

Information for Free-Response Question 2

Timing	The student should spend approximately 20–25 minutes on this question.
Essential Knowledge	3.B.3 Restoring forces can result in oscillatory motion. When a linear restoring force is exerted on an object displaced from an equilibrium position, the object will undergo a special type of motion called simple harmonic motion. Examples should include gravitational force exerted by the Earth on a simple pendulum and mass-spring oscillator. 5.B.3 A system with internal structure can have potential energy. Potential energy exists within a system if the objects within that system interact with conservative forces.
Science Practice	1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 4.2 The student can design a plan for collecting data to answer a particular scientific question. 5.1 The student can analyze data to identify patterns or relationships.
Learning Objectives	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. 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. 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. 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.

Characteristics of a STRONG Response	Part (a) The student is able to draw a graph with the following properties: • A reasonable sine squared shape • Maxima located at the times labeled on the axis • A difference between maximum and minimum potential energy of about 0.16 J. Part (b) The student is able to draw a graph with the following properties: • A sine or cosine curve • An appropriate phase relationship to the given graphs (i.e., the acceleration is at a positive maximum at $t = 0$ and the period is 1.0 s) • An amplitude of approximately 10 m/s^2 Part (c) The student describes an experimental setup with the following characteristics: • The setup allows useful measurements • An indication of all measurements needed with no extraneous ones • Evidence of multiple trails. Part (d) The student provides an analysis of the data that includes the following: • A check for a linear relationship between force and rubber band elongation • Indication of a correct characteristic that signifies a linear relationship • No assumption of linearity.
Characteristics of a GOOD Response	Part (a) The student is able to draw a graph with any two of the following properties: • A reasonable sine squared shape • Maxima located at the times labeled on the axis • A difference between maximum and minimum potential energy of about 0.16 J. Part (b) The student is able to draw a graph with any two of the following properties: • A sine or cosine curve • An appropriate phase relationship to the given graphs (i.e., the acceleration is at a positive maximum at $t = 0$ and the period is 1.0 s) • An amplitude of approximately 10 m/s^2 Part (c) The student describes an experimental setup with any two of the following characteristics: • The setup allows useful measurements • An indication of all measurements needed with no extraneous ones • Evidence of multiple trails. Part (d) The student provides an analysis of the data that includes any two the following: • A check for a linear relationship between force and rubber band elongation • Indication of a correct characteristic that signifies a linear relationship • No assumption of linearity.

Characteristics of a WEAK Response	Part (a) The student is able to draw a graph with only one or none of the following properties: • A reasonable sine squared shape • Maxima located at the times labeled on the axis • A difference between maximum and minimum potential energy of about 0.16 J. Part (b) The student is able to draw a graph with only one or none of the following properties: • A sine or cosine curve • An appropriate phase relationship to the given graphs (i.e., the acceleration is at a positive maximum at $t = 0$ and the period is 1.0 s) • An amplitude of approximately 10 m/s^2 Part (c) The student describes an experimental setup with only one or none of the following characteristics: • The setup allows useful measurements • An indication of all measurements needed with no extraneous ones • Evidence of multiple trials. Part (d) The student provides an analysis of the data that includes only one or none of the following: • A check for a linear relationship between force and rubber band elongation • Indication of a correct characteristic that signifies a linear relationship.
--	---

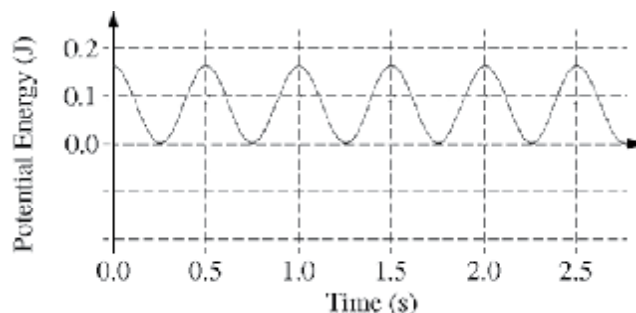
Scoring Guidelines for Free-Response Question 2

Question 2

12 points total

Distribution
of points

(a) 3 points



Zero potential energy can be defined at any point. For convenience define it to be at the equilibrium point of the hanging object. The graph above uses this definition.

