Question 4: Short Answer Paragraph Argument — 7 points

(a) For a correct expression for the angular acceleration of the pulley in terms of the appropriate quantities: $\alpha_D = \frac{2F_T}{MR}$ — **1 point**

Example Response

$\alpha_D = \frac{RF_T}{\frac{1}{2}MR^2}$ ***OR*** $\alpha_D = \frac{2F_T}{MR}$

Total for part (a) — **1 point**

(b) For indicating that the torque, τ, is the same for both pulleys — **1 point**

For indicating that the impulse, $\tau\Delta t$, (or change in momentum ΔL) is the same for both pulleys because τ and Δt are the same — **1 point**

For indicating that the rotational inertia, I, of the disk and hoop are different — **1 point**

For providing reasoning that because the rotational inertia, I, are different for the disk and hoop, the kinematic quantities ($\Delta\theta$, ω, α) are also different for the disk and hoop — **1 point**

For **one** of the following: — **1 point**

- Relating I and ω to reason that ΔK is greater for the disk
- Indicating that because $\Delta\theta$ is greater for the disk the work done on the disk is greater

For a logical, relevant, and internally consistent argument that follows the guidelines described in the published requirements for the paragraph-length response — **1 point**

Example Response

The rotational inertia, I, of the hoop is larger than the rotational inertia of the disk because the hoop's mass is all on the outside instead of distributed throughout like the disk. Equal forces are applied to both pulleys at the same distance, which means that the torques exerted on the pulleys will also be equal. Since the same torque is applied to both pulleys for the same time period, the change in angular momentum will be the same for the disk and hoop. The magnitude of the angular velocity for the hoop will be smaller than that of the disk since angular velocity is inversely proportional to the rotational inertia $\left(\omega = \frac{L}{I}\right)$. Since kinetic energy is proportional to rotational inertia and the square of angular velocity $\left(K_R = \frac{1}{2}I\omega^2\right)$, the difference in angular velocity more greatly affects the rotational kinetic energy. That means the disk will have a greater rotational kinetic energy than the hoop.

Total for part (b) — **6 points**

Total for question 4 — **7 points**

Question 5: Short Answer — 7 points

(a)(i) For indicating "Frame C" with correct reasoning about the magnitude of the torque being the greatest — **1 point**

Accept **one** of the following:

- This is the instant when the lever arm is greatest.
- This is when the angle between radius vector and weight force vector is most perpendicular.

For correctly relating torque and angular acceleration: $\alpha \propto \tau$ — **1 point**

Example Response

The angular acceleration is greatest in Frame C because angular acceleration is proportional to torque, and in Frame C the gravitational force vector is directed perpendicular to the rod (lever arm) which means this is where the torque will be the greatest.

(a)(ii) For indicating "Frame E" with correct reasoning — **1 point**

Accept **one** of the following:

- Work or energy (e.g., this is when the maximum work has been done on the system by gravity.)
- Angular momentum (e.g., the torque due to gravity is clockwise the entire time, causing the rod to gain angular momentum.)
- Kinematics (e.g., the rod speeds up the entire time.)

Example Response

The rotational kinetic energy is greatest in Frame E because this is where the rod-sphere system has the greatest rotational speed since the torque has been in the same direction as the motion the entire time.

Total for part (a) — **3 points**

(b)(i) For a multistep derivation that begins with conservation of energy **1 point**

$E_i = E_f$ **OR** $\Delta E = 0$ **OR** $U_{gi} + K_i = U_{gf} + K_f$

For indicating the change in height is equal to $\frac{3}{2}L$ **1 point**

$\Delta y = \frac{3}{2}L$

For an answer consistent with the height change indicated previously in the response **1 point**

$K_f = \frac{3}{2}MgL$

Scoring Note: A correct answer of $K_f = \frac{3}{2}MgL$ with no supporting work can earn only this point.

Example Response

$E_i = E_f$
$U_{gi} + K_i = U_{gf} + K_f$
$\Delta K = U_{gi} - U_{gf}$
$\Delta K = Mg\Delta y$
$\Delta y = \frac{3L}{4} + \frac{3L}{4} = \frac{3}{2}L$
$\Delta K = \frac{3}{2}MgL$

(b)(ii) For indicating that the gravitational force is the external force that does work on the rod-sphere system **1 point**

Example Response

The rod and sphere gain kinetic energy due to the positive work done by the gravitational force, which is an external force for the rod-sphere system.

