2022

AP® Physics C: Mechanics

Scoring Guidelines
Set 1

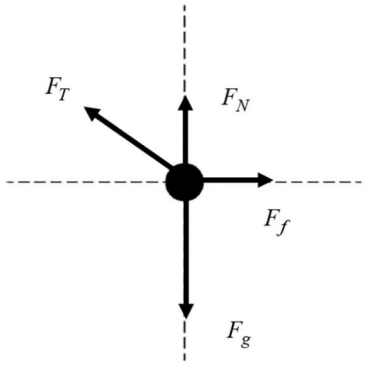
Question 1: Free-Response Question — 15 points

(a) For correctly drawing and labeling the force of gravity and the normal force on the block of mass m — **1 point**

For correctly drawing and labeling the force of friction on the block of mass m — **1 point**

For correctly drawing and labeling the force of tension on the block of mass m — **1 point**

Example Response



Scoring Notes:

- Examples of appropriate labels for the force due to gravity include: F_G, F_g, F_{grav}, W, mg, Mg, "grav force," "F Earth on block," "F on block by Earth" $F_{\text{Earth on block}}$, $F_{E,Block}$. The labels G and g are not appropriate labels for the force due to gravity. F_n, F_N, N, "normal force," "ground force," or similar labels may be used for the normal force. F_{string}, F_s, F_T, $F_{Tension}$, T, "string force," "tension force," or similar labels may be used for the tension force exerted by the string.
- A response with extraneous forces or vectors can earn a maximum of two points.

Total for part (a) — 3 points

(b) For a trigonometric expression relating the angle to the horizontal distance of the block from the left corner of the table, x. — **1 point**

For any correct trigonometric expression for θ in terms of the given quantities — **1 point**

Example Responses

First Point	Second Point
$\sin\theta = \dfrac{H}{\sqrt{H^2 + x^2}}$	$\theta = \sin^{-1}\left(\dfrac{H}{\sqrt{H^2 + x^2}}\right)$
$\cos\theta = \dfrac{x}{\sqrt{H^2 + x^2}}$	$\theta = \cos^{-1}\left(\dfrac{x}{\sqrt{H^2 + x^2}}\right)$
$\tan\theta = \dfrac{H}{x}$	$\theta = \tan^{-1}\left(\dfrac{H}{x}\right)$

Total for part (b) — 2 points

(c)(i) For using Newton's second law to sum the forces in the vertical direction and write an equation that is consistent with part (a) **1 point**

$\Sigma F_y = ma$

$F_{net,y} = F_N + F_{T,y} - F_g = 0$

$F_N = F_g - F_{T,y}$

For correctly substituting the vertical component of the tension in terms of the given variables consistent with part (b) **1 point**

$F_N = mg - F_T \sin\theta$

$F_N = mg - F_T\left(\frac{H}{\sqrt{H^2 + x^2}}\right)$

(c)(ii) For using Newton's second law to sum the forces in the horizontal direction and write an equation that is consistent with part (a) **1 point**

$F_{net,x} = F_{T,x} - F_f$

For correctly substituting the horizontal component of the force of tension in terms of the given variables consistent with part (b) **1 point**

$F_{net,x} = F_T \cos\theta - F_f$

$F_{net,x} = F_T\left(\frac{(x)}{\sqrt{H^2 + x^2}}\right) - F_f$

For correctly substituting the expression for the normal force from part (c)(i) into the expression for the force of friction **1 point**

$F_{net,x} = F_T\left(\frac{(x)}{\sqrt{H^2 + x^2}}\right) - \mu_k F_N$

$F_{net,x} = F_T\left(\frac{(x)}{\sqrt{H^2 + x^2}}\right) - \mu_k\left(mg - F_T\left(\frac{H}{\sqrt{H^2 + x^2}}\right)\right)$

Total for part (c) 5 points

(d) For any indication that the work done on the block by the string is due only to the horizontal component of the tension in the string **1 point**

$W = \int F_{T,x} dx$

For using the horizontal component of the force of tension consistent with part (c) **1 point**

For indicating that work is the integral of the force with respect to x, including limits or a constant of integration **1 point**

$W = \int_{x=L}^{x=0} -F_T\left(\frac{x}{\sqrt{H^2 + x^2}}\right) dx$

Total for part (d) 3 points

(e)	For selecting "More work …" with an attempt at a relevant justification	**1 point**
	For a correct justification relating the smaller angle to a larger component of the force of tension, thus resulting in greater work.	**1 point**

Example Response

F_T stays the same for both halves, the displacement is the same in both halves, but from $x = L$ to $x = L/2$ the angle is smaller, resulting in a larger component of the tension force that aligns with the displacement.

