2024

AP® Physics C: Mechanics

Sample Student Responses and Scoring Commentary
Set 1

Inside:

Free-Response Question 1

☑ Scoring Guidelines

☑ Student Samples

☑ Scoring Commentary

Question 1: Free-Response Question — 15 points

(a)(i) For a multi-step derivation with an application of the conservation of mechanical energy that indicates that all of the energy of the system is initially U_s — **1 point**

Example Response

$$E_{\text{initial}} = E_{\text{final}}$$
$$\frac{1}{2}kx_c^{\,2} = \frac{1}{2}mv^2$$

For a correct solution for v — **1 point**

Example Response

$$v = x_c\sqrt{\frac{k}{m}}$$

Example Solution

$$E_{\text{initial}} = E_{\text{final}}$$
$$U_s = K$$
$$\frac{1}{2}kx_c^{\,2} = \frac{1}{2}mv^2$$
$$v = \sqrt{\frac{kx_c^{\,2}}{m}}$$
$$v = x_c\sqrt{\frac{k}{m}}$$

(a)(ii) For a derivation to solve for the speed at x_2 that includes **one** of the following: **1 point**

- An appropriate application of the conservation of energy
- An appropriate kinematics equation

Example Responses

$K_{\text{initial}} - \Delta E_{\text{friction}} = K_{\text{final}}$ **OR** $v^2 = v_0^2 + 2a\Delta x$

For **one** of the following that is consistent with the previous point in the response for part (a)(ii): **1 point**

- A correct expression for the energy dissipated by friction
- A correct expression for the acceleration of the block in the region with nonnegligible friction

Example Responses

$\Delta E_{\text{friction}} = \mu mgD$ **OR** $a = -\mu g$

For attempting to derive an expression for $v_{\text{A,B}}$ by using the conservation of momentum **1 point**

Example Response

$m_{\text{initial}} v_{\text{initial}} = m_{\text{A,B}} v_{\text{A,B}}$

For substituting the expression for the speed at x_2 that is consistent with the first point of the response in part (a)(ii) and substituting the correct masses into an expression for conservation of momentum **1 point**

Example Response

$$v_{\text{A,B}} = \frac{m\sqrt{\frac{k{x_c}^2}{m} - 2\mu gD}}{4m}$$

Example Solutions

$$E_{x_1} = E_{\text{before collision}}$$
$$K_{x_1} - \Delta E_{\text{friction}} = K_{\text{before collision}}$$
$$\frac{1}{2}m\left(\sqrt{\frac{kx_c^2}{m}}\right)^2 - \mu mgD = \frac{1}{2}mv_2^2$$
$$v_2 = \sqrt{\frac{kx_c^2}{m} - 2\mu gD}$$

$$\Sigma p_{\text{before collision}} = \Sigma p_{\text{after collision}}$$
$$m_A v_2 = m_{A,B} v_{A,B}$$
$$m_A v_2 = (m + 3m) v_{A,B}$$
$$v_{A,B} = \frac{m\sqrt{\frac{kx_c^2}{m} - 2\mu gD}}{4m}$$
$$v_{A,B} = \frac{1}{4}\sqrt{\frac{kx_c^2}{m} - 2\mu gD}$$

OR

$$v_2^2 = v^2 + 2a\Delta x$$
$$v_2^2 = \left(x_c\sqrt{\frac{k}{m}}\right)^2 + 2aD$$
$$v_2 = \sqrt{\frac{kx_c^2}{m} + 2aD}$$

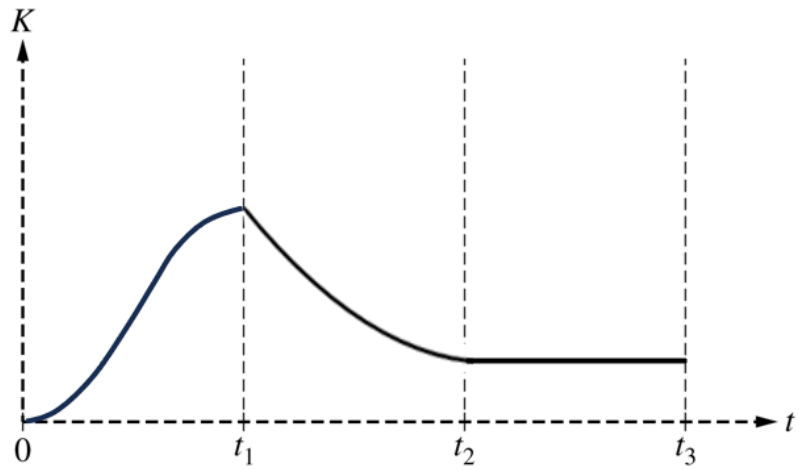
$$\Sigma F_x = -F_f = ma$$
$$-\mu mg = ma$$
$$a = -\mu g$$
$$v_2 = \sqrt{\frac{kx_c^2}{m} - 2\mu gD}$$

