Question 1: Mathematical Routines (MR) — 10 points

A **(i)** For sketching **one** of the following: **Point A1**

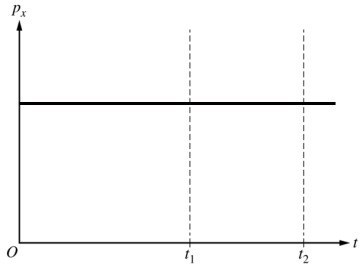
- A constant p_x for $t < t_1$
- A constant p_x for $t > t_1$

For sketching a line that demonstrates momentum is constant **Point A2**

Accept **one** of the following:

- A continuous, nonzero, horizontal line from $t = 0$ to $t = t_2$
- A continuous, nonzero, horizontal line from $t = 0$ to $t > t_2$

Example Response



(ii) For including a conservation of momentum equation **Point A3**

Scoring Note: Part A (ii) and part A (iii) may be scored together, if necessary.

For setting $m_c v_c$ equal to the momentum of the block-cart system after the collision **Point A4**

Scoring Note: A correct, isolated, final expression of $v_f = \frac{5}{6}v_c$ earns points A3 and A4.

Example Response

$p_i = p_f$

$m_c v_c = (m_c + m_b)v_f = \left(m_c + \frac{1}{5}m_c\right)v_f$

$v_f = \frac{5}{6}v_c$

(iii) For a multistep derivation that includes the correct relationship between kinetic energy, mass, and speed (i.e., $K = \frac{1}{2}mv^2$) **Point A5**

Scoring Note: The minimum requirement to earn this point is to show an expression of kinetic energy or change in energy that goes beyond the given equation on the reference information. For example, substituting quantities from the problem into $K = \frac{1}{2}mv^2$ or indicating the change in kinetic energy is $\Delta K = \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2$ earns the point.

For an indication that m_c and $\frac{6}{5}m_c$ are the initial and final masses, respectively, of the objects moving horizontally **Point A6**

For including an expression for v_f consistent with part A (ii) **Point A7**

Scoring Note: A correct, isolated, final expression of $\Delta K = -\frac{1}{12}m_c v_c^2$ earns points A3, A4, A6, and A7.

Example Response

$\Delta K = K_f - K_0$

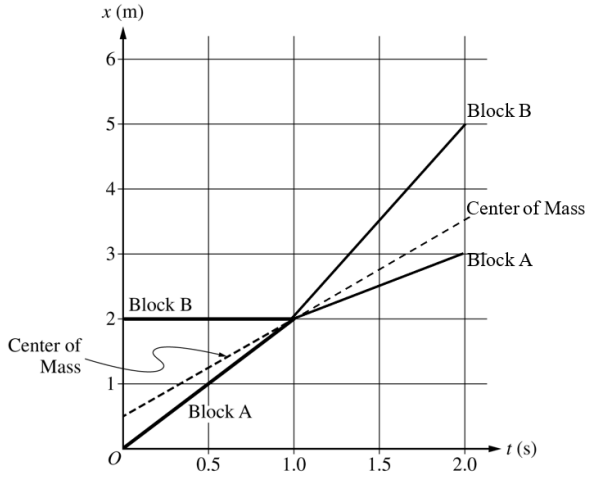
$K_0 = \frac{1}{2}m_c v_c^2$

$K_f = \frac{1}{2}\left(\frac{6}{5}m_c\right)\left(\frac{5}{6}v_c\right)^2 = \frac{5}{12}m_c v_c^2$

$\Delta K = -\frac{1}{12}m_c v_c^2$

B	For indicating "Remains constant" **Scoring Note:** This point is scored independently from the graph drawn in Figure 2 in part A (i).	**Point B1**
	For indicating **one** of the following: • The frictional force exerted on the new block by the cart is equal in magnitude and opposite in direction to the frictional force exerted on the cart by the new block. • The frictional force is internal to the new block-cart system. • The net external force is still zero. • The frictional force does not cause a net external force.	**Point B2**
	For indicating **one** of the following: • The change in momentum of the new block is equal in magnitude and opposite in direction to the change in momentum of the cart. • The impulse exerted on the cart and the impulse exerted on the new block are equal in magnitude and opposite in direction. • The correct relationship between the change in the momentum of the block-cart system and the net external force.	**Point B3**
	Example Response *The momentum of the new block-cart system will remain constant because the frictional force exerted on the new block by the cart is internal to the system and only a net external force will cause a change in momentum of the system.*	

Question 5: Short Answer — 7 points

(a)	For determining the speed of Block B to be 3 m/s	**1 point**
	Example Response $\frac{1}{2}(2\text{ kg})v_f^{\,2} = 9\text{ J}$ $v_f = 3\text{ m/s}$	
	Total for part (a)	**1 point**
(b)	For drawing and labeling a straight line for the position of Block A with a lesser positive slope than the slope of its pre-collision line **Scoring Note:** The correct slope is not required to earn this point.	**1 point**
	For drawing and labeling a straight line for the position of Block B with a positive, nonvertical slope **Scoring Note:** The correct slope is not required to earn this point.	**1 point**
	For drawing a straight line for the center of mass of the two-block system position with the same slope as the pre-collision line	**1 point**
	For drawing lines for Block A and Block B with the correct slopes, 1 m/s and 3 m/s, respectively, that begin at $t = 1.0$ s and $x = 2$ m	**1 point**
	Example Response  	
	Total for part (b)	**4 points**

(c) For indicating the line drawn for the center of mass of both two-block systems is the same **1 point**

For an explanation that indicates **one** of the following: **1 point**

- Momentum is conserved in an inelastic collision
- No external forces exerted on the two-block system

