2024

AP® Physics C: Mechanics

Scoring Guidelines
Set 2

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Question 1: Free-Response Question — 15 points

(a)(i) For a multi-step derivation that includes **one** of the following: **1 point**

- An application of conservation of energy that indicates that the initial mechanical energy of the system is U_g
- An application of Newton's second law that includes the frictional force, including sign

For **one** of the following that is consistent with the previous point: **1 point**

- An expression for the energy dissipated by friction, including the correct sign
- A substitution of acceleration in a kinematics equation

Example Responses

$\Delta E_{\text{friction}} = -F_f D$ **OR** $v^2 = v_0^2 + 2\left(\dfrac{F_{g,x} - F_f}{2m}\right)\Delta x$

For a correct expression for v **1 point**

Example Response

$v = \sqrt{2gD(\sin\theta - \mu\cos\theta)}$

Example Solutions

$$E_{\text{initial}} = E_{\text{final}}$$
$$U_g - \Delta E_{\text{friction}} = K$$
$$m_A gD\sin\theta - \mu m_A gD\cos\theta = \frac{1}{2}m_A v^2$$
$$gD\sin\theta - \mu gD\cos\theta = \frac{1}{2}v^2$$
$$v = \sqrt{2gD(\sin\theta - \mu\cos\theta)}$$

OR

$$a = \frac{F_{\text{net}}}{m}$$
$$2ma = F_{g,x} - F_f$$
$$2ma = 2mg\sin\theta - \mu(2m)g\cos\theta$$
$$a = g\sin\theta - \mu g\cos\theta$$

$$v^2 = v_0^2 + 2a\Delta x$$
$$v^2 = 0^2 + 2(g\sin\theta - \mu g\cos\theta)D$$
$$v = \sqrt{2gD(\sin\theta - \mu\cos\theta)}$$

(a)(ii) For using the conservation of momentum to find $v_{A,B}$ **1 point**

For equating the kinetic energy after the collision between the blocks to the maximum elastic potential energy of the compressed spring **1 point**

Example Response

$K_{\text{after collision}} = U_{s,\text{ max}}$

For indicating v before the collision between the blocks and the spring is equal to $v_{A,B}$ **1 point**

Example Solution

$$p_{\text{before collision}} = p_{\text{after collision}}$$
$$2mv = (2m + m)v_{A,B}$$
$$v_{A,B} = \frac{2m\sqrt{2gD(\sin\theta - \mu\cos\theta)}}{(3m)}$$
$$v_{A,B} = \frac{2}{3}\sqrt{2gD(\sin\theta - \mu\cos\theta)}$$

$$E_{\text{after collision}} = E_{\text{max compression of spring}}$$
$$K_{\text{after collision}} = U_{s,\text{ max}}$$
$$\frac{1}{2}(2m + m)\left(v_{A,B}\right)^2 = \frac{1}{2}kx^2$$
$$(3m)\left(\frac{2}{3}\sqrt{2gD(\sin\theta - \mu\cos\theta)}\right)^2 = kx_c^2$$

$$k = \frac{(3m)}{x_c^2}\left(\frac{2}{3}\sqrt{2gD(\sin\theta - \mu\cos\theta)}\right)^2$$