$$\Sigma p_{\text{before collision}} = \Sigma p_{\text{after collision}}$$
$$m_A v_2 = m_{A,B} v_{A,B}$$
$$m_A v_2 = (m + 3m) v_{A,B}$$
$$v_{A,B} = \frac{m\sqrt{\frac{kx_c^2}{m} - 2\mu gD}}{4m}$$
$$v_{A,B} = \frac{1}{4}\sqrt{\frac{kx_c^2}{m} - 2\mu gD}$$

Total for part (a) 6 points

(b)(i)	For a nonlinear sketch that begins at zero and increases for the entire time interval $0 \le t \le t_1$	**1 point**
	For a sketch that decreases for the entire time interval $t_1 \le t \le t_2$ but does not go to zero	**1 point**
	For a sketch that is concave up for the time interval $t_1 \le t \le t_2$	**1 point**
	For a continuous function for the time interval $t_1 \le t \le t_3$ that has a horizontal line that is greater than zero for the time interval $t_2 \le t \le t_3$	**1 point**

Example Response



(b)(ii)	For a statement about the change in kinetic energy that is consistent with the graph drawn in the response for part (b)(i)	**1 point**
	For a correct explanation for why the kinetic energy is increasing, such as **one** of the following: • An increasing graph means positive work is being done on the block. • An external force is exerted on Block A, causing the velocity of the block to increase and the kinetic energy of the block to increase. • Mechanical energy is conserved and/or there is no work done for the block-spring system, and the potential energy decreases.	**1 point**
	For a correct explanation for why the graph is nonlinear, such as **one** of the following: • The rate at which the slope of the graph changes is related to the rate at which work is being done on the block. • The external force exerted on Block A is changing, which causes a nonuniform change in the velocity of Block A, which results in a nonuniform change in kinetic energy.	**1 point**

Example Response

From $0 < t < t_1$, the kinetic energy of Block A increases. The force exerted on the block by the compressed spring transfers the elastic potential energy in the block-spring system to the kinetic energy of the block. Because the force exerted by the spring is not applied at a constant rate, the kinetic energy of the block does not increase at a constant rate.

Total for part (b) **7 points**

(c)	For selecting $f_{2\ell} < f_\ell$ with an attempt at a relevant justification	**1 point**
	For correctly applying an equation that relates the length of a pendulum to the period or frequency of the pendulum	**1 point**

Example Response

The period of a pendulum is calculated by using $T = 2\pi\sqrt{\frac{l}{g}}$ *. Therefore, as the length is increased, the period will also increase. Because frequency and period are inversely related, an increase in period will result in a decrease in frequency.*

Total for part (c) 2 points

Total for question 1 15 points

Question 1

Begin your response to **QUESTION 1** on this page.

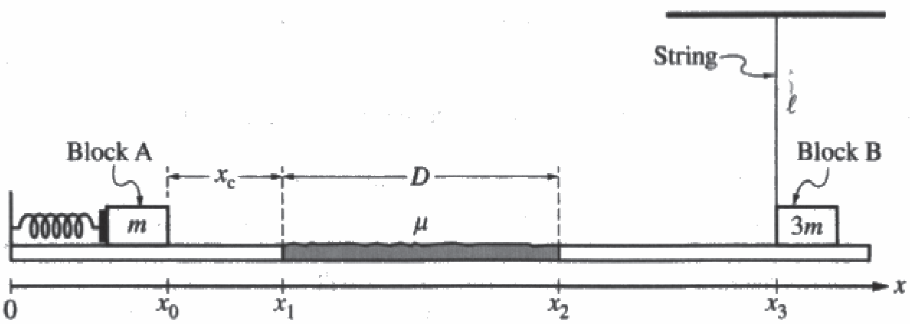
PHYSICS C: MECHANICS

SECTION II

Time—45 minutes

3 Questions

Directions: Answer all three questions. The suggested time is about 15 minutes for answering each of the questions, which are worth 15 points each. The parts within a question may not have equal weight. Show all your work in this booklet in the spaces provided after each part.



