

Question 3: Free-Response Question**15 points**

- (a) For using integral calculus to calculate the rotational inertia of the rod **1 point**

$$I = \int r^2 dm$$

$$dm = \lambda dr = \gamma x^2 dx$$

For correctly substituting γx^2 into the above equation **1 point**

$$I = \int x^2 (\gamma x^2 dx) = \int_{x=0}^{x=L} \gamma x^4 dx = \gamma \left[\frac{x^5}{5} \right]_{x=0}^{x=L} = \left(\frac{3M}{L^3} \right) \left(\frac{L^5}{5} - 0 \right) = \frac{3}{5} ML^2$$

Total for part (a) 2 points

- (b) For using integral calculus to determine the center of mass of the rod **1 point**

$$X_{CM} = \frac{\sum_i m_i x_i}{\sum_i m_i} = \frac{\int x dm}{\int dm}$$

For correctly substituting γx^2 into the numerator of the above equation **1 point**

For correctly substituting M into the denominator of the above equation OR evaluating the integral $\int dm$ to find the mass of the rod **1 point**

$$X_{CM} = \frac{\int x \lambda dx}{M} = \frac{\int x (\gamma x^2) dx}{M} = \frac{\int_{x=0}^{x=L} \gamma x^3 dx}{M} = \frac{\left[\frac{\gamma x^4}{4} \right]_{x=0}^{x=L}}{M} = \frac{\left(\frac{3M}{L^3} \right) \frac{L^4}{4}}{M} = \frac{3}{4} L$$

OR

$$X_{CM} = \frac{\int x \lambda dx}{\int \lambda dx} = \frac{\int_{x=0}^{x=L} x (\gamma x^2) dx}{\int_{x=0}^{x=L} \gamma x^2 dx} = \frac{\int_{x=0}^{x=L} \gamma x^3 dx}{\left[\frac{\gamma x^3}{3} \right]_{x=0}^{x=L}} = \frac{\left[\frac{\gamma x^4}{4} \right]_{x=0}^{x=L}}{\frac{\gamma L^3}{3}} = \frac{\frac{\gamma L^4}{4}}{\frac{\gamma L^3}{3}} = \frac{3}{4} L$$

Total for part (b) 3 points

(c)	For selecting “Greater than” with an attempted justification	1 point
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	For a correct justification	1 point
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Example responses for part (c)

Because more of the mass of the rod is at the end of the rod opposite point P, more mass is concentrated away from the axis of rotation; thus, the rotational inertia of the rod would be greater around point P than around its center of mass.

OR

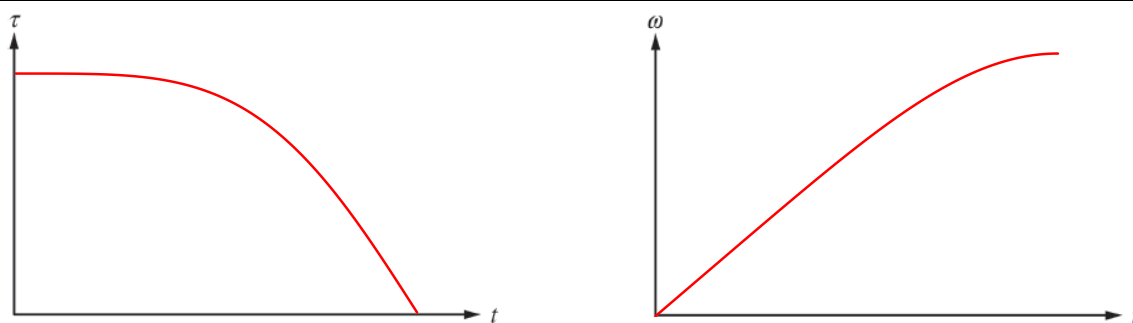
According to the parallel axis theorem, $I = I_{cm} + md^2$, if the axis is at a position away from the center of mass, the rotational inertia is larger than if the axis were at the center of mass.

Total for part (c)		2 points
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(d)	For a concave down curve that decreases to zero for the graph of τ as a function of t	1 point
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	For a concave down curve that approaches horizontal for the graph of ω as a function of t	1 point
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	For consistency between the two graphs	1 point
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Total for part (d)		3 points
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(e)	For selecting “Decreases” with an attempted justification	1 point
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	For a correct justification	1 point
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Example responses for part (e)

As the rod rotates downward, the angle θ in the torque equation $\tau = rF\sin\theta$ decreases. Thus, the torque on the rod decreases.

OR

As the rod rotates downward, the lever arm between point P and the rod's center of mass continues to decrease; thus, the torque on the rod decreases.

Total for part (e)		2 points
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(f)	For using conservation of energy to calculate the speed of the rotating rod	1 point
$U_i + K_i = U_f + K_f$ $U_i + 0 = 0 + K_f$ $U_i = K_f$		
For correctly substituting into the above equation		1 point
$mgh_i = \frac{1}{2}I\omega_f^2$		
For correctly solving for the linear speed of point S		1 point
$Mg\left(\frac{3}{4}L\right) = \frac{1}{2}\left(\frac{3}{5}ML^2\right)\left(\frac{v}{L}\right)^2$ $\frac{3}{4}MgL = \frac{3}{10}Mv^2 \therefore v = \sqrt{\frac{5}{2}gL} = \sqrt{\frac{5}{2}(9.8 \text{ m/s}^2)(1.0 \text{ m})} = 4.9 \text{ m/s}$		
Total for part (f)		3 points
Total for question 3		15 points

Question 2: Free-Response Question**15 points**

- (a) For integrating using the correct limits or constant of integration **1 point**

$$I = \int_{r=0}^{r=2L} \lambda r^2 dr = \lambda \left[\frac{r^3}{3} \right]_{r=0}^{r=2L} = \frac{\lambda}{3} ((2L)^3 - 0)$$

For correctly relating λ to M and L **1 point**

$$\lambda = \frac{m}{\ell} = \frac{M}{2L} \therefore I = \left(\frac{1}{3} \right) \left(\frac{M}{2L} \right) (8L^3) = \frac{4}{3} ML^2$$

Total for part (a) 2 points

- (b) i. For correctly substituting into an equation for the center of mass of an object in the horizontal direction **1 point**

$$X_{CM} = \frac{\sum m_i x_i}{\sum m_i} = \frac{\left[\left(\frac{M}{2} \right) \left(\frac{L}{2} \right) + \left(\frac{M}{2} \right) (L) \right]}{\left(\frac{M}{2} + \frac{M}{2} \right)} = \frac{\left(\frac{ML}{4} + \frac{ML}{2} \right)}{M} = \frac{3}{4} L$$

- ii. For correctly substituting into an equation for the center of mass of an object in the vertical direction **1 point**

$$Y_{CM} = \frac{\sum m_i y_i}{\sum m_i} = \frac{\left[\left(\frac{M}{2} \right) (L) + \left(\frac{M}{2} \right) \left(\frac{L}{2} \right) \right]}{\left(\frac{M}{2} + \frac{M}{2} \right)} = \frac{\left(\frac{ML}{2} + \frac{ML}{4} \right)}{M} = \frac{3}{4} L$$

Total for part (b) 2 points

- (c) For selecting “Less than” and attempting a relevant justification **1 point**

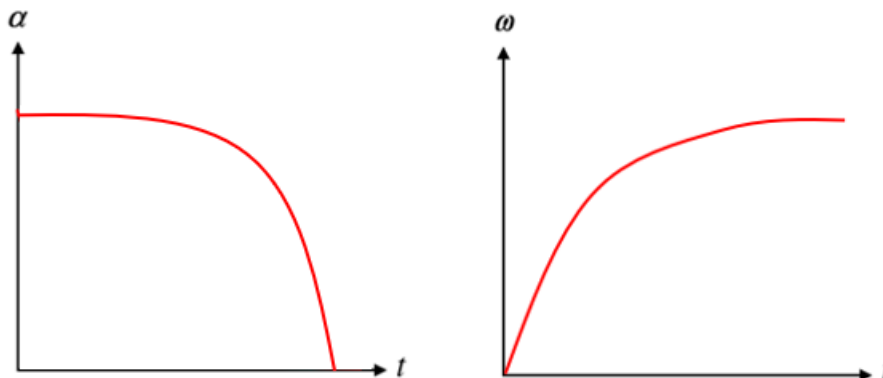
For a correct justification **1 point**

Example response for part (c)

Because object B has more of its mass closer to the pivot than object A, the rotational inertia of object B must be less than that of object A.

Total for part (c) 2 points

(d)	For an acceleration graph that is concave down and begins horizontally	1 point
	For an angular speed graph that is concave down and ends horizontally	1 point
	For consistency between the angular acceleration and angular speed graphs	1 point

Example responses for part (d)**Total for part (d) 3 points**

(e)	For selecting “Decreasing” and attempting a relevant justification	1 point
	For a justification that indicates the lever arm for the torque is decreasing	1 point

Example response for part (e)

Because the horizontal position of the center of mass for the object is moving closer to the pivot, the lever arm for the force of gravity is decreasing so the angular acceleration decreases.

Total for part (e) 2 points

(f)	For using conservation of energy	1 point
	$U_{g1} = K_2$	

For correctly relating the change in rotational kinetic energy to the change in gravitational potential energy

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

For correctly substituting for h into the equation above

$$mg\left(\frac{L}{2}\right) = \frac{1}{2}I\omega^2$$

For an expression for ω that uses only the allowed symbols and is algebraically consistent with the previous steps

$$\omega = \sqrt{\frac{2mgh}{I}} = \sqrt{\frac{2Mg(L/2)}{I_B}}$$

$$\omega = \sqrt{\frac{MgL}{I_B}}$$

Total for part (f) 4 points**Total for question 2 15 points**

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AP[®] Physics C: Mechanics

Scoring Guidelines Set 1

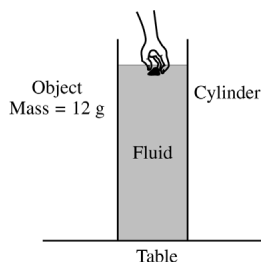
2019 SCORING GUIDELINES**General Notes About 2019 AP Physics Scoring Guidelines**

1. The solutions contain the most common method of solving the free-response questions and the allocation of points for this solution. Some also contain a common alternate solution. Other methods of solution also receive appropriate credit for correct work.
2. The requirements that have been established for the paragraph-length response in Physics 1 and Physics 2 can be found on AP Central at <https://secure-media.collegeboard.org/digitalServices/pdf/ap/paragraph-length-response.pdf>.
3. Generally, double penalty for errors is avoided. For example, if an incorrect answer to part (a) is correctly substituted into an otherwise correct solution to part (b), full credit will usually be awarded. One exception to this may be cases when the numerical answer to a later part should be easily recognized as wrong, e.g., a speed faster than the speed of light in vacuum.
4. Implicit statements of concepts normally receive credit. For example, if use of the equation expressing a particular concept is worth 1 point, and a student's solution embeds the application of that equation to the problem in other work, the point is still awarded. However, when students are asked to derive an expression, it is normally expected that they will begin by writing one or more fundamental equations, such as those given on the exam equation sheet. For a description of the use of such terms as "derive" and "calculate" on the exams, and what is expected for each, see "The Free-Response Sections — Student Presentation" in the *AP Physics; Physics C: Mechanics, Physics C: Electricity and Magnetism Course Description* or "Terms Defined" in the *AP Physics 1: Algebra-Based Course and Exam Description* and the *AP Physics 2: Algebra-Based Course and Exam Description*.
5. The scoring guidelines typically show numerical results using the value $g = 9.8 \text{ m/s}^2$, but the use of 10 m/s^2 is of course also acceptable. Solutions usually show numerical answers using both values when they are significantly different.
6. Strict rules regarding significant digits are usually not applied to numerical answers. However, in some cases answers containing too many digits may be penalized. In general, two to four significant digits are acceptable. Numerical answers that differ from the published answer due to differences in rounding throughout the question typically receive full credit. Exceptions to these guidelines usually occur when rounding makes a difference in obtaining a reasonable answer. For example, suppose a solution requires subtracting two numbers that should have five significant figures and that differ starting with the fourth digit (e.g., 20.295 and 20.278). Rounding to three digits will lose the accuracy required to determine the difference in the numbers, and some credit may be lost.

