2023

AP® Physics 1: Algebra-Based

Sample Student Responses and Scoring Commentary

Inside:

Free-Response Question 5

- ☑ **Scoring Guidelines**
- ☑ **Student Samples**
- ☑ **Scoring Commentary**

Question 5: Short Answer — 7 points

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

Accept **one** of the following:

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

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

Example Response

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

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

Accept **one** of the following:

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

Example Response

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

Total for part (a) 3 points

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

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

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

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

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

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

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

Example Response

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

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

Example Response

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

Total for part (b) 4 points

Total for question 5 7 points

Question 5

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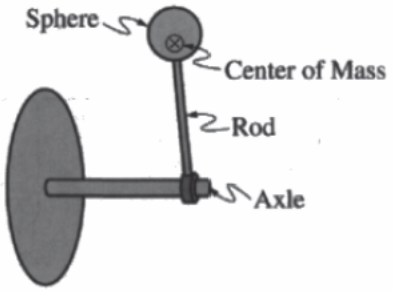

Figure 1

5. (7 points, suggested time 13 minutes)

A rod with a sphere attached to the end is connected to a horizontal mounted axle and carefully balanced so that it rests in a position vertically upward from the axle. The center of mass of the rod-sphere system is indicated with a ⊗, as shown in Figure 1. The sphere is lightly tapped, and the rod-sphere system rotates clockwise with negligible friction about the axle due to the gravitational force.

A student takes a video of the rod rotating from the vertically upward position to the vertically downward position. Figure 2 shows five frames (still shots) that the student selected from the video.
Note: these frames are not equally spaced apart in time.

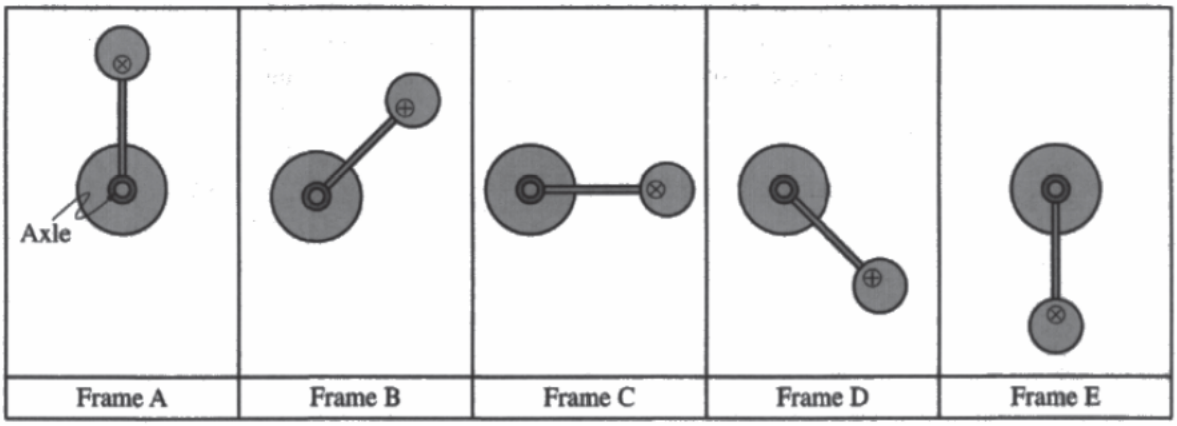

Figure 2

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Question 5

Continue your response to **QUESTION 5** on this page.

(a) Use the frames of the video shown in Figure 2 to answer the following questions.

i. In which frame is the angular acceleration of the rod-sphere system the greatest? Justify your answer.

Frame C. $\tau = I\alpha$, and I is constant in all frames.
The torque is the greatest in Frame C as the force of grav. F_g is perpendicular to the radius.

ii. In which frame is the rotational kinetic energy of the rod-sphere system the greatest? Briefly justify your answer.