Note: Figure not drawn to scale.

Figure 1

1. Block A and Block B of masses m and $3m$, respectively, are arranged in a setup consisting of an ideal spring with spring constant k and a horizontal surface. Friction between the surface and the blocks is negligible except in a region of length D, where the coefficient of kinetic friction between Block A and the surface is μ. Block B is attached to a string of length ℓ and negligible mass, as shown in Figure 1. Block A is held against the spring, compressing the spring a distance x_c.

Question 1

Continue your response to **QUESTION 1** on this page.

At time $t = 0$, Block A is located at position $x = x_0$ and is released from rest. After the block is released, the following occurs.

- At time $t = t_1$, Block A is at $x = x_1$ after traveling a distance x_c. Block A moves with speed v, and the spring is at its equilibrium position.
- At time $t = t_2$, the left side of Block A is at $x = x_2$ after passing through a distance D across the region with nonnegligible friction.
- At time $t = t_3$, Block A is at $x = x_3$ and Block A collides with and sticks to Block B.

(a) For parts (a)(i) and (a)(ii), express your answer in terms of m, k, D, μ, x_c, and physical constants, as appropriate.

i. **Derive** an expression for the speed v of Block A at time t_1.

$$U_o + K_o = U_f + K_f \Rightarrow \frac{1}{2}kx^2 + 0 = 0 + \frac{1}{2}mv^2 \Rightarrow kx^2 = mv^2$$

$$\Rightarrow \frac{kx_c^2}{m} = v^2 \Rightarrow \boxed{v = \sqrt{\frac{kx_c^2}{m}}}$$

ii. **Derive** an expression for the speed $v_{A,B}$ of the two-block system immediately after the collision at time t_3.

$$\Sigma F_x = ma_x \Rightarrow -F_{friction} = ma \Rightarrow -\mu mg = ma \Rightarrow a = -\mu g$$

$$v_f^2 = v_i^2 + 2a\Delta x \Rightarrow v_f^2 = \left(\sqrt{\frac{kx_c^2}{m}}\right)^2 + 2(-\mu g)(D)$$

$$\Rightarrow v_f = \sqrt{\left(\frac{kx_c^2}{m} - 2\mu g D\right)}$$

$$\vec{p}_i = \vec{p}_f \Rightarrow mv_f + 3m(0) = (m+3m)v_{total}$$

$$\boxed{\frac{1}{4}\sqrt{\frac{kx_c^2}{m} - 2\mu g D} = v_{total} = v_{A,B}}$$

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Question 1

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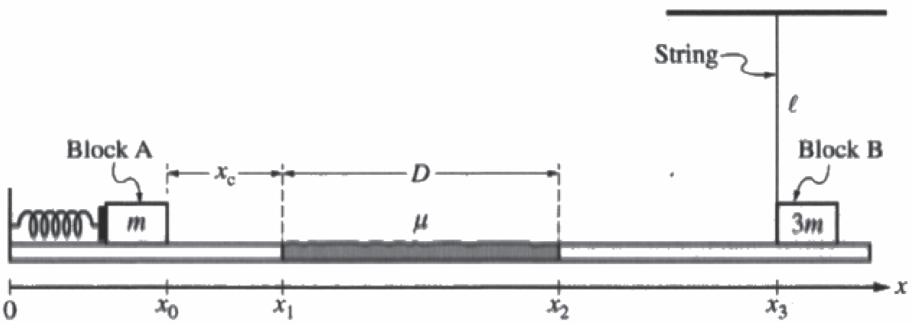
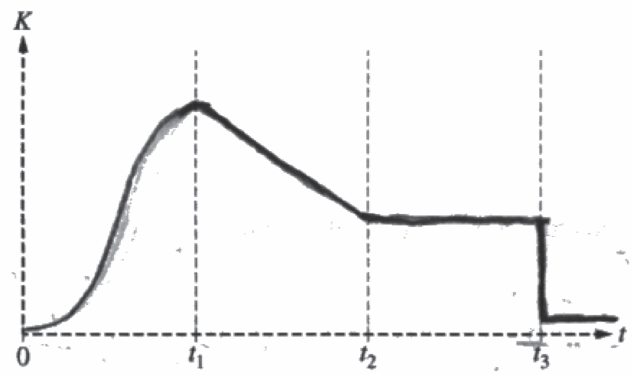


Note: Figure not drawn to scale.

Figure 1

(b)

i. On the following axes, **sketch** a graph of the kinetic energy K of Block A as a function of time t from time $t = 0$ to time t_3.