Example Response

The slope of the line drawn for the center of mass would remain the same as the that of the elastic collision because momentum is conserved. The lines for Block A *and Block* B *would lie along the center of mass line because the blocks slide together.*

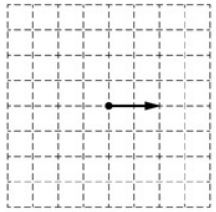
Total for part (c) 2 points

Total for question 5 7 points

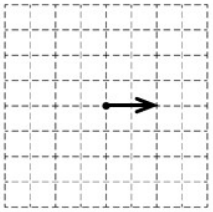
Question 4: Short Answer Paragraph Argument 7 points

(a) For drawing an arrow representing the sphere-block momentum, two grid units in length and pointing to the right **1 point**

Example Response



Case A: Momentum of Clay-Block System, Immediately After Collision



Case B: Momentum of Sphere-Block System, Immediately After Collision

Total for part (a) 1 point

(b) For indicating that momentum is conserved **1 point**

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

- why a greater amount of momentum is transferred by the rubber sphere
- why the block in Case B has greater momentum than in Case A

For indicating that a larger momentum leads to a greater speed **1 point**

For indicating the blocks fall for the same amount of time **1 point**

For indicating that a block moving at a faster speed lands at a greater horizontal distance **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

The momentum of the clay-block and sphere-block systems before the collision is the same for both cases and because momentum does not change in the collision; it is the same after the collision also. The sphere in Case B bounces off the block, so it has less (or negative) momentum after the collision than the clay in Case A. In order for the systems in both cases to have the same momentum after the collision, Block B must have greater momentum, and therefore greater speed, than Block A. The blocks take the same amount of time to fall, so the horizontal distance traveled by Block B (launch speed x time to fall) is greater than d_A.

Total for part (b) 6 points

Total for question 4 7 points

Question 3: Qualitative/Quantitative Translation — 12 points

(a) i.

For a correct answer $v_D = \frac{F_H t_f}{M_D}$ — **1 point**

ii.

For indicating the total momentum of the system is the same before and after the collision — **1 point**

Scoring Note: If the response only includes a correct final answer of $\frac{M_S}{M_D}$, the response earns this point but not the next point.

For correctly substituting the appropriate variables into a conservation of momentum equation
AND
an answer in the form $\frac{v_D}{v_S} = \ldots$ — **1 point**

Scoring Notes:
This point can be earned only if the first point is earned.
The answer need not be correct to earn this point.

Example response for part (a)(ii)

$p_i = p_f$

$0 = M_S v_S - M_D v_D$

$\frac{v_D}{v_S} = \frac{M_S}{M_D}$

Total for part (a) — **3 points**

(b)

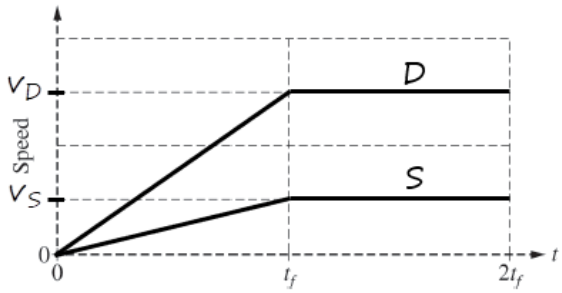
For two functions that
are straight segments for $t < t_f$,
AND
begin at the origin,
AND
have two different positive slopes — **1 point**

For two functions that are
horizontal functions for $t > t_f$
AND
are continuous over the entire time range $0 < t < 2t_f$ — **1 point**

For labeling values on the vertical axis with $v_D > v_S$
OR
The curve labeled D is greater than the curve labeled S for all t > 0 — **1 point**

Scoring note: This point can still be earned if the labels are not on the vertical axis but clearly indicate that $v_D > v_S$.

Example response for part (b)



Total for part (b) — **3 points**

(c) i.

For stating or mathematically representing that if the disk is much more massive, then the block will have little effect on the motion of disk 1 — **1 point**
OR
For stating or mathematically representing that when $M_D >> M_B$, $v_{cm} = v_1$

ii.

For correct reasoning. — **1 point**
Correct answer: When $M_D << M_B$, $v_{cm} = 0$

Example response for part (c) (ii)
If the block is much more massive, then it will barely move when the disk collides and sticks to it.

iii.

For using conservation of momentum — **1 point**

For a correct answer — **1 point**

$v_{cm} = \frac{m_D v_1}{m_D + m_B}$

iv.

For an attempt to use limiting-case reasoning or functional dependence with the equation in part (c)(iii) — **1 point**

For recognizing the equation from (c)(iii) reduces to a simpler form and the simplified form is correctly compared to their answer in (c)(i) — **1 point**

Example 1 response for part (c) (iv)
Yes. If M_B is very small, then the denominator of the equation simplifies to M_D, which then can cancel out of the equation leaving $v_{cm} = v_1$.

Total for part (c) — **6 points**

Total for question 3 — **12 points**

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2016 Scoring Guidelines

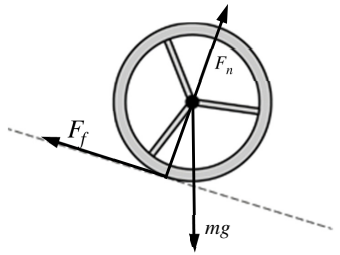
2016 SCORING GUIDELINES

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).

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

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

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

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

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

(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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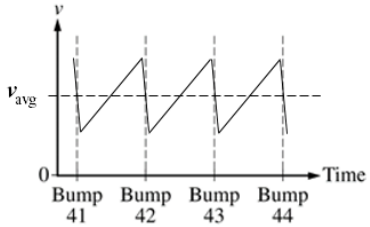
Question 3

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