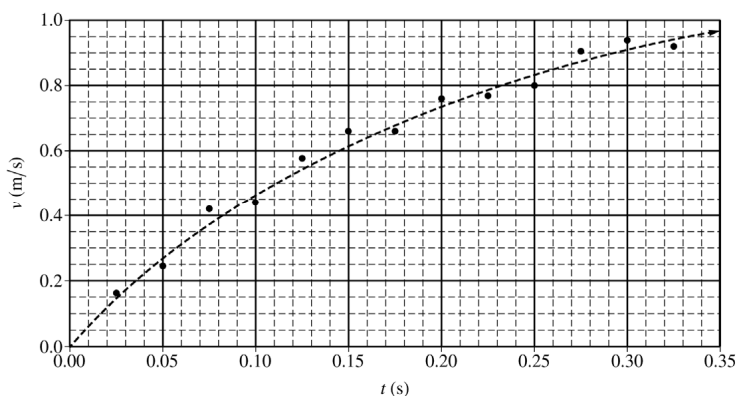
2019 SCORING GUIDELINES

Question 1

15 points



In an experiment, students used video analysis to track the motion of an object falling vertically through a fluid in a glass cylinder. The object of $m = 12\text{ g}$ is released from rest at the top of the column of fluid, as shown above. The data for the speed v of the falling object as a function of time t are graphed on the grid below. The dashed curve represents the best fit chosen by the students for these data.



(a)

- i. LO CHA-1.C, SP 7.A
1 point

Does the speed of the object increase, decrease, or remain the same?

☐ Increase ☐ Decrease ☐ Remain the same

For selecting "Increase"

1 point

- ii. LO CHA-1.C, SP 4.D
2 points

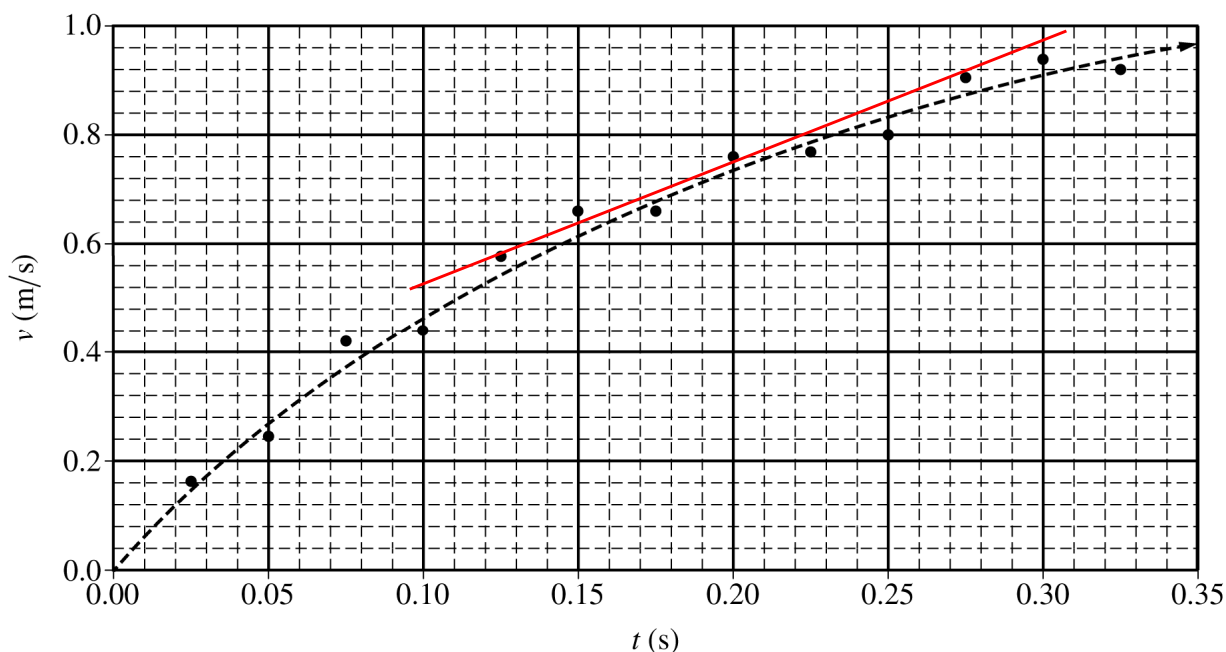
In a brief statement, describe the direction of the object's acceleration and how the magnitude of this acceleration changed as the object fell.

For a description that includes the direction of the acceleration as being "downwards"	1 point
For a description that includes the decrease in the magnitude of the acceleration	1 point
Example: Because the object is moving downwards and speeding up, the acceleration must be downwards. Because the slope of the graph of speed as a function of time is decreasing, the magnitude of the acceleration must be decreasing.	

2019 SCORING GUIDELINES

Question 1 (continued)

(a) continued



- iii. LO CHA-1.C, SP 4.D, 6.C
2 points

Using the graph, calculate an approximate value for the magnitude of the acceleration of the object at $t = 0.20$ s.

For calculating the slope of a trend line at $t = 0.20$ s	1 point
$\text{slope} = a = \frac{\Delta v}{\Delta t} = \frac{(0.8 - 0.6) \text{ m/s}}{(0.226 - 0.136) \text{ s}}$	
For a correct answer using points from a tangent line	1 point
$a = 2.22 \text{ m/s}^2$	

The students use the equation $v = A(1 - e^{-Bt})$ to model the speed of the falling object and find the best-fit coefficients to be $A = 1.18 \text{ m/s}$ and $B = 5 \text{ s}^{-1}$.

2019 SCORING GUIDELINES

Question 1 (continued)

(b) Use the above equation to:

- i. LO CHA-1.B, SP 6.B, 6.C
3 points

Derive an expression for the magnitude of the vertical displacement $y(t)$ of the falling object as a function of time t .

For indicating that the vertical displacement is the integration of the velocity	1 point
$\Delta y = \int v dt = \int A(1 - e^{-Bt}) dt$	
For the equation for speed using appropriate limits or constant of integration	1 point
$\Delta y = \int_{t'=0}^{t'=t} A(1 - e^{-Bt'}) dt' = A \left[t' - \frac{1}{-B} e^{-Bt'} \right]_{t'=0}^{t'=t} = A \left[\left(t + \frac{1}{B} e^{-Bt} \right) - \left(0 + \frac{1}{B} e^0 \right) \right]$	
For a correct answer	1 point
$\Delta y = A \left(t + \frac{1}{B} (e^{-Bt} - 1) \right) = (1.18) \left(t + \frac{1}{5} (e^{-5t} - 1) \right)$	
<u>Note:</u> Credit given for using A and B or plugging in the given values	

- ii. LO INT-1.C.d, SP 6.B, 6.C
3 points

Derive an expression for the magnitude of the net force $F(t)$ exerted on the object as it falls through the fluid as a function of time t .

For attempting the derivative of the equation for speed	1 point
$a = \frac{dv}{dt} = \frac{d}{dt} [A(1 - e^{-Bt})]$	
For a correct equation for the acceleration	1 point
$a = ABe^{-Bt}$	
For multiplying the equation above by the mass of the object	1 point
$F = ma = m(ABe^{-Bt}) = mABe^{-Bt}$	
$F = (.012)(1.18)(5)e^{-5t} = 0.071e^{-5t}$	
<u>Note:</u> Credit given for using A , B , and m or plugging in the given values	

2019 SCORING GUIDELINES**Question 1 (continued)**

(c)

The students repeat the experiment with a taller glass cylinder that is filled with the same fluid. The cylinder is tall enough so that the object reaches a constant speed.

i. LO INT-1.I, SP 7.A, 7.C

2 points

Determine the constant speed of the object.

Justify your answer.

For stating the constant speed is $v = A$	1 point
For indicating that the constant speed can be determined by setting the time equal to infinity	1 point
Example: After a long time, the falling object will reach a terminal constant speed in the fluid. This can be determined by setting the time t in the equation for speed equal to infinity. By doing this, the constant speed is determined to be $v = A$.	
<u>Note:</u> Credit given for solving mathematically	

ii. LO INT-1.H.b, SP 7.A, 7.C

2 points

Determine the force exerted by the fluid on the object at this time. Justify your answer.

For indicating that the net force is equal to zero when the object moves with constant speed	1 point
For indicating the resistive force is equal to the weight of the object at this time	1 point
Example: When the falling object reaches a constant speed in the fluid, the net force must be zero. Because the only vertical forces acting on the object are Earth's gravitational pull and the resistive force of the fluid, these two forces must be equal. So, the resistive force must be equal to the weight of the object or 0.12 N.	
<u>Note:</u> Credit given for solving mathematically	

2019 SCORING GUIDELINES**Question 1 (continued)****Learning Objectives**

CHA-1.B: Determine functions of position, velocity, and acceleration that are consistent with each other, for the motion of an object with a nonuniform acceleration.

CHA-1.C: Describe the motion of an object in terms of the consistency that exists between position and time, velocity and time, and acceleration and time.

INT-1.C.d: Derive an expression for the net force on an object in translational motion.

INT-1.H.b: Describe the acceleration, velocity, or position in relation to time for an object subject to a resistive force (with different initial conditions, i.e., falling from rest or projected vertically).

INT-1.I: Calculate the terminal velocity of an object moving vertically under the influence of a resistive force of a given relationship.

Science Practices

4.D: Select relevant features of a graph to describe a physical situation or solve problems.

6.B: Apply an appropriate law, definition, or mathematical relationship to solve a problem.

6.C: Calculate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

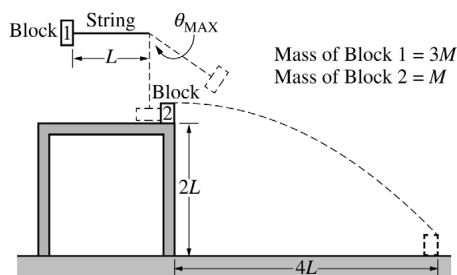
7.A: Make a scientific claim.

7.C: Support a claim with evidence from physical representations.

2019 SCORING GUIDELINES

Question 2

15 points



Note: Figure not drawn to scale.

A pendulum of length L consists of block 1 of mass $3M$ attached to the end of a string. Block 1 is released from rest with the string horizontal, as shown above. At the bottom of its swing, block 1 collides with block 2 of mass M , which is initially at rest at the edge of a table of height $2L$. Block 1 never touches the table. As a result of the collision, block 2 is launched horizontally from the table, landing on the floor a distance $4L$ from the base of the table. After the collision, block 1 continues forward and swings up. At its highest point, the string makes an angle θ_{MAX} to the vertical. Air resistance and friction are negligible. Express all algebraic answers in terms of M , L , and physical constants, as appropriate.

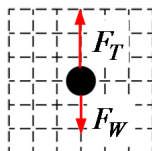
- (a) LO CON-2.C.a, SP 5.E
1 point

Determine the speed of block 1 at the bottom of its swing just before it makes contact with block 2.

For correctly calculating the speed of block 1		1 point
$U_{g1} = K_2 \therefore mgh = \frac{1}{2}mv^2 \therefore gL = \frac{1}{2}v^2$		
$v = \sqrt{2gL}$		
Note: Credit is earned even if no work is shown.		

- (b) LO INT-2.B.b, SP 3.D
2 points

On the dot below, which represents block 1, draw and label the forces (not components) that act on block 1 just before it makes contact with block 2. Each force must be represented by a distinct arrow starting on, and pointing away from, the dot. Forces with greater magnitude should be represented by longer vectors.



For correctly drawing and labeling the weight of the block and the tension in the string		1 point
For drawing the tension longer than the weight of the block		1 point
Note: A maximum of one point can be earned if there are any extraneous vectors.		

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Question 2 (continued)

- (c) LO INT-2.B.b, SP 5.A, 5.E
2 points

Derive an expression for the tension F_T in the string when the string is vertical just before block 1 makes contact with block 2. If you need to draw anything other than what you have shown in part (b) to assist in your solution, use the space below. Do NOT add anything to the figure in part (b).