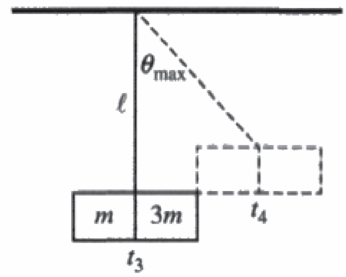


ii. Use principles of work and energy to **justify** the graph drawn in part (b)(i) for the time interval $t = 0$ to $t = t_1$. Explicitly reference features of the shape of the graph you drew in part (b)(i).

At $t=0$, the potential energy is at a maximum because the spring is at maximum compression, and K increases while the potential energy U decreases. K increases with velocity because $K = \frac{1}{2}mv^2$, and where v reaches a max, t_1 (top of the velocity sine curve), so will K.

Question 1

Continue your response to **QUESTION 1** on this page.



Note: Figure not drawn to scale.

Figure 2

After the collision, the two-block system instantaneously comes to rest at time t_4, which occurs when the string makes a small angle θ_{max} with the vertical, as shown in Figure 2. For times $t > t_4$, the system oscillates with frequency f_ℓ. The support holding the string is raised, and the procedure is then repeated using a new string of length 2ℓ.

(c) **Indicate** how the new frequency of oscillation $f_{2\ell}$ of the system on the new string of length 2ℓ will compare to the frequency of oscillation f_ℓ from the original procedure.

____ $f_{2\ell} > f_\ell$ ✓ $f_{2\ell} < f_\ell$ ____ $f_{2\ell} = f_\ell$

Briefly **justify** your answer.

The frequency $f_{pendulum} = \frac{1}{2\pi}\omega$ where $\omega_{pendulum} = \sqrt{\frac{g}{\ell}}$, so $f = \sqrt{\frac{g}{\ell}}$. This equation implies that as the length of the string on the pendulum lengthens, the frequency decreases, so $f_{2\ell} < f_\ell$

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Question 1

Begin your response to **QUESTION 1** on this page.

PHYSICS C: MECHANICS

SECTION II

Time—45 minutes

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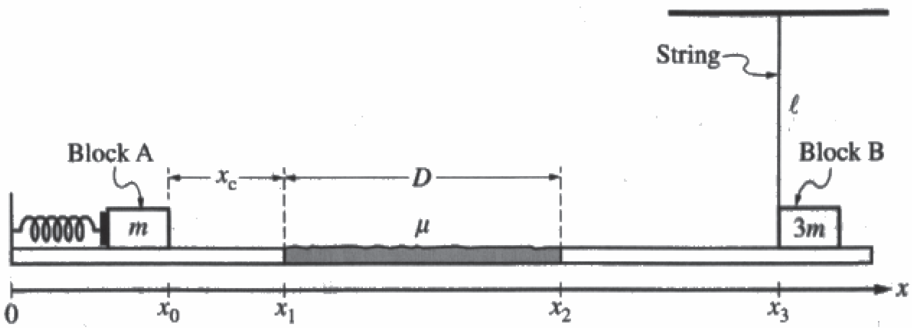

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Figure 1

1. Block A and Block B of masses m and $3m$, respectively, are arranged in a setup consisting of an ideal spring with spring constant k and a horizontal surface. Friction between the surface and the blocks is negligible except in a region of length D, where the coefficient of kinetic friction between Block A and the surface is μ. Block B is attached to a string of length ℓ and negligible mass, as shown in Figure 1. Block A is held against the spring, compressing the spring a distance x_c.

GO ON TO THE NEXT PAGE.

Question 1

Continue your response to QUESTION 1 on this page.

At time $t = 0$, Block A is located at position $x = x_0$ and is released from rest. After the block is released, the following occurs.

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- At time $t = t_2$, the left side of Block A is at $x = x_2$ after passing through a distance D across the region with nonnegligible friction.
- At time $t = t_3$, Block A is at $x = x_3$ and Block A collides with and sticks to Block B.

(a) For parts (a)(i) and (a)(ii), express your answer in terms of m, k, D, μ, x_c, and physical constants, as appropriate.

i. **Derive** an expression for the speed v of Block A at time t_1.

$\frac{1}{2}kx^2 = \frac{1}{2}mv^2$ energy is conserved

$v = \sqrt{\frac{kx_c^2}{m}}$

ii. **Derive** an expression for the speed $v_{A,B}$ of the two-block system immediately after the collision at time t_3.