Total for part (b) 4 points

Total for question 5 7 points

Question 3: Experimental Design — 12 points

(a)

For listing relevant equipment that matches the measured quantities — **1 point**

For listing measurements of quantities sufficient to determine the kinetic energy of the block — **1 point**

For listing measurements of quantities sufficient to determine the gravitational potential energy of the block-Earth system — **1 point**

For a plausible procedure (i.e., can be done in a typical school physics lab) — **1 point**

For attempting to reduce uncertainty — **1 point**

Example Response

Quantity to Be Measured	Symbol for Quantity	Equipment for Measurement
Mass of block	m_B	Mass balance
Distance that block falls (initial height above floor)	d	Meterstick
Time for block to fall	t_B	Stopwatch

1. *Measure the mass of the block with the mass balance.*
2. *Hold the block in place with the string taut and measure the distance d with the meterstick.*
3. *Release the block and start the stopwatch.*
4. *Stop the stopwatch when the block hits the floor.*
5. *Record* d *and* t_B.
6. *Repeat steps* 3-5 *to get three separate trials at the same starting distance* d.
7. *Repeat steps* 2-6 *for several different starting distances* d.

Total for part (a) — **5 points**

(b)

For indicating that mass and velocity are needed — **1 point**

Scoring Note: This need not be the final velocity.

For a valid explanation of how the final kinetic energy could be determined — **1 point**

Scoring Note: This needs to be the FINAL kinetic energy.

Example Response

You can calculate the block's average speed by dividing $\frac{d}{t_B}$. *The block's final speed* v_F *is twice the average,* $\frac{2d}{t_B}$. *The kinetic energy* K *can then be calculated from* $K = \frac{1}{2} m_B (v_F)^2$.

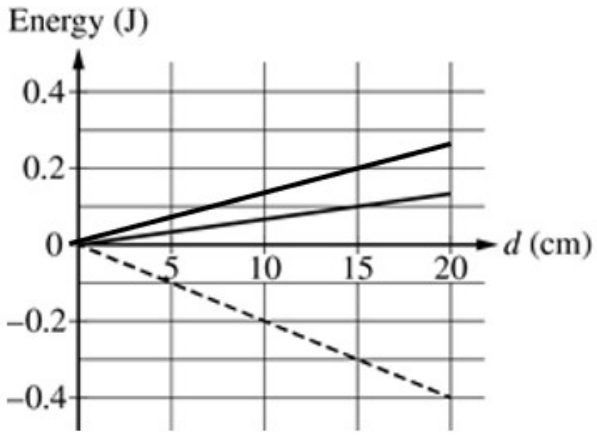
Total for part (b) — **2 points**

(c) For drawing a straight line that passes through the origin and has a positive slope **1 point**

For drawing a line that yields a total energy sum of zero at all values of d **1 point**

Scoring Note: The correct line passes through the origin and (15 cm, 0.2 J).

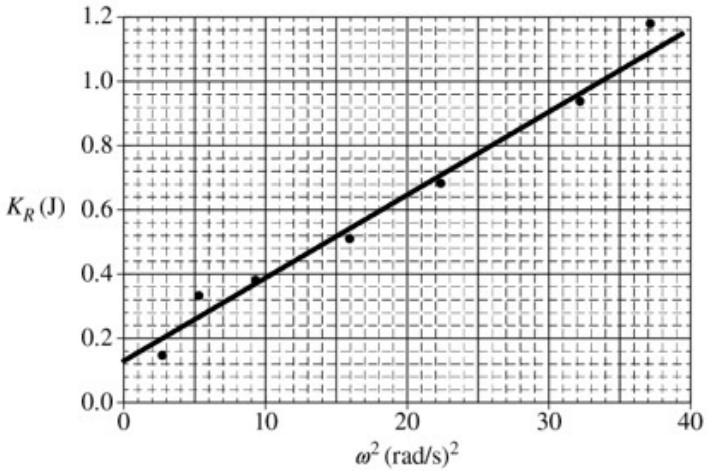
Example Response



Total for part (c) **2 points**

(d)(i) For drawing a reasonable best-fit line **1 point**

Example Response



(d)(ii) For correctly calculating a value for the slope using points on the line drawn, or a statement that a calculator was used to do a linear regression **1 point**