Frame E, angular velocity is the greatest as positive torque has been applied for the maximum amount of time and $KE_{rot} = \frac{1}{2} I \omega^2$

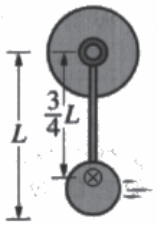

Figure 3

$\Delta KE = W = F_g d$
$\Delta KE = Mg\pi\frac{3}{4}L$ $d = 2\pi\left(\frac{3}{4}\right)L$

(b) The rod-sphere system has mass M and length L, and the center of mass is located a distance $\frac{3}{4}L$ from the axle, shown in Figure 3.

i. Derive an expression for the change in kinetic energy of the rod-sphere-Earth system from the moment shown in Frame A to the moment shown in Frame E. Express your answer in terms of M, L, and fundamental constants, as appropriate.

$KE_i + U_g = KE_f$ $\Delta KE = KE_{final} - KE_{initial}$
$U_g = KE_f - KE_i = \Delta KE$
$U_g = mgh$ $\Delta KE = \frac{6}{4} M g L$

ii. Briefly explain why the rod and sphere gain kinetic energy, even if Earth is not included in the system.

If Earth is not included in the system, work is done on the system by gravity, thereby gaining kinetic energy.

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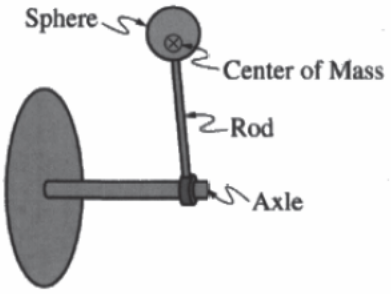

Figure 1

5. (7 points, suggested time 13 minutes)

A rod with a sphere attached to the end is connected to a horizontal mounted axle and carefully balanced so that it rests in a position vertically upward from the axle. The center of mass of the rod-sphere system is indicated with a ⊗, as shown in Figure 1. The sphere is lightly tapped, and the rod-sphere system rotates clockwise with negligible friction about the axle due to the gravitational force.

A student takes a video of the rod rotating from the vertically upward position to the vertically downward position. Figure 2 shows five frames (still shots) that the student selected from the video.
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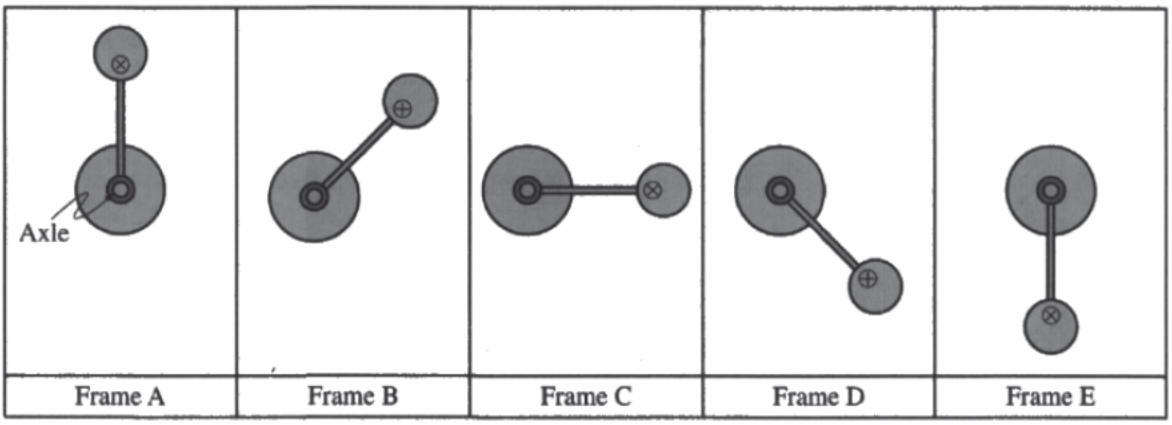

Figure 2

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Question 5

Continue your response to **QUESTION 5** on this page.