$\Sigma F = ma$

$kx_c - \mu mg = ma$

$a = \frac{kx_c - \mu mg}{m}$

$m_1 v_1 = m_2 v_2$

$m\left(\sqrt{\frac{kx^2}{m}} + \frac{kx_c - \mu mg}{m}(t_2 - t_1)\right) = 4m\, v_{A,B}$

$v_f = v_i + at$

$v_f = \sqrt{\frac{kx^2}{m}} + \frac{kx_c - \mu mg}{m}(t_2 - t_1)$

$v_{A,B} = \frac{m\sqrt{\frac{kx^2}{m}} + kx_c - \mu mg(t_2 - t_1)}{4m}$

Question 1

Continue your response to **QUESTION 1** on this page.

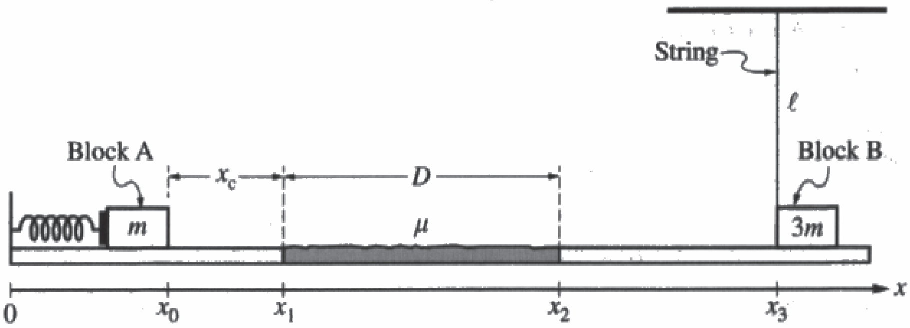

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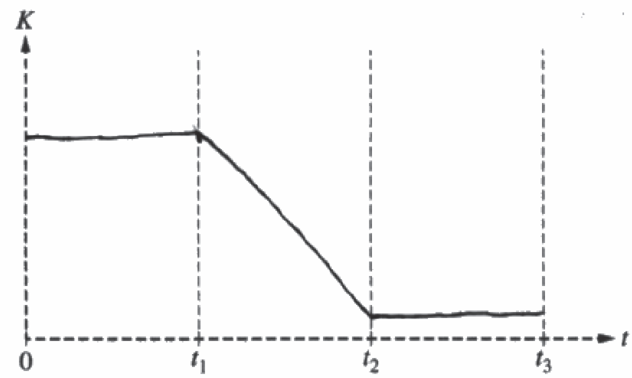
Figure 1

(b)

i. On the following axes, **sketch** a graph of the kinetic energy K of Block A as a function of time t from time $t = 0$ to time t_3.



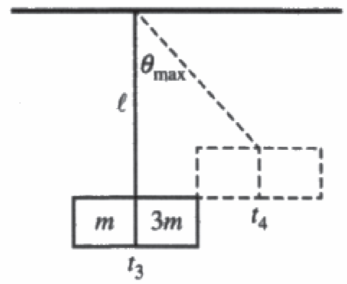
ii. Use principles of work and energy to **justify** the graph drawn in part (b)(i) for the time interval $t = 0$ to $t = t_1$. Explicitly reference features of the shape of the graph you drew in part (b)(i).

The slope of the graph is zero because there is no work acting on the block, energy is conserved. There is no work because there is no external force acting on the block, friction.

Use a pencil or a pen with black or dark blue ink. Do NOT write your name. Do NOT write outside the box.

Question 1

Continue your response to **QUESTION 1** on this page.



Note: Figure not drawn to scale.

Figure 2

After the collision, the two-block system instantaneously comes to rest at time t_4, which occurs when the string makes a small angle θ_{max} with the vertical, as shown in Figure 2. For times $t > t_4$, the system oscillates with frequency f_ℓ. The support holding the string is raised, and the procedure is then repeated using a new string of length 2ℓ.

(c) **Indicate** how the new frequency of oscillation $f_{2\ell}$ of the system on the new string of length 2ℓ will compare to the frequency of oscillation f_ℓ from the original procedure.

~~X~~ $f_{2\ell} > f_\ell$ X $f_{2\ell} < f_\ell$ ____ $f_{2\ell} = f_\ell$

Briefly **justify** your answer.

Because the string makes a small angle, the system can be considered a pendellum so $T = 2\pi\sqrt{\frac{\ell}{g}}$. Because ℓ is in the numerator as ℓ increases, T ~~decreases~~ increases. And $T = \frac{1}{f}$, so $f = \frac{1}{T}$, so as T increases, f decreases.