Total for part (e) 2 points

Total for question 1 15 points

Question 2: Free-Response Question — 15 points

(a)

For selecting "Equal to" with an attempt at a relevant justification — **1 point**

For a correct justification — **1 point**

Example Response

Newton's third law says equal/opposite forces, time intervals are same during same collision, so magnitudes of impulse must be equal.

Total for part (a) 2 points

(b)

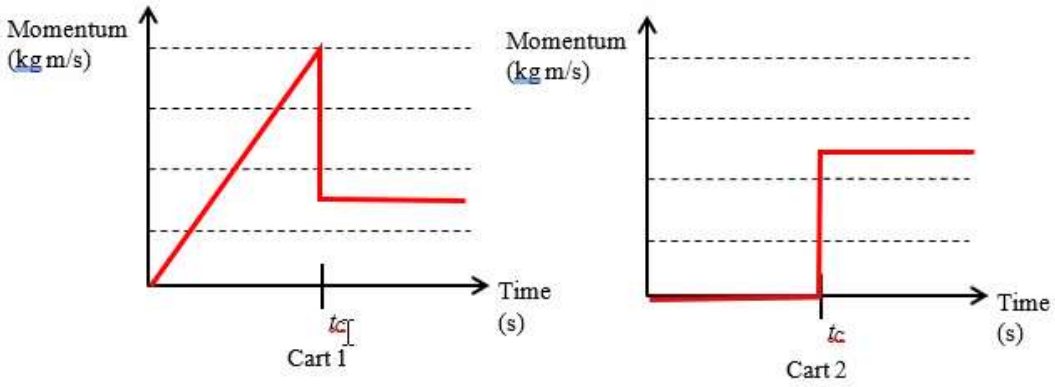
For correctly drawing the momentum for carts 1 and 2 for the time interval $0 < t < t_C$: Linear increasing momentum for Cart 1 and zero for Cart 2 — **1 point**

For drawing a horizontal line for Cart 1 when $t > t_C$ that is smaller in magnitude than the momentum of Cart 1 at time $t = t_C$ — **1 point**

For drawing a horizontal line for Cart 2 when $t > t_C$ that is greater in magnitude than the momentum of Cart 1 after time $t = t_C$ — **1 point**

For carts 1 and 2 having a change in momentum that is equal in magnitude, such that Cart 1 loses momentum and Cart 2 gains momentum or a response with changes in momentum consistent with the response in part (a) — **1 point**

Example Response



Total for part (b) 4 points

(c)

For using conservation of energy to find the speed of Cart 1 at the bottom of the incline — **1 point**

OR

For a correct substitution of acceleration and displacement in a kinematics equation to find the speed of Cart 1 at the bottom of the incline

For using conservation of momentum to find the speed of the two-cart system after the collision — **1 point**

For combining correct equations from above — **1 point**

Example Response

Conservation of energy:

$m_1 gH = \frac{1}{2} m_1 v_1^2$

$v_1 = \sqrt{2gH}$

OR

$v_f^2 = v_i^2 + 2g\sin(\theta)L$

$H = L\sin(\theta)$

$v_f^2 = v_i^2 + 2g\sin(\theta)\left(\frac{H}{\sin\theta}\right)$

$v_f^2 = 2gH$

Conservation of momentum:

$m_1 v_1 = (m_1 + m_2) v_f$

$v_f = \frac{m_1}{m_1 + m_2} v_1$

Combining:

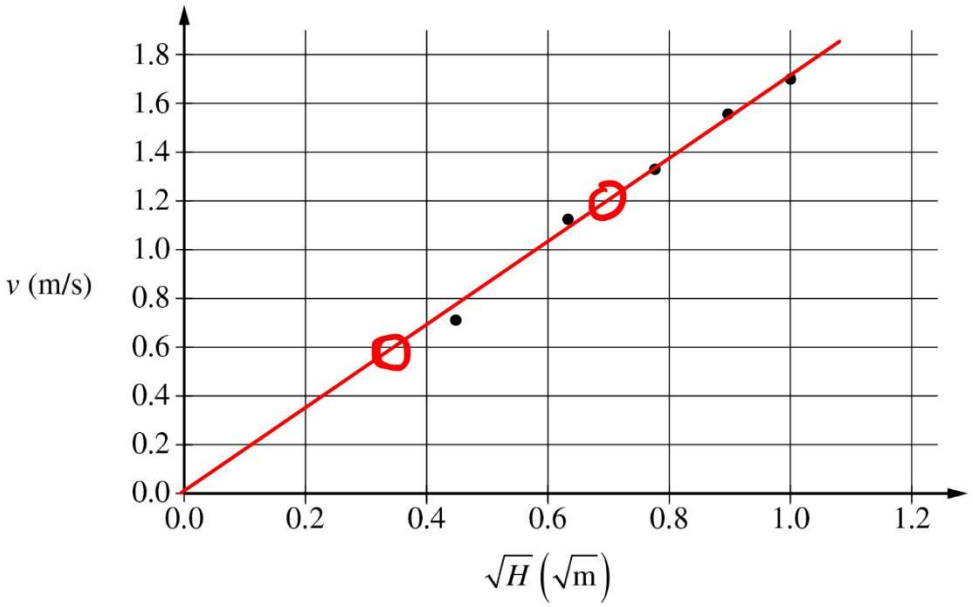
$v_f = \frac{m_1}{m_1 + m_2}\sqrt{2gH}$

$v_f = \sqrt{2g}\left(\frac{m_1}{m_1 + m_2}\right)\sqrt{H}$

Total for part (c) 3 points

(d)(i) For drawing an appropriate best-fit line including approximately the same number of points above and below the line **1 point**

Example Response



(d)(ii) For calculating the slope using two points on the best-fit line **1 point**

For correctly relating the slope of the best-fit line to the mass of Cart 2 **1 point**

For a correct mass of Cart 2 **1 point**

Example Response

$$slope = \frac{(1.20 - 0.60)\,\text{m/s}}{(0.70 - 0.35)\sqrt{\text{m}}} = 1.72\,\frac{\sqrt{\text{m}}}{\text{s}}$$

$$slope = \frac{m_1}{m_1 + m_2}\sqrt{2g}$$

$$m_2 = \frac{m_1\sqrt{2g}}{slope} - m_1$$

$$m_2 = \frac{(0.25\ \text{kg})\sqrt{2\left(9.8\,\frac{\text{m}}{\text{s}^2}\right)}}{1.72\,\frac{\sqrt{\text{m}}}{\text{s}}} - (0.25\ \text{kg})$$

$$\therefore m_2 = 0.39\ \text{kg}$$

Scoring Note: Acceptable responses for mass are 0.30 to 0.60 kg

Total for part (d) 4 points

(e)	For selecting "$m_1' < 0.250$ kg" with an attempt at a relevant justification	**1 point**
	For a correct justification	**1 point**

Example Response

A smaller m_2 indicates that the initial energy and momentum was smaller. With identical slope and height H this means that the mass m_1' must be smaller.

Total for part (e) 2 points

Total for question 2 15 points

Question 3: Free-Response Question — 15 points

(a)

For indicating that the sum of the torques on the disk equals zero — **1 point**

$\Sigma\tau_{\text{on disk}} = 0$

$\tau_{\text{g}} = \tau_{\text{s}}$

OR

For indicating that the sum of the forces equals zero

$\Sigma F = 0$

$F_{\text{g}} = F_{\text{s}}$

For correctly substituting the expressions for the forces — **1 point**

$F_{\text{g}}R = F_{\text{s}}R$

$m_{\text{B}}gR = k\Delta xR$

$m_{\text{B}}g = k\Delta x$

OR

$F_{\text{g}} = F_{\text{s}}$

$m_{B}g = k\Delta x$

For correctly substituting for Δx — **1 point**

$m_{\text{B}}g = kR\theta$

$m_{\text{B}} = \dfrac{kR\theta}{g}$

Total for part (a) — 3 points

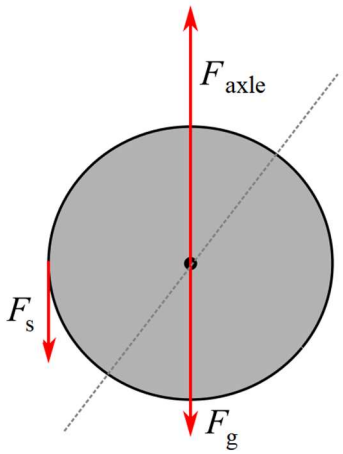
(b)