Then $E = U + K = \frac{1}{2}mv_{\max}^2$, so

$$U = \frac{1}{2}mv_{\max}^2 - K = \frac{1}{2}mv_{\max}^2 - \frac{1}{2}m[v(t)]^2.$$

The amplitude of the velocity graph is approximately 1.6 m/s, and the period is 1 s. So $v(t) = (1.6 \text{ m/s})\sin(2\pi t/1 \text{ s})$.

$$U = \frac{1}{2}(0.125 \text{ kg})(1.6 \text{ m/s})^2(1 - \sin^2(2\pi t/1 \text{ s})) = (0.16 \text{ J})(1 - \sin^2(2\pi t/1 \text{ s}))$$

For a graph with a reasonable sine squared shape

1 point

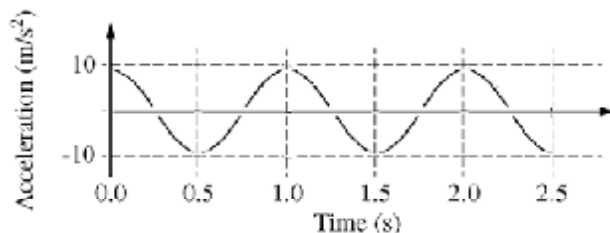
For having the maxima of the graph at the labeled times

1 point

For having maxima and minima with a potential energy difference of about 0.16 J

1 point

(b) 3 points



For a graph that is either a sine or cosine curve

1 point

For a graph that has the appropriate phase relationship to the given position and velocity graphs

1 point

$$a_{\max} = F_{\max}/m = kx_{\max}/m$$

The spring constant k can be determined using the period.

$$T = 2\pi\sqrt{m/k}, \text{ so } k = 4\pi^2 m/T^2 = 4\pi^2(0.125 \text{ kg})/(1 \text{ s})^2 = 0.5\pi^2 \text{ kg/s}^2$$

$$a = (0.5\pi^2 \text{ kg/s}^2)(0.25 \text{ m})/0.125 \text{ kg} = 9.87 \text{ m/s}^2$$

For an amplitude of approximately 10 m/s²

1 point

Question 2 (continued)		Distribution of points
(c)	3 points	
	For a reasonable experimental setup that would allow useful measurements	1 point
	For indicating all measurements needed and no extraneous ones	1 point
	For evidence that multiple trials are performed	1 point
	For example: Hook the rubber band over a horizontal rod, and measure its length. Hang an object of known mass from it and measure the new length. Repeat for a number of different objects.	
(d)	3 points	
	For an appropriate analysis that would check for a linear relationship between force and rubber band stretch	1 point
	For indicating an appropriate characteristic from the analysis that signifies a linear relationship	1 point
	For indicating that a linear graph means that the rubber band exhibits $F \propto x$ like an ideal spring	1 point
	For example: Plot the rubber band stretch as a function of the mass of the objects. A linear graph would show that the stretch and the force exerted on the rubber band (i.e. the weight of the object) are directly proportional, as they are for a spring.	

Information for Free-Response Question 3

Timing	The student should spend approximately 20–25 minutes on this question.
Essential Knowledge	1.B.1 Electric charge is conserved. The net charge of a system is equal to the sum of the charges of all the objects in the system. 5.B.9 Kirchhoff’s loop rule describes conservation of energy in electrical circuits. The application of Kirchhoff’s laws to circuits is introduced in Physics 1 and further developed in Physics 2 in the context of more complex circuits, including those with capacitors. 5.C.3 Kirchhoff’s junction rule describes the conservation of electric charge in electrical circuits. Because charge is conserved, current must be conserved at each junction in the circuit. Examples should include circuits that combine resistors in series and parallel. [Physics 1: covers circuits with resistors in series, with at most one parallel branch, one battery only.]
Science Practices	2.2 The student can make claims and predictions about natural phenomena based on scientific theories and models. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objectives	1.B.1.1 The student is able to make claims about natural phenomena based on conservation of electric charge. 5.B.9.3 The student is able to apply conservation of energy (Kirchhoff’s loop rule) in calculations involving the total electric potential difference for complete circuit loops with only a single battery and resistors in series and/or in, at most, one parallel branch. 5.C.3.1 The student is able to apply conservation of electric charge (Kirchhoff’s junction rule) to the comparison of electric current in various segments of an electrical circuit with a single battery and resistors in series and in, at most, one parallel branch and predict how those values would change if configurations of the circuit are changed.
Characteristics of a STRONG Response	Part (a) Of the five aspects that can be identified between the two observers, the student is able to correctly identify four or five aspects of reasoning as correct or incorrect, and explain why. Part (b) The student is able to identify equations 1 and 3 as support for Student 1’s reasoning, and equation 4 as support for Student 2’s reasoning with correct explanations. Part (c) The student is able to • Indicate a valid quantity to compare brightness • Manipulate equations to determine the quantity • Use the work to arrive at a conclusion • Explain how the calculations support the conclusion.

