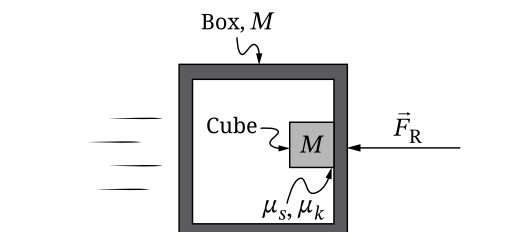


Question 1: Version J

1. A box of mass M slides to the right on a horizontal surface. A small cube, also of mass M , is inside the box. The cube is against the right wall of the box and above the bottom of the box, as shown in Figure 1. The coefficients of static and kinetic friction between the cube and the wall of the box are μ_s and μ_k , respectively, where $\mu_s > \mu_k$.

Figure 1

The speed of the box is decreasing as a result of a resistive force that is exerted on the box. The resistive force $\vec{F}_R$ is modeled by $\vec{F}_R = -b\vec{v}$, where b is a positive constant and $\vec{v}$ is the velocity of the box. Friction between the box and horizontal surface is negligible.

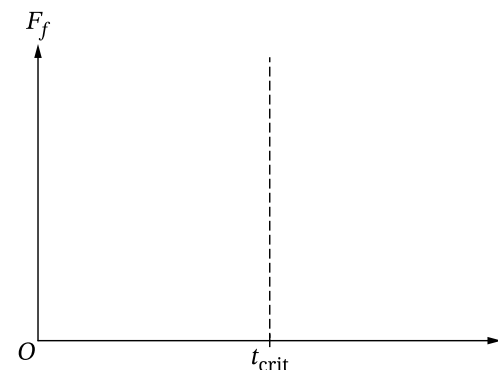
Consider the motion of the box and cube for the following times.

- At time $t = 0$, the box-cube system slides to the right with speed v_0 .
- For $0 \leq t < t_{\text{crit}}$, the cube remains in contact with the wall of the box at a constant height above the bottom of the box.
- At $t = t_{\text{crit}}$, the cube begins to slide downward along the wall of the box.

Part A

The magnitude of the normal force exerted on the cube by the wall of the box is F_N .

- Determine** an expression for the magnitude of the acceleration of the cube. Express your answer in terms of M , F_N , and physical constants, as appropriate.
- Derive** an expression for F_N as a function of t from $t = 0$ until immediately before the cube reaches the bottom of the box. Express your answer in terms of M , b , v_0 , t , and physical constants, as appropriate. Begin your derivation with a fundamental physics principle or an equation from the reference information.
- On the axes shown in Figure 2, **sketch** a graph of the magnitude F_f of the frictional force exerted on the cube by the wall of the box as a function of t from $t = 0$ until immediately before the cube reaches the bottom of the box.

Figure 2**Part B**

Derive an expression for t_{crit} in terms of M , b , μ_s , v_0 , and physical constants, as appropriate. Begin your derivation with a fundamental physics principle or an equation from the reference information.

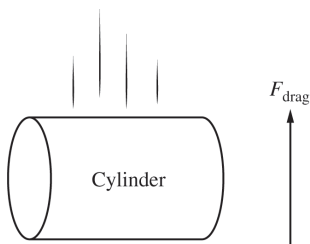
Begin your response to **QUESTION 2** on this page.

Figure 1

2. A student drops a cylinder of mass m from rest. The air exerts a drag force of magnitude F_{drag} on the cylinder, as shown in Figure 1. The student models the magnitude of the drag force as $F_{\text{drag}} = bv^2$, where v is the speed of the cylinder and b is a positive constant with appropriate units.

(a) **Derive**, but do NOT solve, a differential equation that could be used to determine the speed v of the cylinder as a function of time t . Express your answer in terms of given quantities and physical constants, as appropriate.

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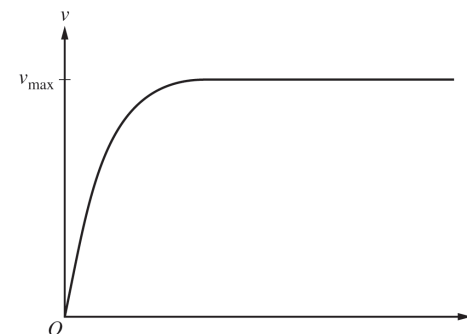
Continue your response to **QUESTION 2** on this page.

Figure 2

- (b) The student correctly sketches the speed v of the cylinder as a function of time t , as shown in Figure 2.

i. **Draw** a vertical line on the sketch in Figure 2 to indicate the earliest time at which F_{drag} on the cylinder is equal to the magnitude of the weight of the cylinder. Label this time as t_1 on the time axis.

ii. **Justify** the location of t_1 . Explicitly reference appropriate features of the sketch in Figure 2.

- (c) Rather than dropping the cylinder from rest, the student throws the cylinder upward with a nonzero initial speed. The cylinder is in the same orientation as when the cylinder was previously dropped. The student allows the cylinder to fall toward the ground.

Indicate whether the magnitude of the cylinder's maximum downward speed after being thrown upward would be greater than, less than, or equal to the maximum speed v_{max} in Figure 2.