For **both** of the following: **1 point**

- correctly relating the slope of the graph to the rotational inertia
- a value of the rotational inertia I consistent with the calculated slope with correct units

Example Response

$$\text{slope} = \frac{1.04 - 0.20}{35 - 2.5} = 0.0258 \text{ kg} \cdot \text{m}^2$$

From $K = \frac{1}{2} I\omega^2$, *we have* $\text{slope} = \frac{1}{2} I$

The rotational inertia is $I = 2 \times \text{slope} = 0.0517 \text{ kg} \cdot \text{m}^2$

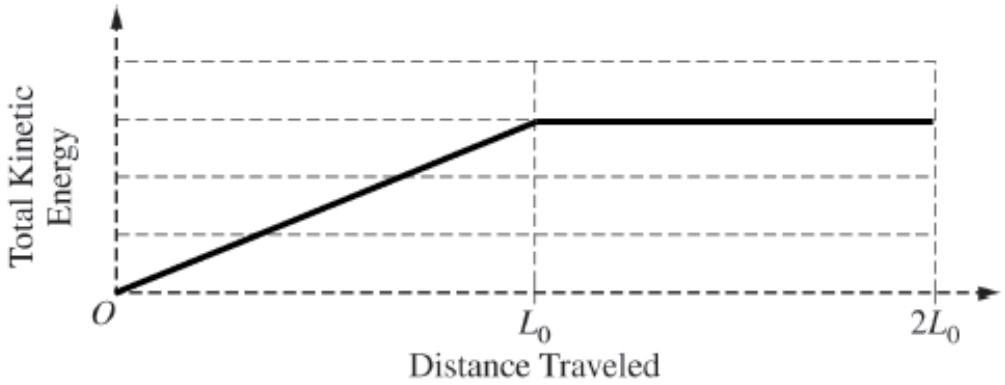
Total for part (d) 3 points

Total for question 3 12 points

Question 4: Paragraph-Length Response — 7 points

(a)	For a straight line with a positive slope beginning at the origin and reaching a maximum value when the distance traveled is L_0	**1 point**
	For a nonzero horizontal line between L_0 and $2L_0$	**1 point**

Example response for part (a)



Total for part (a)	**2 points**

(b)	For indicating that both objects start with the same gravitational potential energy in the object-Earth system	**1 point**
	For a correct statement about the energy transformations that occur to the cylinder as it travels down the ramp	**1 point**
	For a correct statement about the energy transformations that occur to the block as it travels down the ramp	**1 point**
	For indicating that the cylinder's final rotational kinetic energy is equal to the amount of the block-Earth system's initial mechanical energy that is dissipated by friction	**1 point**
	For a logical, relevant, and internally consistent argument that addresses the required argument or question asked, and follows the guidelines described in the published requirements for the paragraph-length response	**1 point**

Example response for part (b)

Both objects start with the same gravitational potential energy in the object-Earth system. The block-Earth system's mechanical energy is converted into kinetic energy, and some of it is dissipated by friction as the block slides down the ramp. The cylinder-Earth system's mechanical energy is transformed into translational kinetic energy and some is transformed into rotational kinetic energy. The cylinder's final rotational kinetic energy is equal to the amount of the block-Earth system's initial mechanical energy that is dissipated by friction.

Total for part (b)	**5 points**
Total for question 4	**7 points**

AP® Physics 1
2016 Scoring Guidelines

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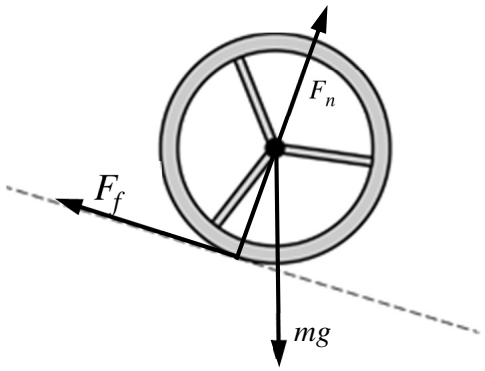
Question 1

7 points total **Distribution of points**

(a)

i. 2 points



For a labeled arrow representing the gravitational force, starting at the wheel's center and directed downward — 1 point

For labeled arrows representing the friction and normal forces or a single arrow representing the resultant of the friction and normal forces (i.e., the force exerted on the wheel by the surface), with no extraneous forces — 1 point

The friction force should start at the wheel-ramp contact and be directed up and left along the ramp.