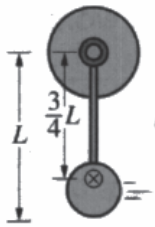
(a) Use the frames of the video shown in Figure 2 to answer the following questions.

i. In which frame is the angular acceleration of the rod-sphere system the greatest? Justify your answer.

The angular acceleration is greatest in Frame C because the torque caused by gravity is greatest there.

ii. In which frame is the rotational kinetic energy of the rod-sphere system the greatest? Briefly justify your answer.

The rotational kinetic energy is greatest at Frame E because the rod-sphere system is moving with the greatest angular velocity there.



This is because the torque has been applied for the longest at Frame E.

Figure 3

(b) The rod-sphere system has mass M and length L, and the center of mass is located a distance $\frac{3}{4}L$ from the axle, shown in Figure 3.

i. Derive an expression for the change in kinetic energy of the rod-sphere-Earth system from the moment shown in Frame A to the moment shown in Frame E. Express your answer in terms of M, L, and fundamental constants, as appropriate.

$h = 2 \cdot \frac{3}{4}L = \frac{3}{2}L$

$mgh = \frac{1}{2}Iw^2$

$mgh = \Delta K$ $\quad \Delta K = M \cdot g \cdot \frac{3}{2}L$

$\boxed{\Delta K = \frac{3}{2}MgL}$

ii. Briefly explain why the rod and sphere gain kinetic energy, even if Earth is not included in the system.

The rod and sphere gain kinetic energy because the angular velocity at Frame E is greater than at Frame A, so the rotational kinetic energy increases since $K_r = \frac{1}{2}Iw^2$

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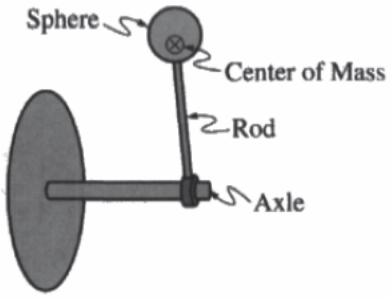

Figure 1

5. (7 points, suggested time 13 minutes)

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A student takes a video of the rod rotating from the vertically upward position to the vertically downward position. Figure 2 shows five frames (still shots) that the student selected from the video.
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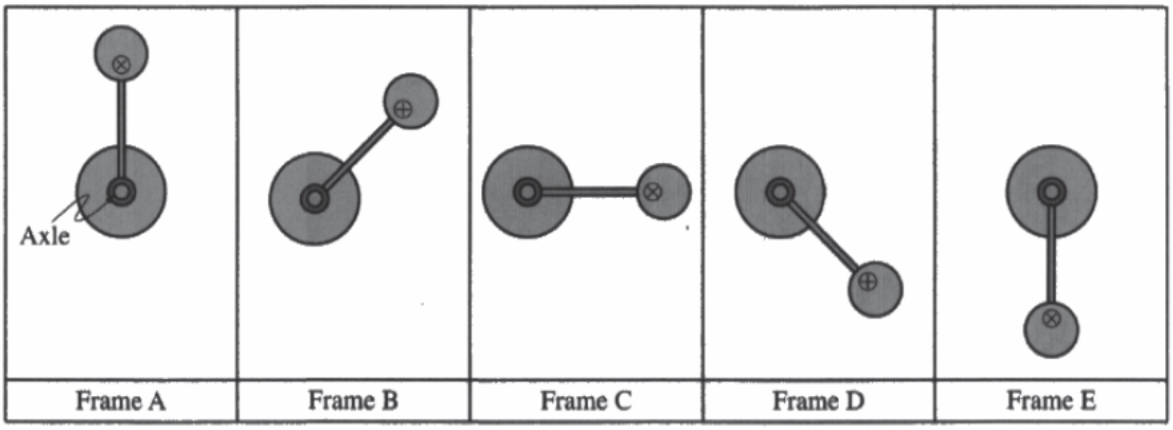

Figure 2

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Question 5

Continue your response to **QUESTION 5** on this page.

(a) Use the frames of the video shown in Figure 2 to answer the following questions.

i. In which frame is the angular acceleration of the rod-sphere system the greatest? Justify your answer.