For using an appropriate equation to calculate the tension in the string		1 point
$F_T = mg + ma_C = mg + \frac{mv^2}{r} = 3Mg + \frac{(3M)(\sqrt{2gL})^2}{L}$		
For a correct answer		1 point
$F_T = 9Mg$		

For parts (d)–(g), the value for the length of the pendulum is $L = 75$ cm.

- (d) LO CHA-2.C, SP 6.A, 6.C
2 points

Calculate the time between the instant block 2 leaves the table and the instant it first contacts the floor.

For using a correct kinematic equation to calculate the time		1 point
$\Delta y = v_1 t + \frac{1}{2}at^2 = \frac{1}{2}at^2 \therefore t = \sqrt{\frac{2\Delta y}{a}} = \sqrt{\frac{2(2L)}{g}} = \sqrt{\frac{(4)(0.75 \text{ m})}{(9.8 \text{ m/s}^2)}}$		
For a correct answer		1 point
$t = 0.55 \text{ s}$		

- (e) LO CHA-2.C, SP 6.A, 6.C
2 points

Calculate the speed of block 2 as it leaves the table.

For using a correct kinematic equation to calculate the speed		1 point
$\Delta x = vt \therefore v = \frac{\Delta x}{t} = \frac{4L}{t}$		
For substituting the time from part (d) into equation above		1 point
$v = \frac{(4)(0.75 \text{ m})}{(0.55 \text{ s})} = 5.45 \text{ m/s}$		

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Question 2 (continued)

- (f) LO CON-4.E.a, SP 6.B, 6.C
3 points

Calculate the speed of block 1 just after it collides with block 2.

For indicating the use of the correct conservation of momentum to calculate the speed	1 point
$p_i = p_f \therefore m_1 v_{1i} + m_2 v_{2i} = m_1 v_{1f} + m_2 v_{2f}$	
For correctly substituting the mass into equation above	1 point
$(3M)v_{1i} + 0 = (3M)v_{1f} + (M)v_{2f}$	
For substituting the speeds from parts (a) and (e) into equation above	1 point
$v_{1f} = \frac{(3M)v_{1i} - (M)v_{2f}}{(3M)} = \frac{(3M)\sqrt{2gL} - (M)v_{2f}}{(3M)}$	
$v_{1f} = \frac{(3)\sqrt{(2)(9.8 \text{ m/s}^2)(0.75 \text{ m})} - (1)(5.45 \text{ m/s})}{(3)} = 2.02 \text{ m/s}$	
$(v_{1f} = 2.06 \text{ m/s when using } g = 10 \text{ m/s}^2)$	

- (g) LO CON-2.C.a, SP 6.B, 6.C
3 points

Calculate the angle θ_{MAX} that the string makes with the vertical, as shown in the original figure, when block 1 is at its highest point after the collision.

For using conservation of energy to calculate the angle	1 point
$K_1 = U_{g2}$	
$\frac{1}{2}mv^2 = mgh$	
For correctly substituting $h = L(1 - \cos\theta)$ into the equation above	1 point
For correctly substituting the speed from part (f) into the equation above	1 point
$\frac{1}{2}mv^2 = mgL(1 - \cos\theta) \therefore \frac{v^2}{2gL} = 1 - \cos\theta$	
$\theta = \cos^{-1}\left(1 - \frac{v^2}{2gL}\right) = \cos^{-1}\left(1 - \frac{(2.02 \text{ m/s})^2}{(2)(9.8 \text{ m/s}^2)(0.75 \text{ m})}\right) = 43.5^\circ$	
$(\theta = 44.1^\circ \text{ when using } g = 10 \text{ m/s}^2)$	

2019 SCORING GUIDELINES**Question 2 (continued)****Learning Objectives**

CHA-2.C: Calculate kinematic quantities of an object in projectile motion, such as displacement, velocity, speed, acceleration, and time, given initial conditions of various launch angles, including a horizontal launch at some point in its trajectory.

INT-2.B.b: Describe forces that are exerted on objects undergoing horizontal circular motion, vertical circular motion, or horizontal circular motion on a banked curve.

CON-2.C.a: Calculate unknown quantities (e.g., speed or positions of an object) that are in a conservative system of connected objects, such as the masses in an Atwood machine, masses connected with pulley/string combinations, or the masses in a modified Atwood machine.

CON-4.E.a: Calculate the changes in speeds, changes in velocities, changes in kinetic energy, or changes in momenta of objects in all types of collisions (elastic or inelastic) in one dimension, given the initial conditions of the objects.

Science Practices

3.D: Create appropriate diagrams to represent physical situations.

5.A: Select an appropriate law, definition, or mathematical relationship or model to describe a physical situation.

5.E: Derive a symbolic expression from known quantities by selecting and following a logical algebraic pathway.

6.A: Extract quantities from narratives or mathematical relationships to solve problems.

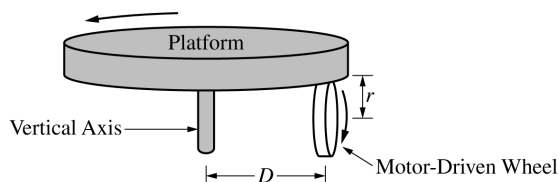
6.B: Apply an appropriate law, definition, or mathematical relationship to solve a problem.

6.C: Calculate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

2019 SCORING GUIDELINES

Question 3

15 points



A horizontal circular platform with rotational inertia I_P rotates freely without friction on a vertical axis. A small motor-driven wheel that is used to rotate the platform is mounted under the platform and touches it. The wheel has radius r and touches the platform a distance D from the vertical axis of the platform, as shown above. The platform starts at rest, and the wheel exerts a constant horizontal force of magnitude F tangent to the wheel until the platform reaches an angular speed ω_P after time Δt . During time Δt , the wheel stays in contact with the platform without slipping.

- (a) LO INT-7.A.b, CHA-4.A.b, SP 5.A, 5.E
2 points

Derive an expression for the angular speed ω_P of the platform. Express your answer in terms of I_P , r , D , F , Δt , and physical constants, as appropriate.

For correctly substituting into the rotational form of Newton's second law			1 point
$\tau = I\alpha \therefore FD = I_P\alpha$			
$\alpha = \frac{FD}{I_P}$			
For correctly substituting into a rotational kinematic equation to calculate the angular speed			1 point
$\omega_2 = \omega_1 + \alpha\Delta t = 0 + \left(\frac{FD}{I_P}\right)\Delta t$			
$\omega_P = \frac{FD\Delta t}{I_P}$			

- (b) LO INT-7.D.a, SP 5.A, 5.E
2 points

Determine an expression for the kinetic energy of the platform at the moment it reaches angular speed ω_P . Express your answer in terms of I_P , r , D , F , Δt , and physical constants, as appropriate.

For using the equation for rotational kinetic energy			1 point
$K = \frac{1}{2}I\omega_P^2 = \left(\frac{1}{2}\right)(I)\left(\frac{FD\Delta t}{I}\right)^2$			
For an answer consistent with part (a)			1 point
$K = \frac{(FD\Delta t)^2}{2I}$			

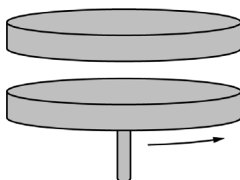
2019 SCORING GUIDELINES

Question 3 (continued)

- (c) LO INT-7.C, SP 5.A, 5.E
2 points

Derive an expression for the angular speed of the wheel ω_W when the platform has reached angular speed ω_P . Express your answer in terms of D , r , ω_P , and physical constants, as appropriate.

For indicating that the linear speed of the platform is equal to the linear speed of the wheel		1 point
$v_P = v_W$ OR $(r\omega)_P = (r\omega)_W$		
For correctly relating the linear speeds to the angular speeds in the above equation		1 point
$D\omega_P = r\omega_W$		
$\omega_W = \frac{D\omega_P}{r}$		



When the platform is spinning at angular speed ω_P , the motor-driven wheel is removed. A student holds a disk directly above and concentric with the platform, as shown above. The disk has the same rotational inertia I_P as the platform. The student releases the disk from rest, and the disk falls onto the platform. After a short time, the disk and platform are observed to be rotating together at angular speed ω_f .

- (d) LO CON-5.D.c, SP 5.A, 5.E
2 points

Derive an expression for ω_f . Express your answer in terms of ω_P , I_P , and physical constants, as appropriate.

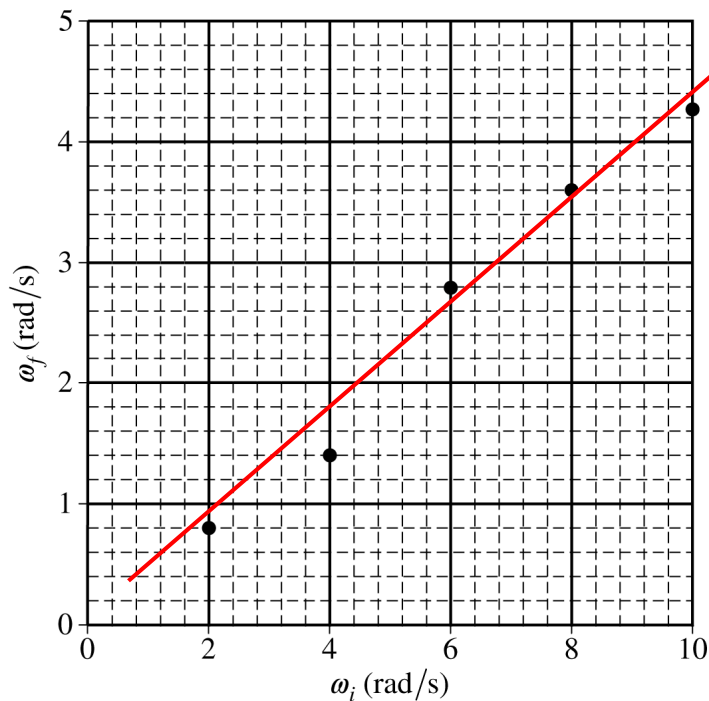
For using an expression for the conservation of angular momentum		1 point
$L_1 = L_2 \therefore I_1\omega_1 = I_2\omega_2$		
For correctly substituting into the above equation		1 point
$I\omega_P = (2I)\omega_f$		
$\omega_f = \frac{1}{2}\omega_P$		

2019 SCORING GUIDELINES**Question 3 (continued)**

A student now uses the rotating platform ($I_P = 3.1 \text{ kg} \cdot \text{m}^2$) to determine the rotational inertia I_U of an unknown object about a vertical axis that passes through the object's center of mass. The platform is rotating at an initial angular speed ω_i when the unknown object is dropped with its center of mass directly above the center of the platform. The platform and object are observed to be rotating together at angular speed ω_f . Trials are repeated for different values of ω_i . A graph of ω_f as a function of ω_i is shown on the axes below.

- (e)
- i. LO CON-5.D.c, SP 4.C
1 points

On the graph on the previous page, draw a best-fit line for the data.



For an appropriate best-fit line for the graph above	1 point
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2019 SCORING GUIDELINES

Question 3 (continued)

(e) continued

ii. LO CON-5.D.c, SP 4.D, 6.C

2 points

Using the straight line, calculate the rotational inertia of the unknown object I_U about a vertical axis passing through its center of mass.

For using conservation of angular momentum to derive an expression that includes I_U	1 point
$L_i = L_f \therefore I_P \omega_i = (I_P + I_U) \omega_f$	
$I_U = I_P \left(\frac{\omega_i}{\omega_f} \right) - I_P$	
For substituting points from the best-fit line into the expression above	1 point
$I_U = (3.1 \text{ kg}\cdot\text{m}^2) \left(\frac{(4.0 - 1.0) \text{ rad/s}}{(9.3 - 2.4) \text{ rad/s}} \right) - (3.1 \text{ kg}\cdot\text{m}^2) = 4.1 \text{ kg}\cdot\text{m}^2$	
<u>Note:</u> The point (0, 0) can be used implicitly if the best-fit line goes through the origin.	