Characteristics of a GOOD Response	Part (a) Of the five aspects that can be identified between the two observers, the student is able to correctly identify three or four aspects of reasoning as correct or incorrect, and explain why. Part (b) The student is able to identify equation 1 OR 3 as support for Student 1's reasoning, and equation 4 as support for Student 2's reasoning with correct explanations. OR The student is able to identify equation 1 and 3 as support for Student 1's reasoning, and fails to identify equation 4 as support for Student 2's reasoning with correct explanations. Part (c) The student is able to • Indicate a valid quantity to compare brightness • Manipulate equations to determine the quantity • Use the work to arrive at a conclusion.
Characteristics of a WEAK Response	Part (a) Of the five aspects that can be identified between the two observers, the student is able to correctly identify less than three aspects of reasoning as correct or incorrect, and explain why. Part (b) The student is able to identify equation 1 OR 3 as support for Student 1's reasoning, OR equation 4 as support for Student 2's reasoning with correct explanations. Part (c) The student is able to indicate a valid quantity to compare brightness and/or manipulate equations to determine the quantity.

Scoring Guidelines for Free-Response Question 3

Question 3		
12 points total		Distribution of points
(a) 5 points		
(i)		
For indicating that Student 1 is correct that bulbs <i>A</i> and <i>B</i> “get all the current coming out of the battery”, and explaining that it is because there is only one loop in the circuit	1 point	
For indicating that bulbs <i>C</i> and <i>D</i> each get half the current, and explaining that it is because of the junction rule	1 point	
(ii)		
For indicating that while bulbs <i>C</i> and <i>D</i> do get half the current in their circuit, Student 1 is incorrect in assuming that this means they must have less current than <i>A</i> and <i>B</i> , and explaining that it is because the total current is not the same in both circuits	1 point	
(iii)		
For indicating that Student 2 is correct that the potential difference across bulbs <i>C</i> and <i>D</i> is the same and equal to the battery voltage, and explaining that for each bulb you can trace a loop that only goes through the bulb and the battery	1 point	
(iv)		
For indicating that Student 2 is incorrect in saying that current is “used up” by bulb <i>A</i> before it reaches bulb <i>B</i> , and explaining that a current moves an equal amount of charge through all the circuit elements carrying it	1 point	
(b) 3 points		
(i)		
Equations 1 and 3 support Student 1’s reasoning.		
For indicating that equation 1 shows that series bulbs <i>A</i> and <i>B</i> each carry the total current in the circuit	1 point	
For indicating that equation 3 shows that parallel bulbs <i>C</i> and <i>D</i> share the total current in the circuit	1 point	
(ii)		
Equation 4 directly supports Student 2’s reasoning. Equation 2 can also be considered as providing support for the implied contrast between circuits.		
For indicating that equation 4 shows that the potential difference across bulbs <i>C</i> and <i>D</i> is the same	1 point	
No penalty for also indicating that equation 2 shows that the voltage is shared in the series circuit.		

Question 3 (continued)		Distribution of points
(c)	4 points	
	For indicating a valid quantity that can be used to compare bulb brightness across circuits (power, current, or voltage)	1 point
	For correctly manipulating equations in an attempt to determine some quantity for the circuits with a valid assumption	1 point
	For stating a conclusion that follows from the work for the two points above (even if that work is incorrect)	1 point
	For explaining how the calculations support the conclusion (connecting ideas by using the chosen valid quantity to determine how it affects power which determines brightness)	1 point
	For example, calculating currents and comparing power: Substituting I_S into equation 2 and solving gives $I_S = \Delta V / (R_A + R_B)$ Solving each part of equation 4 gives $I_C = \Delta V / R_C$ and $I_D = \Delta V / R_D$ Since the resistors are identical, $I_S = I_C / 2 = I_D / 2$ Power is given by $P = I^2 R$, and for identical resistors depends on the current. Therefore the power and thus the brightness of bulbs A and B is less.	