$$k = \frac{8}{3}\frac{mgD(\sin\theta - \mu\cos\theta)}{x_c^2}$$

Total for part (a) 6 points

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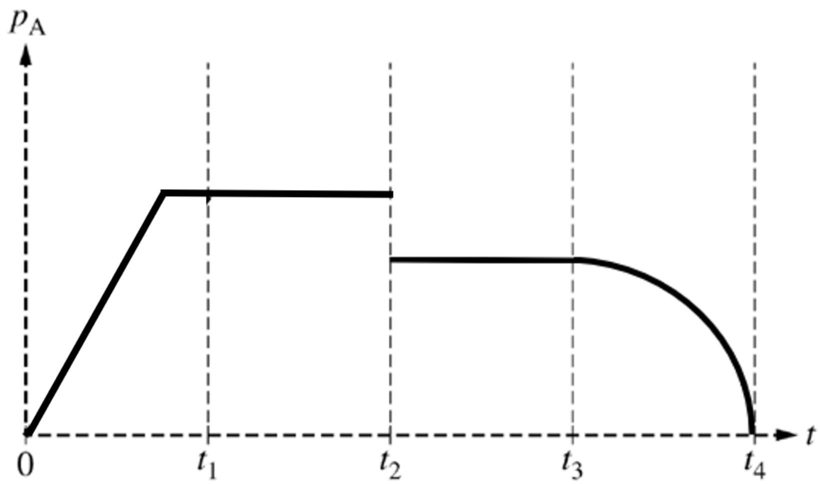
(b)(i)	For a sketch that increases linearly during the time interval $0 \le t < t_1$ **Scoring Note:** A sketch that only increases linearly from $t = 0$ to $t = t_1$ earns this point.	**1 point**
	For a horizontal line for the time interval $t_1 \le t \le t_2$ that is continuous at t_1	**1 point**
	For a horizontal line for the time interval $t_2 \le t \le t_3$ that has a smaller magnitude than the previous time interval	**1 point**
	For drawing a concave down curve, continuous at t_3, in the interval $t_3 \le t < t_4$ that reaches zero at t_4	**1 point**

Example Response



(b)(ii)	For a statement about the change in momentum that is consistent with the graph drawn in the response for part (b)(i)	**1 point**
	For indicating that a decreasing graph means that the force exerted on Block A is in a direction opposite to the motion of Block A **Scoring Note:** A response that indicates that an increasing graph means that the force exerted on Block A is in the same direction as the motion of Block A also earns this point.	**1 point**
	For relating the change in momentum to the magnitude of the force exerted on Block A	**1 point**

Example Response

The momentum of Block A *decreases between* t_3 *and* t_4 *because the spring exerts a force on the blocks in the opposite direction of the velocity of the blocks, causing the blocks to slow to a stop. The spring force increases the more the spring compresses, so the momentum of Block* A *decreases at an increasing rate, which is shown in the slope of the curve becoming steeper with time.*

Total for part (b) 7 points

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(c)	For selecting $T_N = T_O$ with an attempt at a relevant justification	**1 point**
	For a correct justification that includes **one** of the following: • The period of a spring-block oscillator is only dependent on the mass on the spring and spring constant, which do not change. • The period of a spring-block oscillator is not dependent on increasing amplitude, velocity, or compression distance.	**1 point**
	Example Response *Repeating the experiment on a smooth ramp will only affect the compression distance of the spring. The period of oscillation of a spring-block system depends only on mass and the spring constant, therefore the period of oscillation will not change.*	
	Total for part (c)	**2 points**
	Total for question 1	**15 points**

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Question 2: Free-Response Question — 15 points

(a) For a multi-step derivation that includes Newton's second law of motion — **1 point**

For indicating that the net force exerted on the sphere includes only the gravitational force and a drag force — **1 point**

Example Response

$F_{net} = F_g - F_{drag}$

For a correct differential equation that is in terms of the given variables — **1 point**

Scoring Note: Variables do not have to be separated for this point to be earned.