(f)

LO CON-5.D.c, SP 7.A, 7.C

2 points

The kinetic energy of the spinning platform before the object is dropped on it is K_i . The total kinetic energy of the platform-object system when it reaches angular speed ω_f is K_f . Which of the following expressions is true?

___ $K_f < K_i$ ___ $K_f = K_i$ ___ $K_f > K_i$

Justify your answer.

For selecting $K_f < K_i$ with an attempt at a relevant justification	1 point
For a correct justification	1 point
Example: Because the two disks will be rotating with the same final angular speed, this is an inelastic collision, and kinetic energy will be lost during the collision.	

2019 SCORING GUIDELINES

Question 3 (continued)

- (g) LO INT-6.E, SP 7.A, 7.C
2 points

One of the students observes that the center of mass of the object is not actually aligned with the axis of the platform. Is the experimental value of I_U obtained in part (e) greater than, less than, or equal to the actual value of the rotational inertia of the unknown object about a vertical axis that passes through its center of mass?

_____ Greater than _____ Less than _____ Equal to

Justify your answer.

For selecting “Greater than” with an attempt at a relevant justification		1 point
For a correct justification		1 point
Example: Because the center of mass of the object is off the axis of the platform, the parallel axis theorem would be used to calculate the total rotational inertia of the platform-object system. Using $I = I_{CM} + Mh^2$, the experimental value will be increased by Mh^2 .		

Learning Objectives

INT-6.E: Derive the moments of inertia of an extended rigid body for different rotational axes (parallel to an axis that goes through the object’s center of mass) if the moment of inertia is known about an axis through the object’s center of mass.

CHA-4.A.b: Calculate unknown quantities such as angular positions, displacement, angular speeds, or angular acceleration of a rigid body in uniformly accelerated motion, given initial conditions.

INT-7.A.b: Calculate unknown quantities such as net torque, angular acceleration, or moment of inertia for a rigid body undergoing rotational acceleration.

INT-7.C: Derive expressions for physical systems such as Atwood Machines, pulleys with rotational inertia, or strings connecting discs or strings connecting multiple pulleys that relate linear or translational motion characteristics to the angular motion characteristics of rigid bodies in the system that are: **(a)** rolling (or rotating on a fixed axis) without slipping. **(b)** rotating and sliding simultaneously.

INT-7.D.a: Calculate the rotational kinetic energy of a rotating rigid body.

CON-5.D.c: Calculate the changes of angular momentum of each disc in a rotating system of two rotating discs that collide with each other inelastically about a common rotational axis.

Science Practices

4.C: Linearize data and/or determine a best-fit line or curve.

4.D: Select relevant features of a graph to describe a physical situation or solve problems.

5.A: Select an appropriate law, definition, or mathematical relationship or model to describe a physical situation.

5.E: Derive a symbolic expression from known quantities by selecting and following a logical algebraic pathway.

6.C: Calculate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

7.A: Make a scientific claim.

7.C: Support a claim with evidence from physical representations.

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AP Physics C: Mechanics

Scoring Guidelines

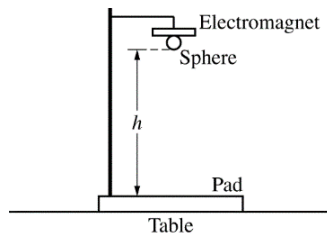
2018 SCORING GUIDELINES**General Notes About 2018 AP Physics Scoring Guidelines**

1. The solutions contain the most common method of solving the free-response questions and the allocation of points for this solution. Some also contain a common alternate solution. Other methods of solution also receive appropriate credit for correct work.
2. The requirements that have been established for the paragraph-length response in Physics 1 and Physics 2 can be found on AP Central at <https://secure-media.collegeboard.org/digitalServices/pdf/ap/paragraph-length-response.pdf>.
3. Generally, double penalty for errors is avoided. For example, if an incorrect answer to part (a) is correctly substituted into an otherwise correct solution to part (b), full credit will usually be awarded. One exception to this may be cases when the numerical answer to a later part should be easily recognized as wrong, e.g., a speed faster than the speed of light in vacuum.
4. Implicit statements of concepts normally receive credit. For example, if use of the equation expressing a particular concept is worth 1 point, and a student's solution embeds the application of that equation to the problem in other work, the point is still awarded. However, when students are asked to derive an expression, it is normally expected that they will begin by writing one or more fundamental equations, such as those given on the exam equation sheet. For a description of the use of such terms as “derive” and “calculate” on the exams, and what is expected for each, see “The Free-Response Sections — Student Presentation” in the *AP Physics; Physics C: Mechanics, Physics C: Electricity and Magnetism Course Description* or “Terms Defined” in the *AP Physics 1: Algebra-Based Course and Exam Description* and the *AP Physics 2: Algebra-Based Course and Exam Description*.
5. The scoring guidelines typically show numerical results using the value $g = 9.8 \text{ m/s}^2$, but the use of 10 m/s^2 is of course also acceptable. Solutions usually show numerical answers using both values when they are significantly different.
6. Strict rules regarding significant digits are usually not applied to numerical answers. However, in some cases answers containing too many digits may be penalized. In general, two to four significant digits are acceptable. Numerical answers that differ from the published answer due to differences in rounding throughout the question typically receive full credit. Exceptions to these guidelines usually occur when rounding makes a difference in obtaining a reasonable answer. For example, suppose a solution requires subtracting two numbers that should have five significant figures and that differ starting with the fourth digit (e.g., 20.295 and 20.278). Rounding to three digits will lose the accuracy required to determine the difference in the numbers, and some credit may be lost.

2018 SCORING GUIDELINES

Question 1

15 points total

Distribution
of points

A student wants to determine the value of the acceleration due to gravity g for a specific location and sets up the following experiment. A solid sphere is held vertically a distance h above a pad by an electromagnet, as shown in the figure above. The experimental equipment is designed to release the sphere when the electromagnet is turned off. A timer also starts when the electromagnet is turned off, and the timer stops when the sphere lands on the pad.

(a) 2 points

While taking the first data point, the student notices that the electromagnet actually releases the sphere after the timer begins. Would the value of g calculated from this one measurement be greater than, less than, or equal to the actual value of g at the student's location?

____ Greater than ____ Less than ____ Equal to

Justify your answer.

For selecting "Less than" with an attempt at a relevant justification	1 point
For a correct justification	1 point
<i>Example: Because the measured time to fall the same distance will be larger, the acceleration must be less.</i>	
<i>Example: Because the time is larger and $a \propto 1/t^2$, then g must decrease.</i>	

2018 SCORING GUIDELINES

Question 1 (continued)

Distribution of points

The electromagnet is replaced so that the timer begins when the sphere is released. The student varies the distance h . The student measures and records the time Δt of the fall for each particular height, resulting in the following data table.

h (m)	0.10	0.20	0.60	0.80	1.00
Δt (s)	0.105	0.213	0.342	0.401	0.451

(b) 1 point

Indicate below which quantities should be graphed to yield a straight line whose slope could be used to calculate a numerical value for g .

Vertical axis: _____

Horizontal axis: _____

Use the remaining rows in the table above, as needed, to record any quantities that you indicated that are not given in the table. Label each row you use and include units.

For correctly indicating two variables that will yield a straight line that could be used to determine a value for g		1 point
<i>Example: Vertical Axis: h</i> <i>Horizontal Axis: $(\Delta t)^2$</i>		
Note: Student earns full credit if axes are reversed or if they use another acceptable combination.		

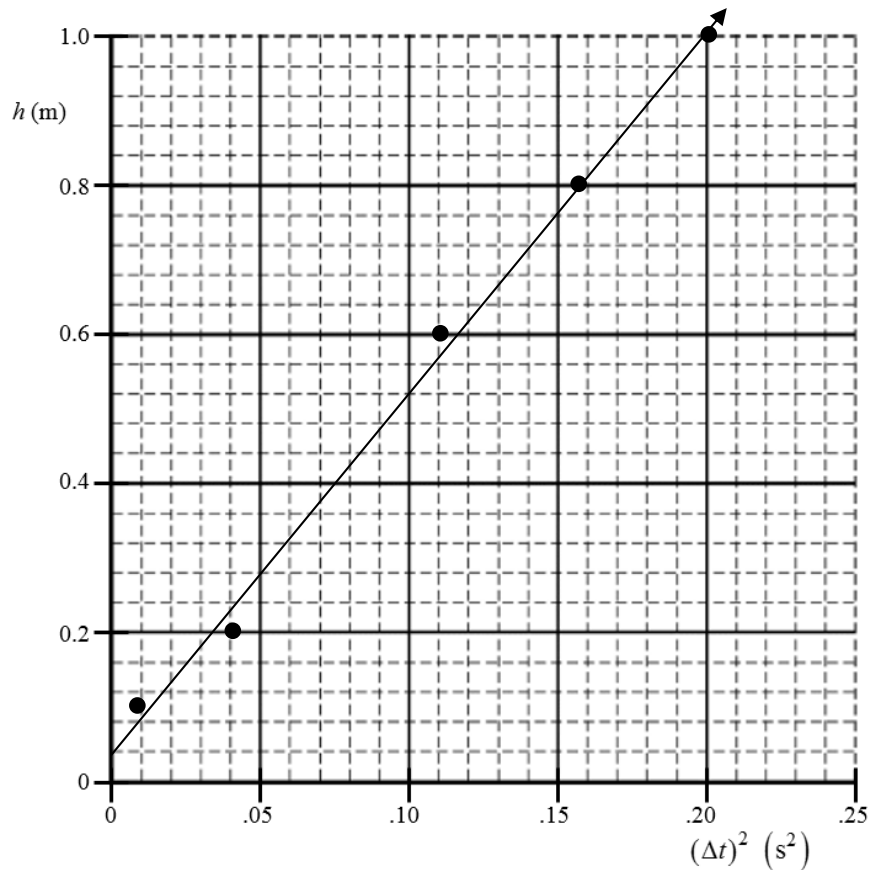
2018 SCORING GUIDELINES

Question 1 (continued)

**Distribution
of points**

(c) 4 points

Plot the data points for the quantities indicated in part (b) on the graph below. Clearly scale and label all axes, including units if appropriate. Draw a straight line that best represents the data.



For a correct scale that uses more than half the grid	1 point
For correctly labeling the axis with variables and units consistent with part (b)	1 point
For correctly plotting data consistent with part (b)	1 point
For drawing a straight line consistent with the plotted data	1 point

2018 SCORING GUIDELINES

Question 1 (continued)

Distribution
of points

(d) 2 points

Using the straight line, calculate an experimental value for g .

For using points on the line rather than the data to calculate the slope	1 point
$\text{slope} = \frac{\Delta h}{\Delta(\Delta t)^2} = \frac{(0.80 - 0.20) \text{ m}}{(0.160 - 0.039) \text{ s}^2} = 4.96 \text{ m/s}^2$ (Linear regression = 4.83 m/s^2)	
For correctly relating the slope to the acceleration due to gravity	1 point
$\text{slope} = \frac{1}{2}g \therefore g = 2 \times \text{slope} = 2 \times (4.96 \text{ m/s}^2)$	
$g = 9.92 \text{ m/s}^2$ (Linear regression = 9.66 m/s^2)	

Another student fits the data in the table to a quadratic equation. The student's equation for the distance fallen y as a function of time t is $y = At^2 + Bt + C$, where $A = 5.75 \text{ m/s}^2$, $B = -0.524 \text{ m/s}$, and $C = +0.080 \text{ m}$. Vertically down is the positive direction.

(e) Using the student's equation above, do the following.

i. 1 point

Derive an expression for the velocity of the sphere as a function of time.

For correctly taking the time derivative of the given equation	1 point
$y = y_0 + v_1t + \frac{1}{2}at^2 = At^2 + Bt + C$	
$v(t) = \frac{dy}{dt} = 2At + B$	
Note: Credit is earned for substituting numbers: $v(t) = (11.5 \text{ m/s}^2)t - 0.524 \text{ m/s}$.	

ii. 2 points

Calculate the new experimental value for g .