The normal force should start at the wheel-ramp contact and be perpendicular to the ramp and toward the wheel's center. It does not have to go exactly through the center but must come reasonably close.

ii. 1 point

Correct answer: The friction force

No points are earned if the wrong force is given.

For correctly explaining that friction is the only force that exerts a torque with respect to the wheel's center of mass — 1 point

This point is also earned for a causal chain of reasoning about forces: e.g., the gravitational force leads to a normal force (and acceleration down the ramp), which leads to a frictional force, which exerts a torque (or changes the angular velocity).

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Question 1 (continued)

Distribution of points

(b) 2 points

For an expression for the sum of the force components parallel to the ramp that recognizes that there are two forces with components parallel to the ramp — 1 point

The expression need not be correct or consistent with the force diagram in part (a).

$$\sum F_{||} = Mg\sin\theta - F_f$$

For indicating that the frictional force is $(0.4)Mg\sin\theta$ (explicitly or implicitly) and correctly solving for the acceleration in terms of correct variables — 1 point

$$\sum F_{||} = Mg\sin\theta - (0.4)Mg\sin\theta$$

$$a = \frac{\sum F_{||}}{M} = \frac{Mg\sin\theta - 0.4Mg\sin\theta}{M} = \frac{0.6Mg\sin\theta}{M}$$

$$a = 0.6g\sin\theta$$

(c)

i. 1 point

Correct answer: Block

No credit for answer without explanation.

For a correct explanation in terms of forces — 1 point

Example: The wheel experiences a counteracting frictional force, so the block has a greater net force exerted upon it and therefore has greater acceleration.

ii. 1 point

For a correct explanation in terms of energy conservation — 1 point

Example: Both object-Earth systems lose the same amount of potential energy and therefore gain the same amount of kinetic energy. With the ice block — but not the wheel — all the kinetic energy is translational, and none is rotational, so the block is faster.

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Question 2

12 points total **Distribution of points**

Note: For parts (a) and (b), quantities that are proportional to mechanical energy, rather than energy itself, may be calculated, because terms like g or the ball's mass do not change during the experiment.

(a) 4 points

Parts i, ii, and iii are scored as a unit.

For an overall plan in which quantities are measured that could be used to compare mechanical energy before and after a collision with a hard surface — 1 point

For a conceptually plausible plan to measure pre- and post-collision positions and/or speeds that could be used to compare pre- and post-collision mechanical energies, without extraneous equipment and/or measurements — 1 point

For having lab equipment and measurement procedures well specified — 1 point

For a procedure that includes trials of different pre-collision speeds, ranging from low speed to high speed (as is needed to test the student's hypothesis) — 1 point

Example 1:

i. The drop height of the ball and the bounce height.
ii. A meterstick to measure the heights and a video camera to record the ball's motion.
iii. Place the meterstick upright against the wall.
Drop the ball from 10 different drop heights, using the video camera to record the bounce heights.

Example 2:

i. The speed of the ball immediately before and immediately after it bounces.
ii. A photogate near the floor, at a height just above the diameter of the ball, to measure the ball's speed.
iii. Drop the ball through the photogate.
Record the speeds measured by the photogate before and after the bounce.
Change the drop height of the ball at least five times, covering a range of heights from "low" to "high."