Example Response

$$m\frac{dv}{dt} = mg - bv$$

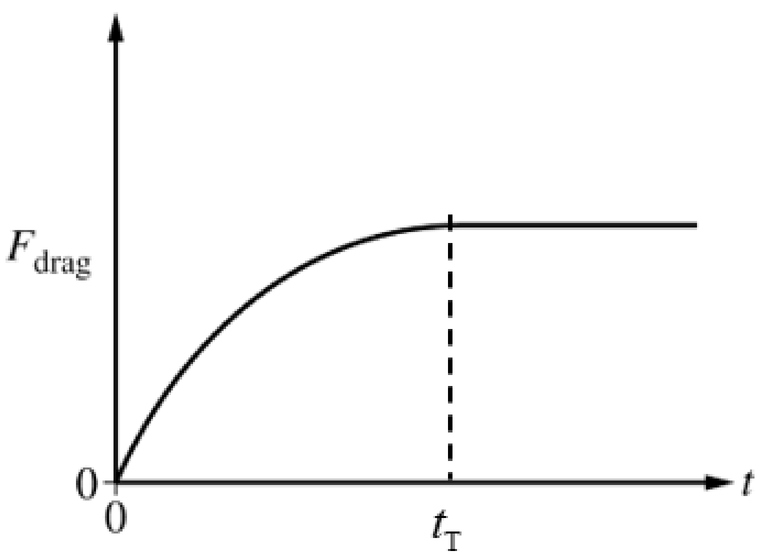
Example Solution

$$\Sigma F = ma$$
$$F_g - F_{drag} = ma$$
$$mg - bv = ma$$
$$m\frac{dv}{dt} = mg - bv$$

Total for part (a) — 3 points

(b)(i) For a vertical line labeled t_T at the approximate location at which the line becomes horizontal — **1 point**

Example Response



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(b)(ii)	For a response that references the slope of the graph or the rate at which the slope changes	**1 point**
	For correctly relating a feature of the graph to the forces exerted on the sphere as the sphere reaches terminal speed	**1 point**

Example Response

For the times leading up to t_T, the slope of the graph is positive which means that the magnitude of the drag force is still increasing. After t_T, the slope of the graph is zero which means that the magnitude of the drag force is constant and equal to the downward gravitational force, which indicates that the net force is zero and that the sphere has reached a constant terminal velocity.

Total for part (b) 3 points

(c)	For selecting "Equal to" with an attempt at a relevant justification	**1 point**
	For a correct justification	**1 point**

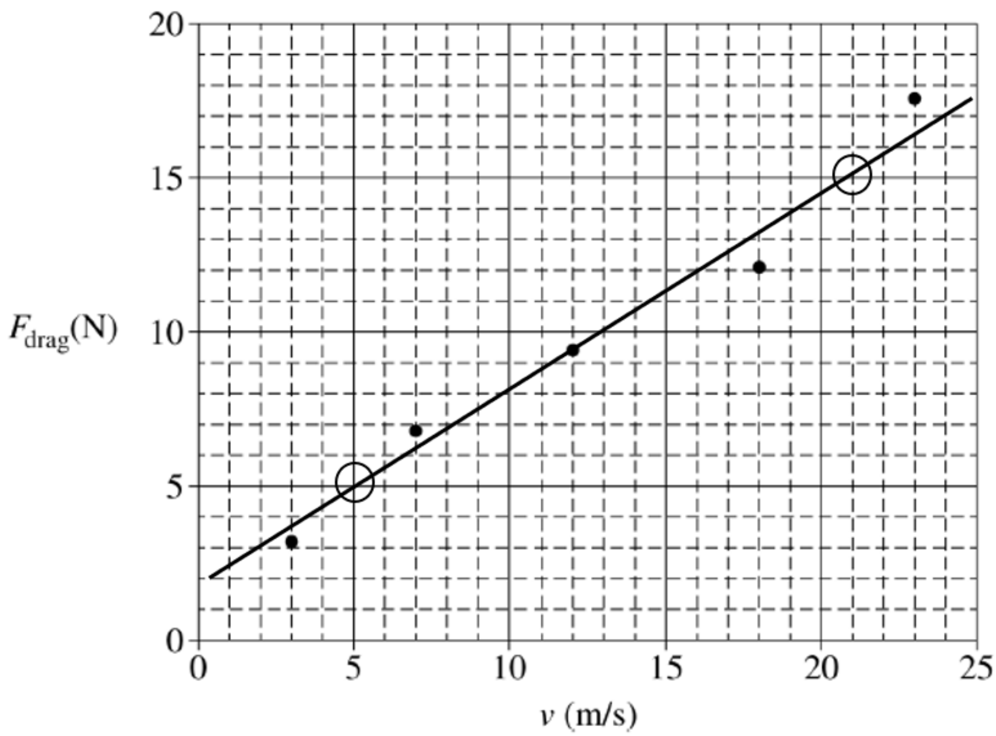
Example Response

The magnitude of the drag force at terminal speed does not change since the mass of the sphere is not changed and the drag force at terminal speed does not depend on the initial speed of the sphere.