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Question 1

Begin your response to **QUESTION 1** on this page.

PHYSICS C: MECHANICS

SECTION II

Time—45 minutes

3 Questions

1:46

Directions: Answer all three questions. The suggested time is about 15 minutes for answering each of the questions, which are worth 15 points each. The parts within a question may not have equal weight. Show all your work in this booklet in the spaces provided after each part.

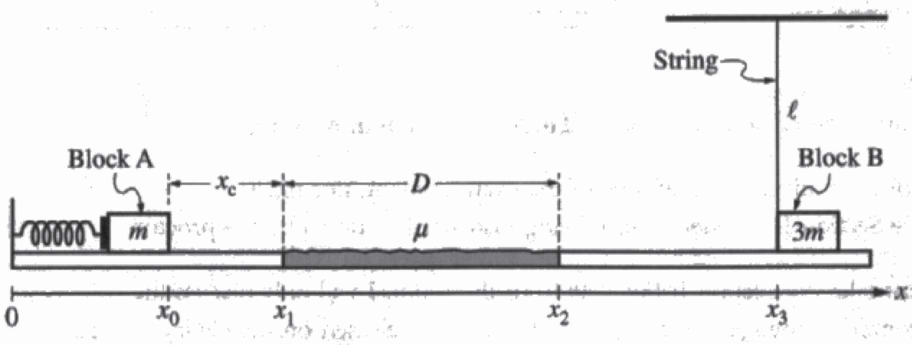

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Figure 1

1. Block A and Block B of masses m and $3m$, respectively, are arranged in a setup consisting of an ideal spring with spring constant k and a horizontal surface. Friction between the surface and the blocks is negligible except in a region of length D, where the coefficient of kinetic friction between Block A and the surface is μ. Block B is attached to a string of length ℓ and negligible mass, as shown in Figure 1. Block A is held against the spring, compressing the spring a distance x_c.

Question 1

Continue your response to **QUESTION 1** on this page.

At time $t = 0$, Block A is located at position $x = x_0$ and is released from rest. After the block is released, the following occurs.

- At time $t = t_1$, Block A is at $x = x_1$ after traveling a distance x_c. Block A moves with speed v, and the spring is at its equilibrium position.
- At time $t = t_2$, the left side of Block A is at $x = x_2$ after passing through a distance D across the region with nonnegligible friction.
- At time $t = t_3$, Block A is at $x = x_3$ and Block A collides with and sticks to Block B.

(a) For parts (a)(i) and (a)(ii), express your answer in terms of m, k, D, μ, x_c, and physical constants, as appropriate.

i. **Derive** an expression for the speed v of Block A at time t_1.

$$V_x^2 = \cancel{V_{x0}^2}^{\,0} + 2a_x(x - x_0)$$

$$V_x^2 = 2a_x(x - x_0)$$

$$\sqrt{V_x^2} = \sqrt{2(x_c)(D)}$$

$$V = \sqrt{2x_cD}$$

ii. **Derive** an expression for the speed $v_{A,B}$ of the two-block system immediately after the collision at time t_3.

$KE = \frac{1}{2}mv^2$ $\qquad$ $KE = \frac{1}{2}mv^2$

$KE_A = \frac{1}{2}mV_A^2$ $\qquad$ $KE_B = \frac{1}{2}(3m)(V_B)^2$

$$\frac{1}{2}mV_A^2 = \frac{1}{2}(3m)(V_B)^2$$

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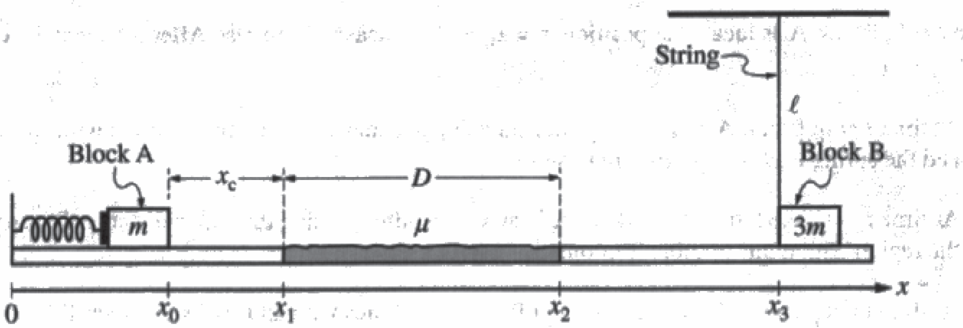
Question 1

Continue your response to QUESTION 1 on this page.