(b) 4 points

For describing how to plot or otherwise represent the data in a way that could be used to test the hypothesis — 1 point

For describing how to compare the post-collision to pre-collision mechanical energy (or a plausible alternative) to quantify the elasticity of the collision — 1 point

For comparing the low-speed versus high-speed results — 1 point

For addressing the hypothesis with an analysis such as a slope, ratio, or difference — 1 point

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Question 2 (continued)

Distribution of points

(b) (continued)

Example 1:

Make a graph of the bounce height h_f as a function of the drop height h_i. If the data are consistent with the hypothesis, then the data will (1) lie close to the line $h_f = h_i$ for low drop heights, and (2) lie below this line for high drop heights.

Example 2:

Make a graph of $v_f{}^2 - v_i{}^2$ as a function of v_i, where v_f and v_i are the ball's speed just after and just before the bounce, respectively. If the data are consistent with the hypothesis, then $v_f{}^2 - v_i{}^2$ will (1) be close to zero for low speeds, and (2) be negative for high speeds.

(c)

i. 2 points

For drawing a graph or table that shows that the low-speed collisions are nearly perfectly elastic — 1 point

For drawing a graph or table that shows a violation of a physics principle for higher-speed collisions — 1 point

Example for energy conservation:

A graph of the ratio $\frac{\text{Post-collision mechanical energy}}{\text{Pre-collision mechanical energy}}$ as a function of pre-collision speed, in which the graph stays near 1.0 for low initial speeds but becomes greater than 1.0 for high-speed collisions.

ii. 2 points

For a correct description of the aspect of the graph or table that shows a violation of the physical principle indicated — 1 point

For a correct explanation of why the representation shows a violation of the physical principle indicated — 1 point

Example for energy conservation using the graph described above: The value of the energy ratio shows a violation of conservation of energy when it becomes greater than 1.0 because the final energy cannot be greater than the initial energy.

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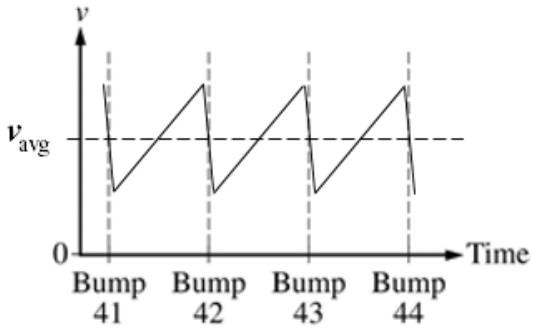
Question 3

12 points total **Distribution of points**

(a)



i. 3 points

For having a constant upward slope in each segment between bumps 1 point
For having the velocity "reset" abruptly at each bump (i.e., as a sawtooth function, not a sinusoidal curve) to a minimum positive value that is the same for each bump 1 point
For having the same maximum value in each cycle that occurs near the bump times (This point can be earned for a sinusoidal curve with peaks at the bump times.) 1 point

ii. 1 point

For drawing a v_{avg} line that is horizontal and consistent with the graph drawn, even if that graph is wrong 1 point

(b) 2 points

Correct answer: Greater than
No points are earned if the correct answer is selected, but the explanation is completely incorrect or there is no explanation.
No points are earned if the wrong answer is selected.
For indicating that there is more time between bumps 1 point
For connecting that the cart has more time or more distance to accelerate between bumps 1 point
Example: The maximum speed is greater because the cart has more space (or time) to accelerate (build up speed) between bumps.

Alternate solution in terms of energy *Alternate points*

For indicating that the potential energy difference increases due to increased height between successive bumps *1 point*
For relating the increase in potential energy to an increase in kinetic energy *1 point*

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Question 3 (continued)

Distribution of points

(c) 2 points

Correct answer: Greater than
No points are earned if the correct answer is selected, but the explanation is completely incorrect or there is no explanation.
No points are earned if the wrong answer is selected.
For indicating that the acceleration is greater — 1 point
For indicating that the component of the gravitational force increases — 1 point

Alternate solution in terms of energy — *Alternate points*

For indicating that the potential energy difference increases due to increased height between successive bumps — *1 point*
For relating the increase in potential energy to an increase in kinetic energy — *1 point*

(d)

i. 2 points

Correct answer: No
No points are earned if the correct answer is selected, but the explanation is completely incorrect or there is no explanation.