For correctly relating the given equation to a correct kinematic equation	1 point
$\Delta y = y - y_0 = v_1t + \frac{1}{2}at^2$	
$y = y_0 + v_1t + \frac{1}{2}at^2 = At^2 + Bt + C$	
For correctly relating the equation to the value of g	1 point
$A = \frac{1}{2}a = \frac{1}{2}g$	
$g = 2A = (2)(5.75 \text{ m/s}^2) = 11.5 \text{ m/s}^2$	

2018 SCORING GUIDELINES

Question 1 (continued)

Distribution
of points

iii. 1 point

Using 9.81 m/s^2 as the accepted value for g at this location, calculate the percent error for the value found in part (e)(ii).

For correctly calculating the percent error	1 point
$\% \text{error} = \frac{ \text{acc} - \text{exp} }{\text{acc}} \times 100\% = \frac{ (11.5 \text{ m/s}^2) - (9.81 \text{ m/s}^2) }{(9.81 \text{ m/s}^2)} \times 100\%$	
$\% \text{error} = 17.2\%$	
Note: Credit is earned if percent error is expressed as positive or negative.	

iv. 2 points

Assuming the sphere is at a height of 1.40 m at $t = 0$, calculate the velocity of the sphere just before it strikes the pad.

For relating the coefficients of the equation to the kinematic variables	1 point
$y = At^2 + Bt + C \therefore v_1 = B = -0.524 \text{ m/s}$	
$a = 2A = 2 \times (5.75 \text{ m/s}^2) = 11.5 \text{ m/s}^2$	
$y_0 = C = 0.080 \text{ m}$	
For correctly using an appropriate kinematics equation to determine the velocity of the sphere	1 point
$v_2^2 = v_1^2 + 2a\Delta y$	
$v = \sqrt{v_1^2 + 2a\Delta y} = \sqrt{(-0.524 \text{ m/s})^2 + (2)(11.5 \text{ m/s}^2)(1.40 \text{ m} - 0.080 \text{ m})}$	
$v = 5.54 \text{ m/s}$	
Alternate solution:	Alternate Points
For correctly determining the time of fall for the sphere	1 point
$y = At^2 + Bt + C$	
$1.40 = (5.75 \text{ m/s}^2)t^2 + (-0.524 \text{ m/s})t + (0.080 \text{ m})$	
$5.75t^2 - 0.524t - 1.32 = 0$	
$t = 0.53 \text{ s}$ or $-0.44 \text{ s} \therefore t = 0.53 \text{ s}$	
For correctly using the equation from part (e)(i)	1 point
$v(t) = (11.5 \text{ m/s}^2)(0.53 \text{ s}) - 0.524 \text{ m/s}$	
$v = 5.54 \text{ m/s}$	

AP PHYSICS C: MECHANICS
2018 SCORING GUIDELINES

Question 1 (continued)

**Distribution
of points**

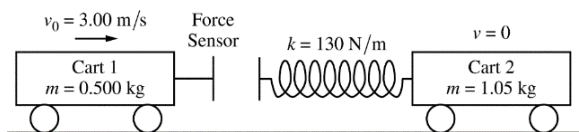
- (e)
iv. (continued)

<i>Alternate Solution — Conservation of Energy</i>		
<i>For relating the coefficients of the equation to the initial height and speed</i>		1 point
$y = At^2 + Bt + C \therefore v_1 = B = -0.524 \text{ m/s}$		
$y_0 = C = 0.080 \text{ m}$		
<i>For correctly using conservation of energy to determine the velocity of the sphere</i>		1 point
$U_i + K_i = U_f + K_f$		
$mgh + \frac{1}{2}mv_1^2 = \frac{1}{2}mv^2$		
$v = \sqrt{2(11.5)(1.40 - 0.080) + (-0.524)^2} = 5.54 \text{ m/s}$		

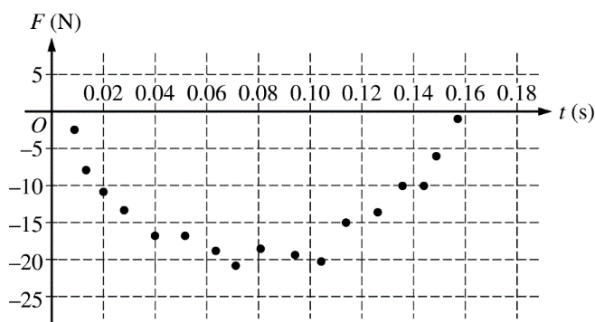
2018 SCORING GUIDELINES

Question 2

15 points total

Distribution
of points

Two carts are on a horizontal, level track of negligible friction. Cart 1 has a sensor that measures the force exerted on it during a collision with cart 2, which has a spring attached. Cart 1 is moving with a speed of $v_0 = 3.00 \text{ m/s}$ toward cart 2, which is at rest, as shown in the figure above. The total mass of cart 1 and the force sensor is 0.500 kg , the mass of cart 2 is 1.05 kg , and the spring has negligible mass. The spring has a spring constant of $k = 130 \text{ N/m}$. The data for the force the spring exerts on cart 1 are shown in the graph below. A student models the data as the quadratic fit $F = 3200 \text{ N/s}^2 t^2 - 500 \text{ N/s } t$.



(a) 3 points

Using integral calculus, calculate the total impulse delivered to cart 1 during the collision.

For using the given force equation in the integral to determine the impulse delivered to the cart	1 point
$J = \int F \cdot dt = \int 3200t^2 - 500t \, dt$	
For integrating the force using the correct limits or constant of integration	1 point
$J = \int_{t=0}^{t=0.16 \text{ s}} (3200t^2 - 500t) dt = \left[\frac{3200}{3}t^3 - 250t^2 \right]_{t=0}^{t=0.16}$	
$J = \left(\left(\frac{3200}{3} \right) (0.16)^3 - (250)(0.16)^2 \right) - 0$	
For a correct answer	1 point
$J = -2.03 \text{ N}\cdot\text{s}$	

2018 SCORING GUIDELINES

Question 2 (continued)

Distribution
of points

- (b)
- i. 1 point

Calculate the speed of cart 1 after the collision.

For correct substitution into the impulse-momentum equation of the answer from part (a) to determine the speed of cart 1		1 point
$J = m_1(v_{1f} - v_{1i}) \therefore v_{1f} = \frac{J}{m_1} + v_{1i} = \frac{(-2.03 \text{ N}\cdot\text{s})}{(0.500 \text{ kg})} + (3.00 \text{ m/s})$		
$v_{1f} = -1.06 \text{ m/s}$		

- ii. 1 point

In which direction does cart 1 move after the collision?

____ Left ____ Right

____ The direction is undefined, because the speed of cart 1 is zero after the collision.

For correctly selecting “Left”		1 point
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- (c)
- i. 2 points

Calculate the speed of cart 2 after the collision.

For using a correct equation to determine the speed of cart 2		1 point
$-J = -m_1(v_{1f} - v_{1i}) = m_2 v_{2f} \therefore v_{2f} = \frac{-J}{m_2}$		
For correct substitution of the answer from part (a)		1 point
$v_{2f} = \frac{(2.03 \text{ N}\cdot\text{s})}{(1.05 \text{ kg})}$		
$v_{2f} = 1.93 \text{ m/s}$		

2018 SCORING GUIDELINES

Question 2 (continued)

Distribution
of points

- (c)
i. (continued)

<i>Alternate solution</i>		<i>Alternate Points</i>
<i>For using the conservation of momentum to calculate the speed of cart 2 after the collision</i>		<i>1 point</i>
$m_1 v_{1i} = m_1 v_{1f} + m_2 v_{2f} \therefore v_{2f} = \frac{m_1 (v_{1i} - v_{1f})}{m_2}$		
<i>For correct substitution of the answer from part (b)(i)</i>		<i>1 point</i>
$v_{2f} = \frac{(0.500 \text{ kg})((3.00 \text{ m/s}) - (-1.06 \text{ m/s}))}{(1.05 \text{ kg})} = 1.93 \text{ m/s}$		

- ii. 2 points

Show that the collision between the two carts is elastic.

For indicating that the initial and final kinetic energies must be equal		1 point
$K_{1i} = K_{1f} + K_{2f}$		
For correct substitutions of answers from parts (b)(i) and (c)(i) into the calculations of the initial and final kinetic energies		1 point
$\left(\frac{1}{2}\right)(0.500 \text{ kg})(3.00 \text{ m/s})^2 = \left(\frac{1}{2}\right)(0.500 \text{ kg})(-1.06 \text{ m/s})^2 + \left(\frac{1}{2}\right)(1.05 \text{ kg})(1.93 \text{ m/s})^2$		
$2.25 \text{ J} \approx 2.24 \text{ J}$		

- (d)
i. 2 points

Calculate the speed of the center of mass of the two-cart-spring system.

For using the equation for the conservation of momentum to calculate the speed for the center of mass of the system		1 point
$m_1 v_{1i} = (m_1 + m_2) v_{cm} \therefore v_{cm} = \frac{m_1 v_{1i}}{(m_1 + m_2)}$		
For correct substitution into the equation above		1 point
$v_{cm} = \frac{(0.500 \text{ kg})(3.00 \text{ m/s})}{(0.500 \text{ kg} + 1.05 \text{ kg})} = 0.97 \text{ m/s}$		

2018 SCORING GUIDELINES

Question 2 (continued)

Distribution
of points

(d) (continued)

ii. 3 points

Calculate the maximum elastic potential energy stored in the spring.

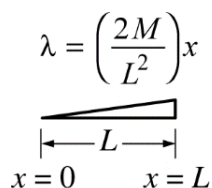
For using conservation of energy to calculate the maximum elastic potential energy stored in the spring	1 point
$K_i = K_f + U_{sf}$	
For using the speed of the center of mass of the system for kinetic energy	1 point
$\frac{1}{2} m_1 v_{1i}^2 = \frac{1}{2} (m_1 + m_2) v_{cm}^2 + U_{sf}$	
$U_{sf} = \frac{1}{2} m_1 v_{1i}^2 - \frac{1}{2} (m_1 + m_2) v_{cm}^2$	
For correct substitution into above equation	1 point
$U_S = \left(\frac{1}{2}\right)(0.500 \text{ kg})(3.00 \text{ m/s})^2 - \frac{1}{2}(0.500 \text{ kg} + 1.05 \text{ kg})(0.97 \text{ m/s})^2$	
$U_S = 1.52 \text{ J}$	
<i>Alternate Solution:</i>	<i>Alternate Points</i>
For correctly determining the magnitude of the maximum force exerted between the carts	1 point
Set $\frac{dF}{dt} = 0 = 6400t - 500 \therefore 6400t = 500 \therefore t = 0.078 \text{ s}$	
$F_{MAX} = 3200(0.078)^2 - 500(0.078) = -19.5$	
$ F_{MAX} = 19.5 \text{ N}$	
<i>Note: Can estimate from the graph, and accept the range of 20 N to 21 N.</i>	
For calculating the maximum compression of the spring	1 point
$F_{MAX} = -kx_{MAX}$	
$x_{MAX} = -\frac{F_{MAX}}{k} = -\frac{(-19.5 \text{ N})}{(130 \text{ N/m})} = 0.15 \text{ m}$	
<i>Note: If estimating from the graph, accept the range from 0.15 m to 0.16 m.</i>	
For substituting into an equation for the elastic potential energy at maximum spring compression	1 point
$U_S = \frac{1}{2} kx_{MAX}^2 = \left(\frac{1}{2}\right)(130 \text{ N/m})(0.15 \text{ m})^2$	
$U_S = 1.46 \text{ J}$	
<i>Note: If estimating from the graph, accept range from 1.46 J to 1.70 J.</i>	

Units point: 1 point for correct units on all calculated answers

2018 SCORING GUIDELINES

Question 3

15 points total

Distribution
of points

A triangular rod, shown above, has length L , mass M , and a nonuniform linear mass density given by the equation $\lambda = \frac{2M}{L^2}x$, where x is the distance from one end of the rod.

(a) 3 points

Using integral calculus, show that the rotational inertia of the rod about its left end is $ML^2/2$.