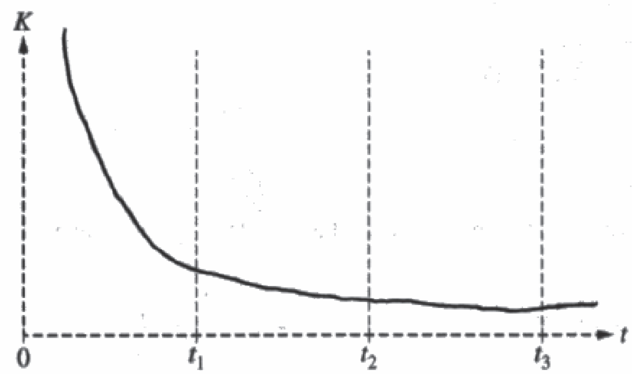


Note: Figure not drawn to scale.

Figure 1

(b)

i. On the following axes, **sketch** a graph of the kinetic energy K of Block A as a function of time t from time $t = 0$ to time t_3.



ii. Use principles of work and energy to **justify** the graph drawn in part (b)(i) for the time interval $t = 0$ to $t = t_1$. Explicitly reference features of the shape of the graph you drew in part (b)(i).

Since work = F.d and kinetic energy is equal to $\frac{1}{2}mv^2$, both of these would make a relationship to make a graph that is an inverse exponential graph. The kinetic energy would be decreasing exponentially as t_1 moves to t_3.

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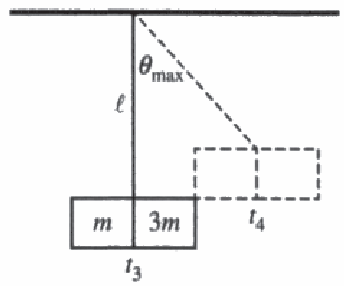
Question 1

Continue your response to **QUESTION 1** on this page.



Note: Figure not drawn to scale.

Figure 2

After the collision, the two-block system instantaneously comes to rest at time t_4, which occurs when the string makes a small angle θ_{max} with the vertical, as shown in Figure 2. For times $t > t_4$, the system oscillates with frequency f_ℓ. The support holding the string is raised, and the procedure is then repeated using a new string of length 2ℓ.

(c) **Indicate** how the new frequency of oscillation $f_{2\ell}$ of the system on the new string of length 2ℓ will compare to the frequency of oscillation f_ℓ from the original procedure.

____ $f_{2\ell} > f_\ell$ __✓__ $f_{2\ell} < f_\ell$ ____ $f_{2\ell} = f_\ell$

Briefly **justify** your answer.

$$T = \frac{2\pi}{\omega} = \frac{1}{f}$$

According to this formula, the grater value of ℓ, the lower the f, or frequency of oscillation would be lower since it is $\frac{1}{f}$.

[redacted]

Question 1

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

Overview

The responses were expected to demonstrate the ability to:

- Derive an expression using conservation of mechanical energy between spring potential energy and kinetic energy.
- Determine the work done on an object by the force of friction.
- Apply conservation of linear momentum during a collision.
- Analyze and interpret a graphical representation of kinetic energy as a function of time.
- Describe the change in kinetic energy in scenarios of both constant and variable forces.
- Determine the relationship between the length of a pendulum and its frequency of oscillation.

Sample: 1A
Score: 13

Part (a) earned 6 points. The first point was earned for a multi-step derivation that applies conservation of mechanical energy and recognizes that all the initial energy consists of spring potential energy. The second point was earned for providing the correct speed at time t_1 in terms of the allowed variables. The third point was earned for applying an appropriate kinematics equation to solve for the speed at x_2. The fourth point was earned for including a correct expression for the acceleration of the block in the region of nonnegligible friction. The fifth point was earned for attempting to derive an expression for v_{AB} by using conservation of momentum. The sixth point was earned for correctly substituting the speed consistent with earlier work and the correct masses into the expression for conservation of momentum. Part (b) earned 5 points. The first point was earned for sketching the function correctly between $t = 0$ and $t = t_1$. The correct velocity function is sinusoidal with a period of $4t_1$. The kinetic energy is proportional to the velocity squared and is, therefore, sinusoidal with period $2t_1$. It should be noted that to earn credit, it is sufficient that the function begins at zero and increases nonlinearly in this region. The second point was earned for showing a function that is uniformly decreasing between $t = t_1$ and $t = t_2$ and does not reach zero. The third point was not earned because the response is linear between $t = t_1$ and $t = t_2$ and not concave up. The fourth point was earned for the function being continuous between $t = t_1$ and $t = t_3$ and having a constant nonzero value between $t = t_2$ and $t = t_3$. The fifth point was earned for clearly indicating that the kinetic energy is increasing, which is consistent with the graph drawn. The sixth point was earned for clearly stating that the kinetic energy of the block is increasing while the spring potential energy of the system is decreasing. The seventh point was not earned because the response does not address why the graph is nonlinear. Part (c) earned 2 points. The first point was earned for selecting the correct relationship and for an attempt at a relevant justification. The second point was earned for the first line correctly showing an appropriate technique for using the equation for the frequency of the oscillation. Although the 2π term is omitted from the final statement of the frequency equation, the response demonstrates the proportional reasoning required to earn this point.