In Frame C the angular acceleration is the greatest. The equation for angular acceleration is $\frac{\tau_{net}}{I}$. Because I remains constant, the only changing value is τ_{net}. τ_{net} is the perpendicular force multiplied by the radius in which that force is applied. The only torque is from gravity, and at C F_g is perpendicular to the rod.

ii. In which frame is the rotational kinetic energy of the rod-sphere system the greatest? Briefly justify your answer.

Frame E. This is because the ω at Frame E is the greatest, since the system has been accelerating for the longest time. The equation for rotational kinetic energy is $KE = \frac{1}{2}I\omega^2$. I remains constant, and ω is greatest at Frame E

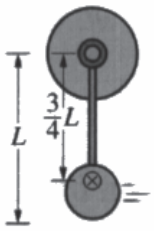

Figure 3

(b) The rod-sphere system has mass M and length L, and the center of mass is located a distance $\frac{3}{4}L$ from the axle, shown in Figure 3.

i. Derive an expression for the change in kinetic energy of the rod-sphere-Earth system from the moment shown in Frame A to the moment shown in Frame E. Express your answer in terms of M, L, and fundamental constants, as appropriate.

$KE_{total} = \frac{1}{2}Mv^2 + \frac{1}{2}I\omega^2 \rightarrow \boxed{KE_{total} = \frac{1}{2}Mv^2 + \frac{1}{2}\left(M\right)\left(\frac{3}{4}L\right)^2}$

ii. Briefly explain why the rod and sphere gain kinetic energy, even if Earth is not included in the system.

The system still has potential energy, and as the system falls, potential energy is converted to kinetic.

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Question 5

Note: Student samples are quoted verbatim and may contain spelling and grammatical errors.

Overview

The responses were expected to demonstrate the ability to:

- Relate the torque on a system to the force and angle at which the force is applied.
- Relate the energy of an object to the position or condition in a system.
- Derive an equation for the kinetic energy of a system using energy conservation.
- Describe how work can be done on a system by a force outside of the system and relate work to the energy change of the system.

Sample: 5A
Score: 7

Part (a) earned 3 points. The first point was earned for stating, "Frame C," and indicates that the force of gravity is perpendicular to the radius. The second point was earned for using the equation for Newton's second law to relate torque and angular acceleration. The third point was earned for stating, "Frame E," and correctly relating the position to the greatest kinetic energy. Part (b) earned 4 points. The first point was earned for beginning with a concept of conservation of energy and having multiple steps. The second point was earned for correctly substituting the value $\frac{6}{4}L$ for the height shown in the equation. The third point was earned for the correct answer. The fourth point was earned for indicating that the gravitational force is now an external force on the system and does work.

Sample: 5B
Score: 5

Part (a) earned 2 points. The first point was not earned because the response does not indicate a relationship between torque and the position of the rod-sphere in Frame C. The second point was earned for indicating a proportional relationship between torque and angular acceleration. The third point was earned for stating, "Frame E," and correctly relating the position to the greatest kinetic energy. Part (b) earned 3 points. The first point was earned for beginning with a concept of conservation of energy and having multiple steps. The second point was earned for correctly substituting the value $\frac{3}{2}L$ for the height shown in the equation. The third point was earned for the correct answer. The fourth point was not earned because the response does not indicate that the gravitational force is now an external force on the system.

Sample: 5C
Score: 3

Part (a) earned 3 points. The first point was earned for stating, "Frame C," and indicates that the force of gravity is perpendicular to the radius. The second point was earned for using the equation for Newton's second law to relate torque and angular acceleration. The third point was earned for stating, "Frame E," and correctly relating the position to the greatest kinetic energy. Part (b) earned no points. The first point was not earned because the response does not begin with a concept of conservation of energy. The second point was not earned because the response has no indication of a height or change in height. The third point was not earned because the response does not have a correct answer. The fourth point was not earned because the response does not indicate that the gravitational force is now an external force on the system.