For relating x to r properly in an integral to calculate the moment of inertia		1 point
$I = \int r^2 dm = \int x^2 dm$		
For correctly using the linear mass density to substitute into the equation above		1 point
$m = \int \lambda dx = \int \left(2M/L^2 \right) x dx \therefore dm = \left(2M/L^2 \right) x dx$		
$I = \int \left(2M/L^2 \right) x^3 dx$		
For integrating using the correct limits or constant of integration		1 point
$I = \int_{x=0}^{x=L} \left(2M/L^2 \right) x^3 dx = \left[\frac{\left(2M/L^2 \right) x^4}{4} \right]_{x=0}^{x=L} = \frac{2M}{L^2} \left(\frac{L^4}{4} - 0 \right) = ML^2/2$		

2018 SCORING GUIDELINES

Question 3 (continued)

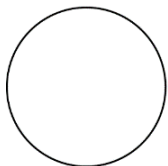
Distribution
of points

Figure 1

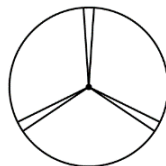


Figure 2

The thin hoop shown above in Figure 1 has a mass M , radius L , and a rotational inertia around its center of ML^2 . Three rods identical to the rod from part (a) are now fastened to the thin hoop, as shown in Figure 2 above.

(b) 2 points

Derive an expression for the rotational inertia I_{tot} of the hoop-rods system about the center of the hoop. Express your answer in terms of M , L , and physical constants, as appropriate.

For setting the total rotational inertia for the hoop-rods system equal to the sum of the rotational inertias of the hoop and the three rods		1 point
$I = 3I_{rod} + I_{hoop}$		
$I = 3\left(ML^2/2\right) + ML^2$		
For a correct answer with work		1 point
$I = \frac{5}{2}ML^2$		

The hoop-rods system is initially at rest and held in place but is free to rotate around its center. A constant force F is exerted tangent to the hoop for a time Δt .

(c) 3 points

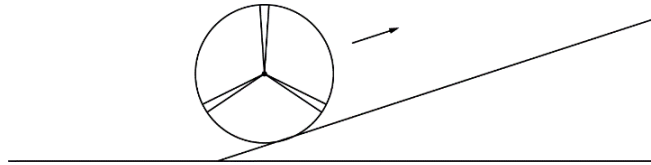
Derive an expression for the final angular speed ω of the hoop-rods system. Express your answer in terms of M , L , F , Δt , and physical constants, as appropriate.

For using an appropriate equation to determine the final angular speed of the hoop		1 point
$\tau\Delta t = I(\omega_2 - \omega_1)$		
$Fr\Delta t = I\omega$		
$\omega = \frac{Fr\Delta t}{I}$		
For relating the lever arm to the length of the rod		1 point
$\omega = \frac{FL\Delta t}{I}$		
For correct substitution from part (b)		1 point
$\omega = \frac{FL\Delta t}{\left(\frac{5}{2}\right)ML^2} = \frac{2F\Delta t}{5ML}$		

2018 SCORING GUIDELINES

Question 3 (continued)

Distribution
of points

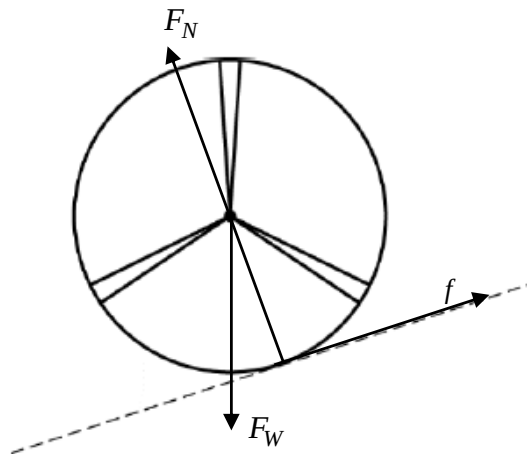


The hoop-rods system is rolling without slipping along a level horizontal surface with the angular speed ω found in part (c). At time $t = 0$, the system begins rolling without slipping up a ramp, as shown in the figure above.

(d)

i. 3 points

On the figure of the hoop-rods system below, draw and label the forces (not components) that act on the system. Each force must be represented by a distinct arrow starting at, and pointing away from, the point at which the force is exerted on the system.



For drawing the weight of the hoop-rod system in the correct direction	1 point
For drawing the normal force in the correct direction	1 point
For drawing the frictional force in the correct direction	1 point
Note: A maximum of two points can be earned if there are any extraneous vectors or any vector has an incorrect point of exertion.	

2018 SCORING GUIDELINES

Question 3 (continued)

Distribution
of points

ii. 1 point

Justify your choice for the direction of each of the forces drawn in part (d)(i).

For a correct justification of the direction of the forces in part (d)(i)	1 point
<i>Example: The normal force is always perpendicular to the surface, so it will be directed up and to the left. The gravitational force is always vertically downward. The friction will be opposite of the direction of rotation; therefore, it is directed up the incline.</i>	

(e) 3 points

Derive an expression for the change in height of the center of the hoop from the moment it reaches the bottom of the ramp until the moment it reaches its maximum height. Express your answer in terms of M , L , I_{tot} , ω , and physical constants, as appropriate.

For including both linear and rotational kinetic energy in an equation for the conservation of energy to determine the final height of the hoop	1 point
$K_1 = U_{g2}$	
$\frac{1}{2}mv^2 + \frac{1}{2}I\omega^2 = mgH$	
$H = \frac{\frac{1}{2}mv^2 + \frac{1}{2}I\omega^2}{mg}$	
For correct substitution of $v = L\omega$	1 point
$H = \frac{\frac{1}{2}m(L\omega)^2 + \frac{1}{2}I_{tot}\omega^2}{mg}$	
$H = \frac{\frac{1}{2}(m_{tot}L^2 + I_{tot})\omega^2}{m_{tot}g}$	
For correct substitution of inertias into energy equation	1 point
$H = \frac{\frac{1}{2}((3M + M)L^2 + I_{tot})\omega^2}{(3M + M)g} = \frac{(4ML^2 + I_{tot})\omega^2}{8Mg}$	

2017**AP[®]** **CollegeBoard**

AP Physics C: Mechanics

Scoring Guidelines

AP[®] PHYSICS
2017 SCORING GUIDELINES

General Notes About 2017 AP Physics Scoring Guidelines

1. The solutions contain the most common method of solving the free-response questions and the allocation of points for this solution. Some also contain a common alternate solution. Other methods of solution also receive appropriate credit for correct work.
2. The requirements that have been established for the paragraph length response in Physics 1 and Physics 2 can be found on AP Central at <https://secure-media.collegeboard.org/digitalServices/pdf/ap/paragraph-length-response.pdf>.
3. Generally, double penalty for errors is avoided. For example, if an incorrect answer to part (a) is correctly substituted into an otherwise correct solution to part (b), full credit will usually be awarded. One exception to this may be cases when the numerical answer to a later part should be easily recognized as wrong, e.g., a speed faster than the speed of light in vacuum.
4. Implicit statements of concepts normally receive credit. For example, if use of the equation expressing a particular concept is worth one point, and a student's solution embeds the application of that equation to the problem in other work, the point is still awarded. However, when students are asked to derive an expression it is normally expected that they will begin by writing one or more fundamental equations, such as those given on the exam equation sheet. For a description of the use of such terms as "derive" and "calculate" on the exams, and what is expected for each, see "The Free-Response Sections—Student Presentation" in the *AP Physics; Physics C: Mechanics, Physics C: Electricity and Magnetism Course Description* or "Terms Defined" in the *AP Physics 1: Algebra-Based and AP Physics 2: Algebra-Based Course and Exam Description*.
5. The scoring guidelines typically show numerical results using the value $g = 9.8 \text{ m/s}^2$, but use of 10 m/s^2 is of course also acceptable. Solutions usually show numerical answers using both values when they are significantly different.
6. Strict rules regarding significant digits are usually not applied to numerical answers. However, in some cases answers containing too many digits may be penalized. In general, two to four significant digits are acceptable. Numerical answers that differ from the published answer due to differences in rounding throughout the question typically receive full credit. Exceptions to these guidelines usually occur when rounding makes a difference in obtaining a reasonable answer. For example, suppose a solution requires subtracting two numbers that should have five significant figures and that differ starting with the fourth digit (e.g., 20.295 and 20.278). Rounding to three digits will lose the accuracy required to determine the difference in the numbers, and some credit may be lost.

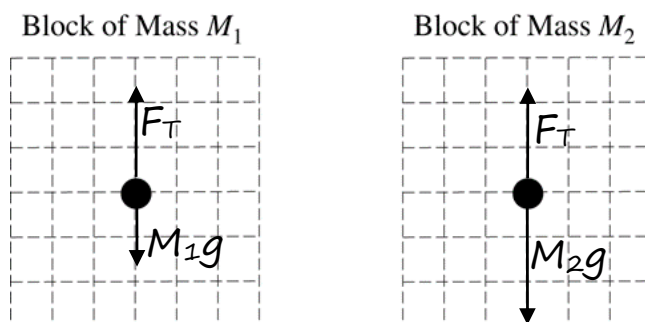
SCORING GUIDELINES

Question 1

15 points total

Distribution
of points

(a) 3 points



For correctly drawing and labeling the vectors for the weight of the block and the tension for block M_1 with the tension larger than the weight

1 point

For correctly drawing and labeling the vectors for the weight of the block and the tension for block M_2 with the weight larger than the tension

1 point

For correctly drawing tension on the two blocks as equal in magnitude

1 point

Note: If any extraneous vectors are drawn, only a maximum of two points may be earned.

(b) 3 points

For correctly applying Newton's second law to block 1

1 point

$$F_T - M_1g = M_1a$$

For correctly applying Newton's second law to block 2

1 point

$$M_2g - F_T = M_2a$$

For combining the two equations above in such a way that will lead to the correct equation

1 point

$$M_2g - M_1g = (M_1 + M_2)a$$

$$a = \frac{(M_2 - M_1)}{(M_1 + M_2)}g$$

(c) 1 point

For indicating variables that will create a straight line whose slope can be used to determine g

1 point

Example: Vertical axis: a

$$\text{Horizontal axis: } \frac{(M_2 - M_1)}{(M_1 + M_2)}$$

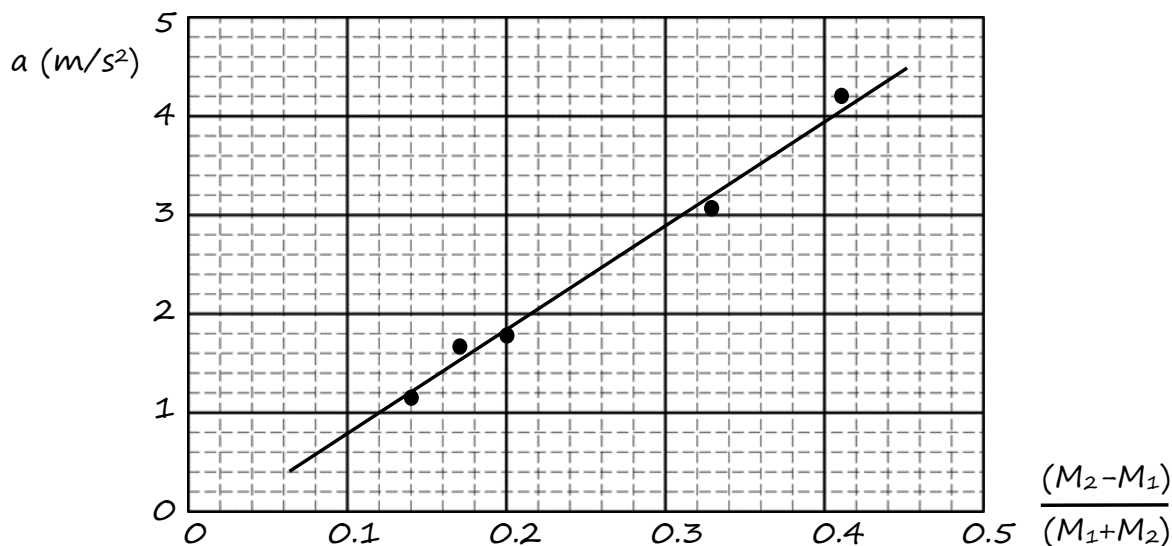
Note: Full credit is earned if axes are reversed, or if the student uses another acceptable combination.