Total for part (c) 2 points

(d)(i)	For drawing an appropriate line of best fit that approximates the data	**1 point**

Example Response



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

Scoring Note: Using data points that fall on the best-fit line earns this point.

Example Response

$$\text{slope} = \frac{15\ \text{N} - 5\ \text{N}}{21\ \text{m/s} - 5\ \text{m/s}}$$

For using the correct relationship between the slope of the best-fit line and the value of b **1 point**

Example Response

$$\text{slope} = \frac{|F_{\text{drag}}|}{v}$$
$$\text{slope} = b$$

For a calculated value of b that is $0.6\ \text{kg/s} < b < 0.8\ \text{kg/s}$ **1 point**

Example Response

$$b = 0.625\ \text{kg/s}$$

Example Solution

$$|F_{\text{drag}}| = bv$$
$$\frac{|F_{\text{drag}}|}{v} = b$$
$$\text{slope} = b$$
$$b = \frac{15\ \text{N} - 5\ \text{N}}{21\ \text{m/s} - 5\ \text{m/s}}$$
$$b = 0.625\ \text{kg/s}$$

Total for part (d) 4 points

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(e)(i)	For indicating the diameter of the sphere should be graphed	**1 point**
	For indicating the terminal velocity of the sphere should be graphed	**1 point**
(e)(ii)	For describing how the quantities graphed are related to the conclusion of the experiment	**1 point**

Example Response

The slope of the diameter vs terminal velocity graph can be used to determine if sphere diameter affects terminal velocity.

Total for part (e) 3 points

Total for question 2 15 points

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Question 3: Free-Response Question — 15 points

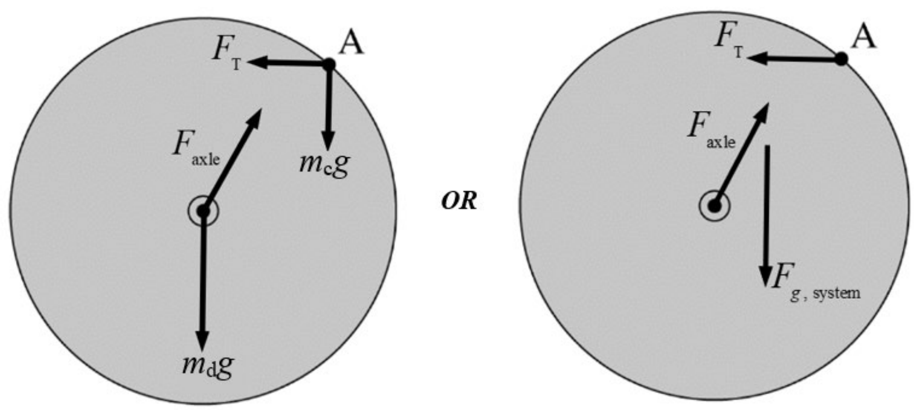
(a) For drawing and appropriately labeling separate gravitational forces that are exerted on the disk and the lump of clay and exerted at the correct locations — **1 point**

Scoring Note: Drawing a downward gravitational force exerted on the clay-disk system at the correct location can earn this point.

For drawing and appropriately labeling a leftward force exerted on the system at Point A — **1 point**

For drawing and appropriately labeling a force directed up and right that is exerted on the system at the axle, and no extraneous forces are present — **1 point**

Example Responses



Scoring Note: Examples of appropriate labels for the gravitational force include F_G, F_g, F_{grav}, W, mg, Mg, "grav force," "F Earth on disk," "F on disk by Earth," $F_{\text{Earth on Disk}}$, $F_{\text{E,Disk}}$, and $F_{\text{Disk,E}}$. The labels G or g are not appropriate labels for the gravitational force.

Scoring Note: Examples of appropriate labels for the normal force from the axle include F_N, F_{axle}, N, "normal force," and "axle force."

Scoring Note: Examples of appropriate labels for the tension force include F_t, F_T, T, F_{string}, and "Force from string."