For indicating that v_{avg} is not proportional to M — 1 point
For connecting the equation to the data — 1 point
Examples:
The y-intercept of the graph is not zero, but the equation indicates that it should be zero.
Doubling the mass from the graph does not double v_{avg}, but the equation indicates that it should double.
If "yes" is selected, one point may be earned for explaining that v_{avg} increases with M or that v_{avg} looks (approximately) proportional to M for a limited portion of the data (e.g., the points at M = 1.0 kg and M = 2.0 kg).

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Question 3 (continued)

Distribution of points

(d)

ii. 2 points

Correct answer: No

For indicating that the distance dependency is incorrect — 1 point

For indicating that, according to the equation, greater *d* leads to a smaller v_{avg}, OR — 1 point

for stating or implying the contradiction between this inverse relation and the reasoning of part (b)

Credit is earned for any answer that is consistent with reasoning in part (b).

Example: According to the equation, a larger *d* corresponds to a smaller v_{avg}, because they are inversely proportional. But according to the reasoning of part (b), a bigger distance *d* between the bumps leads to a larger maximum average speed, showing that the equation is implausible.

If "yes" is selected, one point can be earned for indicating that an increase in the angle increases v_{avg}.

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Question 4

7 points total **Distribution of points**

(a) 3 points

Correct ranking is $(A = D) > (B = C)$.

For indicating that the potential difference is the same across A and D because the current is the same through each (A and D are in series.) 1 point

For indicating that the potential difference is the same across B and C because B and C are in parallel 1 point

For indicating that the potential difference is less across B (and/or C) than across A (and/or D) because the current splits or the current is less through B and C 1 point

Example: The full battery current passes through both A and D, so they have the same current. Because they have the same resistance, $\Delta V_A = \Delta V_D$. B and C are in parallel, so $\Delta V_B = \Delta V_C$. Less than the full current passes through B, and A and B have the same resistance, so ΔV_B is less than ΔV_A.

(b) 2 points

Correct answer: Decrease

No points are earned if the correct answer is selected, but the explanation is completely incorrect, or there is no explanation.

If the wrong answer is selected, up to one point can still be earned.

For indicating that the effective resistance of the circuit increases 1 point

For a correct explanation of why the current through A decreases based on changes in current or potential difference throughout the circuit 1 point

Examples:

Because B is replaced with an infinite resistance, the effective resistance of the circuit increases and the battery current decreases. Because the battery current decreases and that current equals the current through A, the current through A decreases.

When B is removed, the effective resistance of that piece of the circuit increases because there is no longer a parallel combination there. Because the resistance is greater, the potential difference across that piece is a greater percent of the total. So the potential difference across A decreases and thus the current through it decreases.

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Question 4 (continued)

Distribution of points

(c) 2 points

Correct answer: Increase
No points are earned if the correct answer is selected, but the explanation is completely incorrect, or there is no explanation.
If the wrong answer is selected, up to one point can still be earned.
For indicating that all the current from the battery passes through C; the current no longer splits — 1 point
For making either a current argument or potential difference argument for the increase (i.e., an argument for why an increase in current through C more than compensates for the decrease in the full current or explaining that, by the loop rule, the potential difference across C must increase in order for the potential difference around the circuit loop to remain zero) — 1 point

2016 SCORING GUIDELINES

Question 5

7 points total

Distribution of points

(a) 2 points

For indicating that there is more rope or weight below one point than the other — 1 point
For indicating (explicitly or implicitly) that the tension at any point counteracts or supports the weight below that point — 1 point
Examples:
- The rope at P supports more weight than the rope at Q so the tension must be higher at P.
- The section of rope below P has an upward force from the rope above it and a downward gravitational force. The same goes for Q. Because the gravitational force is greater on the longer section (the section below P), the upward force — the tension — must be greater at P.

(b) 5 points

For indicating that the wavelength is longer near the top of the rope (or shorter near the bottom) — 1 point
For indicating (explicitly or implicitly) that the frequency is the same throughout the rope — 1 point
For using $v = \lambda f$ to conclude that wave speed is greater near the top of the rope (or less near the bottom), based on the difference in wavelength — 1 point
For indicating (explicitly or implicitly) that, as stated in part (a), tension is greater near the top of the rope (or less near the bottom) — 1 point
For a response that has sufficient paragraph structure, as described in the published requirements for the paragraph-length response — 1 point