Question 1 (continued)

Sample: 1B
Score: 9

Part (a) earned 4 points. The first point was earned for a multi-step derivation that applies conservation of mechanical energy and recognizes that all the initial energy consists of spring potential energy. The second point was earned for providing the correct speed at time t_1 in terms of the allowed variables. The third point was not earned because, although a kinematics approach was attempted, the response does not use an equation that is appropriate because it requires variables that are not permitted in the solution. The fourth point was not earned because the response does not include a correct expression for the acceleration in the region with nonnegligible friction. The fifth point was earned for attempting to derive an expression for v_{AB} by using conservation of momentum. The sixth point was earned for correctly substituting the speed consistent with earlier work and the correct masses into the expression for conservation of momentum. Even though the substitution uses variables that are not permitted, the point was awarded because the substitution is consistent with previous work. Part (b) earned 3 points. The first point was not earned because the function does not begin at zero, and it does not increase nonlinearly between $t = 0$ and $t = t_1$. The second point was earned for showing a function that is uniformly decreasing between $t = t_1$ and $t = t_2$ and does not reach zero. The third point was not earned because the response is linear between $t = t_1$ and $t = t_2$ and not concave up. The fourth point was earned for showing a continuous function between $t = t_1$ and $t = t_3$ with a constant nonzero value between $t = t_2$ and $t = t_3$. The fifth point was earned for claiming that the slope of the graph is zero, which is consistent with the graph. The sixth point was not earned because the response does not include an explanation of why the kinetic energy should be increasing. The seventh point was not earned because the response does not address why the graph should be nonlinear between $t = 0$ and $t = t_1$. Part (c) earned 2 points. The first point was earned for selecting the correct relationship and attempting a relevant justification. The second point was earned for using an equation to explain that as the length of the pendulum is increased, its period increases.

Question 1 (continued)

Sample: 1C
Score: 3

Part (a) did not earn any points. The first point was not earned because the response does not contain a derivation that applies conservation of energy. The second point was not earned because the response does not provide the correct speed at time t_1. The third point was not earned because, even though there are energy terms in the response, there is no attempt to apply conservation of energy to solve for the speed at x_2. The fourth point was not earned because the response does not include a correct expression for the energy dissipated by friction or the acceleration of the block in the region with nonnegligible friction. The fifth point was not earned because the response does not attempt to derive an expression for v_{AB} by using conservation of momentum. The sixth point was not earned because the response does not substitute a speed consistent with earlier work or the correct mass into an expression for conservation of momentum. Part (b) earned 2 points. The first point was not earned because the sketch does not increase nonlinearly between $t = 0$ and $t = t_1$. The second point was earned for showing a function that is uniformly decreasing between $t = t_1$ and $t = t_2$ and does not reach zero. The third point was earned for showing a function that is concave up during the entire section between $t = t_1$ and $t = t_2$, even though the curvature is relatively small. The fourth point was not earned because the function does not have a constant nonzero value between $t = t_2$ and $t = t_3$. The fifth point was not earned because the response makes no mention of the fact that kinetic energy is decreasing between $t = 0$ and $t = t_1$, as indicated in the graph. The sixth point was not earned because the response does not include an explanation of why the kinetic energy should be increasing between $t = 0$ and $t = t_1$. The seventh point was not earned because the response does not address why the graph should be nonlinear between $t = 0$ and $t = t_1$. Part (c) earned 1 point for selecting the correct relationship and attempting a relevant justification. The second point was not earned because a correct equation is not applied to relate the length of the pendulum to its period or frequency.