Total for part (a) — 3 points

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(b)	For a multi-step derivation that indicates the net torque is zero	**1 point**
	For indicating only the weight of the clay and the tension in the string exert torques on the system about the axle	**1 point**

Example Response

$\tau_{\text{net}} = \tau_{\text{clay}} - \tau_{\text{string}}$

For a correct expression for the torque exerted on the system by the weight of the clay **1 point**

Example Response

$\tau_{\text{clay}} = Rm_{\text{c}}g\cos\theta$

For a correct expression for the torque exerted on the system by the tension in the string **1 point**

Example Response

$\tau_{\text{string}} = RF_{\text{T}}\sin\theta$

Example Solution

$\Sigma\tau = 0$

$\tau_{\text{clay}} - \tau_{\text{string}} = 0$

$F_{g,\text{ clay}}R\cos\theta - RF_{\text{T}}\sin\theta = 0$

$Rm_{\text{c}}g\cos\theta = RF_{\text{T}}\sin\theta$

$$F_{\text{T}} = \frac{Rm_{\text{c}}g\cos\theta}{R\sin\theta}$$

$F_{\text{T}} = m_{\text{c}}g\cot\theta$

Scoring Note: A maximum of three points can be earned if the trigonometric functions ($\sin$ and $\cos$) are reversed for both torque expressions.

Total for part (b) 4 points

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(c)	For indicating a direct relationship between the torque exerted by the clay and the tension in the string	**1 point**
	For correctly relating a greater torque exerted by the clay from at least **one** of the following: • An increase in the angle between the radial direction and the weight of the clay • A greater perpendicular component of the weight of the clay • A greater lever arm	**1 point**

Example Response

The torque caused by the weight of the clay at Point B *is greater than when the clay is at Point* A *because the component of the weight that is perpendicular to the lever arm is larger. To maintain equilibrium, the net torque on the system is still zero, therefore the tension* $F_{\text{T, new}}$ *must be greater.*

Total for part (c) 2 points

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(d)(i) For using integration to calculate rotational inertia **1 point**

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

- Substituting $\rho(2\pi r)dr$ for dm
- Indicating the correct limits of integration

Example Response

$$I = \int_0^{0.3\text{ m}} r^2 \rho(2\pi r)\,dr$$

For a correct answer of $I = 0.012\text{ kg}\cdot\text{m}^2$, including units **1 point**

Example Response

$$I = 0.012\text{ kg}\cdot\text{m}^2$$

Example Solution

$I = \int r^2 dm \qquad dm = \rho dA$ and $dA = 2\pi r\,dr$

$$I = \int_0^R r^2 \rho dA$$

$$I = \int_0^{0.3\text{ m}} 2\pi\beta r^4 dr$$

$$I = \left.\frac{2\pi\beta R^5}{5}\right|_0^{0.3\text{ m}}$$

$$I = \frac{2\pi(4.0\,\text{kg/m}^3)(0.3\text{ m})^5}{5}$$

$$I = 0.012\text{ kg}\cdot\text{m}^2$$

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(d)(ii)	For using the rotational form of Newton's second law	**1 point**
	For a correct expression for the net torque exerted on the clay-disk system	**1 point**

Example Response

$$\tau_{\text{net}} = Rm_{\text{c}}g$$

For indicating that the rotational inertia of the clay-disk system is the sum of the rotational inertia of the disk and the rotational inertia of the lump of clay	**1 point**

Example Response

$$I_{\text{system}} = I_{\text{disk}} + I_{\text{clay}}$$

Example Solution

$$\Sigma\tau = I\alpha$$

$$\alpha = \frac{\tau_{\text{net}}}{I}$$

$$\alpha = \frac{Rm_{\text{c}}g}{I_{\text{disk}} + I_{\text{clay}}}$$

$$\alpha = \frac{(0.3\text{ m})(0.60\text{ kg})\left(9.8\text{ m/s}^2\right)}{\left(\left(0.012\text{ kg}\cdot\text{m}^2\right) + (0.60\text{ kg})(0.3\text{m})^2\right)}$$

$$\alpha = 26.7\ \text{ rad/s}^2$$

Total for part (d) 6 points

Total for question 3 15 points

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