2017 SCORING GUIDELINES

Question 1 (continued)

Distribution
of points

(d) 3 points



For using a correct scale that uses more than half the grid and for correctly labeling the axes, including units as appropriate

1 point

For correctly plotting the data

1 point

For drawing a straight best-fit line consistent with the plotted data

1 point

(e) 2 points

For correctly calculating the slope using the best-fit line and not the data points, unless the points fall on the best-fit line

1 point

(Note: Credit may be given for the linear regression only if the student states linear regression is used.)

$$\text{slope} = \frac{(y_2 - y_1)}{(x_2 - x_1)} = \frac{(3.0 - 1.0) \text{ m/s}^2}{(0.31 - 0.12)} = 10.5 \text{ m/s}^2$$

For correctly relating the slope to g

1 point

$$g = \text{slope} = 10.5 \text{ m/s}^2 \text{ (using linear regression yields } 10.1 \text{ m/s}^2 \text{)}$$

2017 SCORING GUIDELINES**Question 1 (continued)****Distribution
of points**

(f) 2 points

Correct answer: “Lower”

For including a correct statement about the acceleration of the blocks

1 point

For including a correct statement about the forces on the blocks

1 point

Example: Because the block M_1 is on the table, the net force on the system increases, and therefore the acceleration increases. Because the acceleration of M_2 increases, the net force on M_2 must increase. Therefore, there must be a greater difference in the magnitude of the two forces on M_2 . Because the weight of block M_2 stays the same, the retarding force — the tension in the string — must decrease.

(g) 1 point

For a correct justification

1 point

Example: Block M_1 will experience friction with the table. The acceleration of the system will decrease and this will decrease the slope of the line; therefore, the value of g is determined by the experiment.

SCORING GUIDELINES

15 points total	Question	Distribution of points
(a)		
i. 2 points		
	For correctly using conservation of energy for the block moving down the incline	1 point
	$U_g = K$	
	$mgh = \frac{1}{2}mv^2$	
	For a correct answer	1 point
	$v = \sqrt{2gh}$	
ii. 1 point		
	Correct answer: “Greater than”	
	For a correct justification	1 point
	Example: The speed is proportional to the square root of the change in height. So if the height is reduced by a factor of 2, the speed is reduced by a factor of $\sqrt{2} \approx 1.41$. Therefore, the speed halfway down the ramp is more than half the speed at the bottom of the ramp.	
	Note: If the incorrect selection is made, the justification cannot earn credit.	
(b) 1 point		
	For correctly using conservation of energy, consistent with part (a), for the block compressing the spring	1 point
	$U_g = U_s$	
	$mgh = \frac{1}{2}kx_{\max}^2$	
	$x_{\max} = \sqrt{\frac{2mgh}{k}}$	
(c) 2 points		
	For indicating a simple harmonic motion approach	1 point
	For a correct answer	1 point
	$t = \frac{1}{4}T = \left(\frac{1}{4}\right)\left(2\pi\sqrt{\frac{m}{k}}\right) = \frac{\pi}{2}\sqrt{\frac{m}{k}}$	

2017 SCORING GUIDELINES

Question continued)

Distribution
of points

(d)

i. 3 points

For correctly applying Newton's second law for the horizontally sliding block

1 point

For correctly indicating that the direction of F_{net} is opposite the direction of motion

1 point

$$F_{net} = ma$$

$$-\beta v^2 = ma$$

For expressing the equation as a differential equation

1 point

$$-\beta v^2 = m \frac{dv}{dt}$$

ii. 3 points

For correctly separating variables

1 point

$$-\frac{\beta}{m} dt = \frac{1}{v^2} dv$$

For correctly integrating the equation above

1 point

$$\int -\frac{\beta}{m} dt = \int \frac{1}{v^2} dv$$

$$-\frac{\beta}{m} [t] = \left[-\frac{1}{v} \right]$$

For using the correct limits or constant of integration

1 point

$$-\frac{\beta}{m} [t]_0^t = \left[-\frac{1}{v} \right]_{v_0}^{v(t)}$$

$$-\frac{\beta t}{m} = -\frac{1}{v(t)} - \left(-\frac{1}{v_0} \right)$$

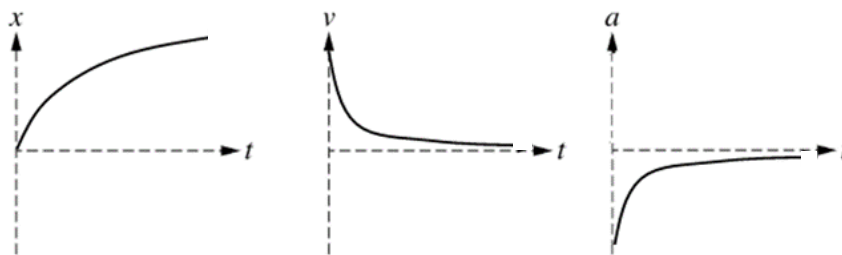
$$\frac{1}{v(t)} = \frac{1}{v_0} + \frac{\beta t}{m}$$

2017 SCORING GUIDELINES

Question continued)

Distribution
of points

(e) 3 points



For a displacement curve that is concave down and approaching a horizontal asymptote

1 point

For a velocity curve that is concave up and has the horizontal axis as an asymptote

1 point

For an acceleration curve that is concave down and has the horizontal axis as an asymptote

1 point

Note: If an incorrect nonlinear velocity graph is generated, 1 point is earned if the position and acceleration graphs are consistent with the velocity graph.

Note: Full credit is earned if all three graphs are flipped vertically.

2017 SCORING GUIDELINES

Question 3

15 points total

Distribution
of points

(a) 2 points

For correctly applying conservation of energy to the cylinder rolling down the incline

1 point

$$U_{g_top} = K_{table}$$

$$K_{table} = mgh = (0.50 \text{ kg})(9.8 \text{ m/s}^2)(1.0 \text{ m})(\sin 30)$$

For a correct answer with units

1 point

$$K_{table} = 2.45 \text{ J (or } 2.5 \text{ J using } g = 10 \text{ m/s}^2)$$

(b) 3 points

For correctly setting the kinetic energy of the cylinder equal to the sum of both the linear and rotational kinetic energy

1 point

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

For correctly substituting into the above equation for the linear velocity and moment of inertia of the cylinder

1 point

$$K = \frac{1}{2}MR^2\omega^2 + \frac{1}{2}\left(\frac{1}{2}MR^2\right)\omega^2 = \frac{1}{2}M(R\omega)^2 + \frac{1}{4}M(R\omega)^2 = \frac{3}{4}M(R\omega)^2$$

$$\omega = \sqrt{\frac{4K}{3MR^2}} = \sqrt{\frac{(4)(2.45 \text{ J})}{(3)(0.50 \text{ kg})(0.10 \text{ m})^2}}$$

For correct substitution into the equation above

1 point

$$\omega = 25.6 \text{ rad/s (or } 26.0 \text{ rad/s using } g = 10 \text{ m/s}^2)$$

(c) 2 points

For using a correct expression for the ratio of the rotational kinetic energy to the total kinetic energy of the cylinder

1 point

$$\frac{K_{rot}}{K_{tot}} = \frac{\frac{1}{2}I\omega^2}{\frac{1}{2}mv^2 + \frac{1}{2}I\omega^2 + mgh} = \frac{\frac{1}{4}M(R\omega)^2}{\frac{3}{4}M(R\omega)^2 + Mgh_{table}} = \frac{(R\omega)^2}{3(R\omega)^2 + 4gh_{table}}$$

For substituting into the above equation

1 point

$$\frac{K_{rot}}{K_{tot}} = \frac{[(0.10 \text{ m})(25.6 \text{ rad/s})]^2}{(3)(0.10 \text{ m})^2(25.6 \text{ rad/s})^2 + (4)(9.81 \text{ m/s}^2)(0.75 \text{ m})}$$

$$\frac{K_{rot}}{K_{tot}} = 0.133 \text{ (or } 0.135 \text{ using } g = 10 \text{ m/s}^2)$$

2017 SCORING GUIDELINE

Question 3 (continued)

Distribution
of points

(c) (continued)

*Alternate Solution**Alternate Points*

For using a correct expression for the ratio of the rotational kinetic energy to the total potential energy of the cylinder

1 point

$$\frac{K_{rot}}{K_{tot}} = \frac{\frac{1}{2}I\omega^2}{U_{total}} = \frac{\frac{1}{4}M(R\omega)^2}{Mg(h+y)}$$

For substituting into the above equation

1 point

$$\frac{K_{rot}}{U_{total}} = \frac{\frac{1}{4}(R\omega)^2}{g(h+y)} = \frac{\frac{1}{4}[(0.10 \text{ m})(25.6 \text{ rad/s})]^2}{(9.81 \text{ m/s}^2)((1.0 \text{ m})\sin(30^\circ) + (0.75 \text{ m}))}$$

$$\frac{K_{rot}}{U_{total}} = 0.13 \text{ (or } 0.135 \text{ using } g = 10 \text{ m/s}^2 \text{)}$$

(d) 2 points

For correctly using motion in the vertical direction to calculate the time for the cylinder to reach the floor

1 point

$$y = y_0 + v_{0y}t + \frac{1}{2}a_y t^2$$

$$y - y_0 = 0 - \frac{1}{2}gt^2$$

Determine the time for the cylinder to reach the floor

$$y - y_0 = -\frac{1}{2}gt^2$$

$$0 - y = -\frac{1}{2}gt^2$$

$$t = \sqrt{\frac{2y}{g}} = \sqrt{\frac{(2)(0.75 \text{ m})}{(9.81 \text{ m/s}^2)}} = 0.39 \text{ s}$$

For correctly using the equation for constant speed in the horizontal direction

1 point

$$x - x_0 = v_{0x}t$$

$$x - x_0 = R\omega t$$

$$x - x_0 = R\omega \sqrt{\frac{2y}{g}}$$

$$D = R\omega t = (0.10 \text{ m})(25.6 \text{ rad/s})(0.39 \text{ s})$$

$$D = 1.0 \text{ m}$$

2017 SCORING GUIDELINE

Question 3 (continued)

Distribution
of points

(e)

i. 2 points

For selecting “Equal to” and attempting a relevant justification
 For a correct justification

1 point
 1 point

Example: Because the sphere falls the same height as the cylinder and because they have the same mass, the sphere-Earth system has the same initial potential energy and, therefore, the same total kinetic energy when it reaches the floor.

ii. 2 points

For selecting “Less than” and attempting a relevant justification
 For a correct justification

1 point
 1 point

Example: Because the rotational inertia of the sphere is less than the rotational inertia of the cylinder, the sphere will rotate faster and, because $v = r\omega$, will move with a greater linear speed. Because the mass is the same and the linear speed is greater, the sphere will have a greater linear kinetic energy. Because the total kinetic energies of the sphere and cylinder are the same, the sphere must have less rotational kinetic energy.

iii. 2 points

For selecting “Greater than” and attempting a relevant justification
 For a correct justification

1 point
 1 point

Example: Because the sphere has a greater linear speed as it leaves the table, it will travel a greater horizontal distance before it reaches the floor.