For drawing and labeling the force of the tension exerted on the disk anywhere between point P and the left edge of the disk, including point P and the left edge of the disk, tangent to the disk — **1 point**

For correct location and label of the force due to gravity exerted on the disk, directed straight down — **1 point**

For correct location and label of the force exerted on the disk by the axle, directed such that the disk remains in translational equilibrium (i.e., $\Sigma F = 0$) — **1 point**

Example Response



Scoring Notes:

- Examples of appropriate labels for the force due to gravity include: F_{G}, F_{g}, F_{grav}, W, mg, Mg, "grav force," "F Earth on block," "F on block by Earth," $F_{\text{Earth on block}}$, $F_{\text{E,Block}}$. The labels G and g are not appropriate labels for the force due to gravity. F_{n}, F_{N}, N, "normal force," "ground force," or similar labels may be used for the normal force, which can be used instead of F_{axle}. F_{spring}, F_{s}, T_{spring}, T, "spring force," or similar labels may be used for the tension force exerted by the spring.
- A response with extraneous forces or vectors can earn a maximum of two points.

Total for part (b) 3 points

(c)

For indicating that the net torque is due only to the force exerted on the disk by the tension in the rotational form of Newton's second law **1 point**

$\tau_{\text{s}} = I_{\text{d}}\alpha$

For correctly expressing the torque on the disk by the tension in terms of the spring force, which is equal to the tension, and the lever (moment) arm **1 point**

$F_{\text{s}}R = I_{\text{d}}\alpha$

For correctly substituting for F_s **1 point**

$-k\Delta xR = I_{\text{d}}\alpha$

For correctly substituting I_{d} and Δx, or an expression for Δx consistent with part (a) **1 point**

$-k(R\theta)R = \frac{1}{2}M_{\text{d}}R^2\alpha$

$\alpha = -\frac{2k\theta}{M_{\text{d}}}$

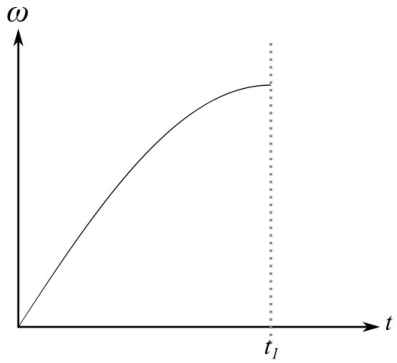
Scoring Note: The negative sign is not necessary to earn this point.

Total for part (c) 4 points

(d) For a sketch that starts at zero and monotonically increases until time $t = t_1$ **1 point**

For a sketch that is concave down between time $t = 0$ and $t = t_1$ **1 point**

Example Response



Scoring Note: Any part of the graph beyond t_1 is not considered in scoring.

Total for part (d) 2 points

(e) For indicating that the torque exerted by the force due to gravity on the disk increased **1 point**

Example Response

The force due to gravity on the disk now has a non-zero lever arm and hence it exerts a larger torque on the disk.

For indicating that the torque exerted by the tension caused by the force due to gravity on the block increased **1 point**

Example Response

The force exerted by the right side of the string (from the block) on the disk has a longer lever arm, hence the torque it exerts is larger.

For indicating that the torque exerted by the tension increased **1 point**

Example Response

The counterclockwise torque due to the tension caused by the spring must increase to counteract the increase in clockwise torques due to the force due to gravity of the disk and tension caused by the force of gravity due to block to keep the disk in equilibrium.

Scoring Notes:

- A response that references the torque due to the force at the axle staying the same can earn all 3 points.
- A response that references the torque due to the force on the axle changing, or any additional torques can earn a maximum of 2 points.

Total for part (e) 3 points

Total for question 3 15 points