Information for Free-Response Question 4

Timing	The student should spend approximately 10–13 minutes on this question.
Essential Knowledge	6.D.1 Two or more wave pulses can interact in such a way as to produce amplitude variations in the resultant wave. When two pulses cross, they travel through each other; they do not bounce off each other. Where the pulses overlap, the resulting displacement can be determined by adding the displacements of the two pulses. This is called superposition. 6.D.3 Standing waves are the result of the addition of incident and reflected waves that are confined to a region and have nodes and antinodes. Examples should include waves on a fixed length of string, and sound waves in both closed and open tubes.
Science Practice	1.1 The student can create representations and models of natural or man-made phenomena and systems in the domain. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.
Learning Objective	6.D.1.1 The student is able to use representations of individual pulses and construct representations to model the interaction of two wave pulses to analyze the superposition of two pulses. 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.
Characteristics of a STRONG Response	Part (a) The student is able to draw a picture of a correct overlapping segment of constructive interference with an amplitude $2A$ and 2 wavelengths of amplitude A on both sides. Part (b) The student is able to draw a straight line on the time axis from $t = 0$ to $t = t_1$. Part (c) The student is able to recognize that standing waves exist at only certain frequencies and wavelengths. With the ends of the string fixed and acting as nodes, standing waves can occur with whole number multiples of antinodes. Because 2 antinodes are required for a full wavelength, the string can be whole number multiples of half the wavelength.
Characteristics of a GOOD Response	Part (a) The student is able to draw a representation of constructive interference in the middle, but does not show the parts of the pulses outside the area of interference. Part (b) The student draws a horizontal line, but not on the time axis. Part (c) The student is able to recognize that the string can be a multiple of half of the wavelength, but doesn't have a reasonable justification.

Characteristics of a WEAK Response	Part (a) The student shows complete destructive interference in the middle of the drawing. OR The student draws something completely unrelated to the problem. Part (b) The student draws anything other than a horizontal line. Part (c) The student states that the string is a multiple of the wavelength.
--	--

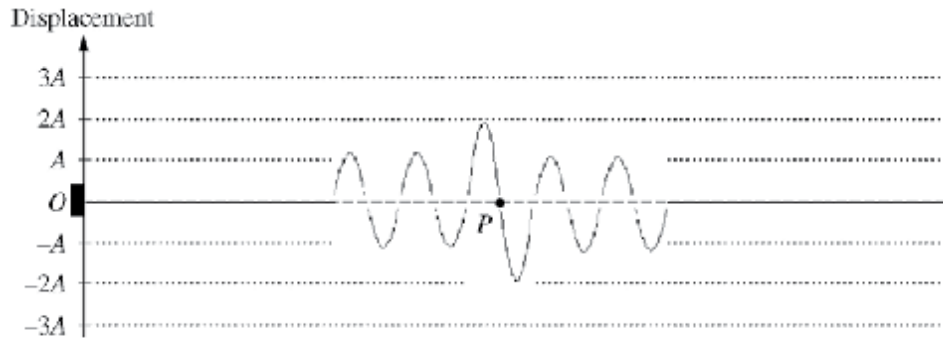
Scoring Guidelines for Free-Response Question 4

Question 4

7 points total

Distribution
of points

(a) 3 points



For overlap of one wavelength showing something other than amplitude A

1 point

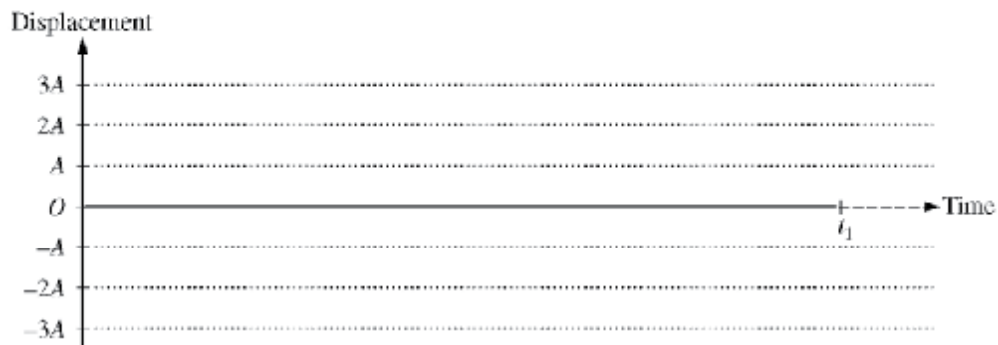
For showing amplitude $2A$ in the overlapping segment

1 point

For showing two wavelengths of amplitude A on both sides

1 point

(b) 2 points



For a straight line at zero displacement

2 points

(c) 2 points

For a complete, correct response with justification

2 points

For example: The length is either a multiple of λ or $\lambda/2$. The ends are nodes, so the pattern has zero amplitude at the ends. That can only happen if the 'middle' or 'end' of a wavelength is at each end.