AP[®] Physics C: Electricity and Magnetism

2015 Scoring Guidelines

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2015 SCORING GUIDELINES

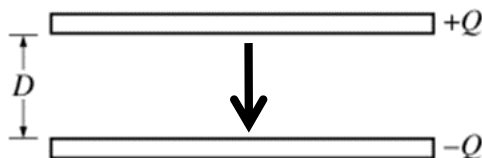
Question 1

15 points total

Distribution
of points

(a)

i. 1 point



For at least one arrow between the plates pointing downward from the positive plates toward the negative plate and no extraneous arrows pointing in any other direction

1 point

ii. 1 point



For drawing an appropriate Gaussian surface (enclosing at least the inner edge of one of the plates) that can be used to determine the electric field between the plates

1 point

iii. 3 points

For using a correct statement of Gauss's law

1 point

$$\oint \vec{E} \cdot d\vec{A} = \frac{Q}{\epsilon_0}$$

For applying Gauss's law, using an enclosed charge and surface area consistent with the surface drawn in part (a)-ii

1 point

$E(A_{GS}) = \frac{q_{enc}}{\epsilon_0}$ (A_{GS} is the area of the end of the Gaussian surface between the plates)

$$E = \frac{q_{enc}}{\epsilon_0 A_{GS}} \quad \left(\text{using } \sigma = \frac{q_{enc}}{A_{GS}} \right)$$

$$E = \frac{\sigma}{\epsilon_0} \quad \left(\text{using } \sigma = \frac{Q}{A} \right)$$

For a correct answer with work shown

1 point

$$E = \frac{Q}{\epsilon_0 A}$$

2015 SCORING GUIDELINES

Question 1 (continued)

Distribution
of points

(b) 1 point

Comparing the equation for electric field between parallel plates to the given equation:

$$E = \frac{Q}{\kappa \epsilon_0 A} = \frac{Q}{\epsilon_0 \kappa_0 e^{-x/D} A}$$

For an answer consistent with part (a)-iii

1 point

$$\kappa = \kappa_0 e^{-x/D}$$

(c)
i. 1 point

Using the equation relating the electric field to potential difference

$$E = -\frac{dV}{dx}$$

For a correct differential equation

1 point

$$\frac{dV}{dx} = -\left(-\frac{Q}{\epsilon_0 \kappa_0 e^{-x/D} A}\right)$$

$$\frac{dV}{dx} = \frac{Q}{\epsilon_0 \kappa_0 e^{-x/D} A}$$

Alternate Solution:

Alternate Point

Using the equation relating the electric field to potential difference:

$$\Delta V = -\int \vec{E} \cdot d\vec{r}$$

For a correct differential equation

1 point

$$\Delta V = -\int -\frac{Q}{\epsilon_0 \kappa_0 e^{-x/D} A} dx$$

$$\Delta V = \int \frac{Q}{\epsilon_0 \kappa_0 e^{-x/D} A} dx$$

2015 SCORING GUIDELINES

Question 1 (continued)

Distribution
of points

(c) (continued)

ii. 4 points

Separating the variables in the differential equation from part (c)(i):

$$\frac{dV}{dx} = \frac{Q}{\epsilon_0 \kappa_0 e^{-x/D} A}$$

$$dV = \left(\frac{Q}{\epsilon_0 \kappa_0 A} \right) e^{x/D} dx$$

For using the correct limits of integration in attempting to integrate the equation above

1 point

$$\int_{V_0}^{V_D} dV = \left(\frac{Q}{\epsilon_0 \kappa_0 A} \right) \int_0^D e^{x/D} dx$$

For correctly integrating the equation

1 point

$$[V]_{V_0}^{V_D} = \left(\frac{Q}{\epsilon_0 \kappa_0 A} \right) [De^{x/D}]_0^D$$

$$(V_D - V_0) = \left(\frac{QD}{\epsilon_0 \kappa_0 A} \right) (e^{D/D} - e^0)$$

For an expression that gives the correct absolute value of the potential difference between the plates

1 point

For having the potential difference be positive

1 point

$$\Delta V = \left(\frac{QD}{\epsilon_0 \kappa_0 A} \right) (e - 1)$$

$$\Delta V = \frac{1.72QD}{\epsilon_0 \kappa_0 A}$$

(d) 1 point

Using the equation for capacitance:

$$C = \frac{Q}{\Delta V} = \frac{Q}{\left(\frac{QD}{\epsilon_0 \kappa_0 A} \right) (e - 1)}$$

For an answer consistent with part (c)-ii

1 point

$$C = \frac{\epsilon_0 \kappa_0 A}{D(e - 1)}$$

$$C = \frac{\epsilon_0 \kappa_0 A}{1.72D}$$

2015 SCORING GUIDELINES

Question 1 (continued)

Distribution
of points

(e) 3 points

For selecting $U_V > U_C$ 1 pointFor correctly comparing the capacitance or the potential difference with the
varying dielectric constant to the capacitance or the potential difference with
the uniform dielectric constant 1 pointFor correctly comparing the two stored energies consistent with the comparison of
the capacitances or potential differences 1 pointExample: According to the equation from part (d), $C_C > C_V$. Since $U = \frac{Q^2}{2C}$, if the
charge stored on the two capacitors is the same, then $U_V > U_C$.

2015 SCORING GUIDELINES

Question 2

15 points total

Distribution
of points

(a)

i. 2 points

Using Ohm's law:

$$V = IR$$

For a correct application of Kirchhoff's loop rule

$$\mathcal{E} = Ir + IR$$

$$I = \frac{\mathcal{E}}{(r + R)}$$

For a correct expression for the measured voltage across the variable resistor

$$V = \frac{\mathcal{E}}{(r + R)} R$$

1 point

1 point

ii. 1 point

For an expression of $1/V$ as a function of $1/R$ consistent with answer from part

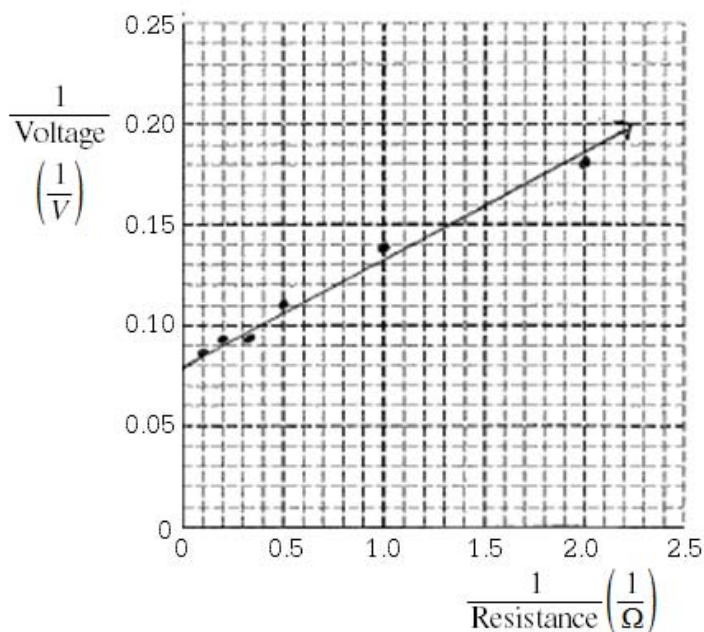
1 point

(a)(i)

$$\frac{1}{V} = \left(\frac{r}{\mathcal{E}}\right) \frac{1}{R} + \frac{1}{\mathcal{E}}$$

(b)

4 points



For correctly labeling both axes with variables and units

1 point

For correctly scaling both axes with an acceptable and appropriate scale

1 point

For correctly plotting the data points

1 point

For correctly drawing a straight line that best represents the data

1 point

2015 SCORING GUIDELINES

Question 2 (continued)

Distribution
of points

(c)		
i.	2 points	
	For using a value for the y-intercept consistent with the straight line drawn in part (b)	1 point
	$y = mx + b$	
	$b = 0.080 \text{ 1/V}$	
	For a correct substitution into the equation from part (a)(ii)	1 point
	$\frac{1}{V} = \frac{(r + R)}{\mathcal{E}} \frac{1}{R}$	
	$\frac{1}{V} = \frac{r}{\mathcal{E}} \frac{1}{R} + \frac{1}{\mathcal{E}}$	
	$b = 1/\mathcal{E}$	
	$\mathcal{E} = 1/(0.080 \text{ 1/V})$	
	$\mathcal{E} = 12.5 \text{ V}$	
ii.	2 points	
	For calculating the slope using the straight line from part (b) and not data points	1 point
	$m = \frac{y_2 - y_1}{x_2 - x_1} = \frac{(0.151 - 0.100)}{(1.50 - 0.40)} = 0.0463 \text{ } \Omega/\text{V}$	
	For a correct substitution into equation from part (a)(ii)	1 point
	$m = \frac{r}{\mathcal{E}}$	
	$r = m\mathcal{E}$	
	$r = (0.0463 \text{ } \Omega/\text{V})(12.5 \text{ V})$	
	$r = 0.58 \text{ } \Omega$	
(d)	2 points	
	For using Ohm's law	1 point
	$\mathcal{E} = Ir$	
	For a correct substitution of values from part (c):	1 point
	$(12.5 \text{ V}) = I(0.58 \text{ } \Omega)$	
	$I = 21.6 \text{ A}$	
(e)	2 points	
	For selecting "The voltmeter with high resistance"	1 point
	For a correct justification	1 point
	Example: The voltmeter acts like a resistor in a circuit with the battery. It will	
	measure the potential difference across its own internal resistance. The higher	
	its internal resistance, the closer its potential difference will be to the emf of the	
	battery.	

2015 SCORING GUIDELINES

Question 3

15 points total

Distribution
of points

(a) 3 points

For properly using a correct equation to calculate the magnetic flux

1 point

$$\Phi_B = \int \vec{B} \cdot d\vec{A}$$

For correct substitution of the area and trigonometric function

1 point

$$\Phi_B = BA(\cos\theta) = B\pi r^2(\cos\theta)$$

For correct substitution into the above equation

1 point

$$\Phi_B = 4(1 - 0.2t)\pi(0.10 \text{ m})^2(\cos 60^\circ)$$

$$\Phi_B = 0.063 - 0.013t \quad (\text{or in terms of } a \text{ and } b, \Phi_B = a(1 - bt)(0.016))$$

(b) 2 points

For using a correct equation to solve for the emf

1 point

$$\mathcal{E} = -\frac{d\Phi_B}{dt}$$

Substituting the expression from part (a):

$$\mathcal{E} = \frac{d}{dt}(0.063 - 0.013t)$$

For an answer consistent with part (a)

1 point

$$\mathcal{E} = 0.013 \text{ V}$$

Note: Any sign on the answer is ignored.

(c)
i. 1 point

For a substitution into Ohm's law consistent with the answer from part (b)

1 point

$$V = IR$$

$$I = \frac{(0.013 \text{ V})}{(50 \, \Omega)}$$

$$I = 2.6 \times 10^{-4} \text{ A}$$

ii. 2 points

The correct choice is "Counterclockwise".

For a justification that incorporates that the original magnetic field is changing

1 point

For a justification that correctly relates the induced current to the direction of a new magnetic field created by that current

1 point

Example: Looking down at the loop from P , the vertical component of the magnetic field of the loop is upward and decreasing. To oppose this change, the current in the loop must create a magnetic field that is directed upward at point P .

This requires a counterclockwise current in the loop.

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Question 3 (continued)

Distribution
of points

(d) 2 points

For using a correct equation to calculate the energy dissipated

1 point

$$E = Pt = I^2 R t \quad \text{or} \quad E = Pt = (\mathcal{E}^2 / R) t$$

For a substitution into either of the above equations with the answer from part (c)(i) or part (b)

1 point

$$E = (2.6 \times 10^{-4} \text{ A})^2 (50 \, \Omega)(4.0 \text{ s}) \quad \text{or} \quad E = \frac{(0.013 \text{ V})^2}{(50 \, \Omega)} (4.0 \text{ s})$$

$$E = 1.4 \times 10^{-5} \text{ J}$$

(e) 4 points

For selecting both “Zero” for the net magnetic force and “Nonzero” for the Net magnetic torque

1 point

For indicating the forces on directly opposite sides of the loop are in opposite directions

1 point

For concluding that the forces cancel & net force is zero

1 point

For indicating that the torques add & net torque is nonzero

1 point

Example: Since the current changes direction relative to the magnetic field as you go around the loop, the magnetic field will exert force of equal magnitude but opposite direction on opposite sides of the loop. These forces all cancel out resulting in zero net force. However, since this force is up on one side of the loop and down on the other side of the loop, this will create torques that rotate the loop in the same direction. Therefore, the net torque is not zero.

Units 1 point

For correct units on at least two parts with a calculated numerical answer and no incorrect units

1 point