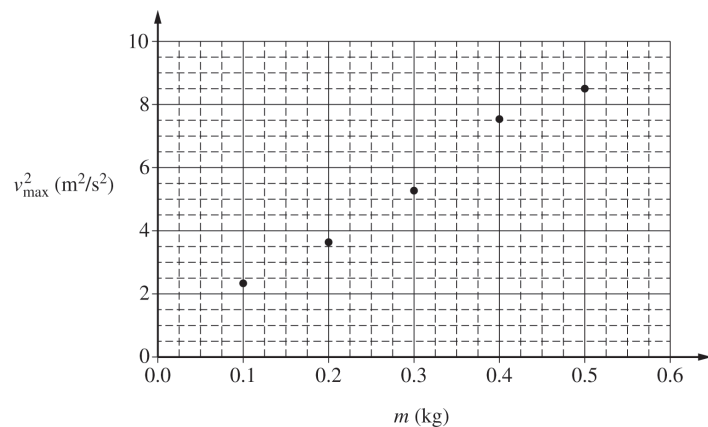
_____ Greater than _____ Less than _____ Equal to

Briefly **justify** your answer.

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Continue your response to **QUESTION 2** on this page.

- (d) The student conducts an experiment to better understand the relationship between maximum speed $v_{\max}$ and mass. The student collects data to determine the maximum speed for cylinders dropped from rest, each with the same physical size and shape but a different mass m . The student then graphs $v_{\max}^2$ as a function of mass.

i. **Draw** the best-fit line for the data.ii. Use the best-fit line to **calculate** an experimental value for b .

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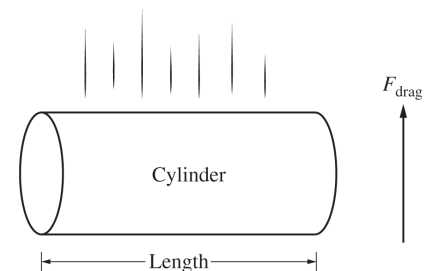
Continue your response to **QUESTION 2** on this page.

Figure 3

A student claims that the magnitude of the maximum speed of a cylinder dropped from rest depends on the length of the cylinder. The student designs an experiment to collect data that can be used to provide evidence to support the claim. The student drops cylinders with the orientation shown in Figure 3.

(e) The student has access to but does not have to use all of the following equipment.

- Cylinder Set 1: cylinders of the same known length with different known masses
- Cylinder Set 2: cylinders of the same known mass with different known lengths
- A motion detector that can measure velocity as a function of time

i. **Indicate** two quantities that when graphed could be used to determine whether the length of the cylinder affects the maximum speed.

Vertical axis: _____ Horizontal axis: _____

ii. Briefly **describe** how the quantities graphed could be used to determine the relationship between cylinder length and maximum speed.

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Continue your response to Question 3 on this page.

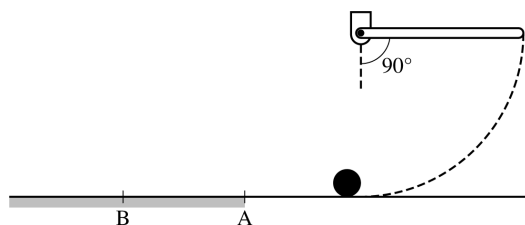
Note: Figure not drawn to scale.

Figure 1

3. A system consists of a small sphere of mass m and radius R at rest on a horizontal surface and a uniform rod of mass $M = 2m$ and length ℓ attached at one end to a pivot with negligible friction, where $R \ll \ell$. There is negligible friction between the surface and the sphere to the right of Point A and nonnegligible friction to the left of Point A. The rod is held horizontally as shown in Figure 1, then is released from rest. The total rotational inertia of the rod about the pivot is $\frac{1}{3}M\ell^2$ and the rotational inertia of the sphere about its center is $\frac{2}{5}mR^2$. After the rod is released, the rod swings down and strikes the sphere head-on. As a result of this collision, the rod is stopped, and the ball initially slides without rotating to the left across the horizontal surface.

- (a) Derive an expression for the angular speed of the rod just before striking the sphere in terms of the length ℓ and physical constants as appropriate.

GO ON TO THE NEXT PAGE.

Continue your response to Question 3 on this page.

- (b) Derive an expression for the linear speed v_0 of the sphere immediately after colliding with the rod in terms of the length ℓ and physical constants as appropriate.

After sliding a short distance, at time $t = 0$ the sphere encounters a region of the horizontal surface with a coefficient of kinetic friction μ , beginning at Point A as indicated in Figure 1. The sphere begins rotating while sliding and eventually begins rolling without sliding at Point B, also as indicated.

- (c) In the following diagram, which represents the sphere while the sphere is traveling between Points A and B, draw and label the forces (not components) that act on the sphere. Each force must be represented by a distinct arrow starting on, and pointing away from, the point of application on the sphere.



- (d) Derive an expression for each of the following as the sphere is rotating and sliding between points A and B in terms of v_0 , μ , R , t , and physical constants as appropriate.

- i. The linear velocity v of the center of mass of the sphere as a function of time t

- ii. The angular velocity ω of the sphere as a function of time t

GO ON TO THE NEXT PAGE.

Name: _____

Continue your response to **QUESTION 3** on this page.

- (e)
- i. Derive an expression for the time it takes the sphere to travel from Point A to Point B in terms of v_0 , μ , and physical constants as appropriate.
- ii. Derive an expression for the linear velocity of the sphere upon reaching Point B in terms of v_0 .

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STOP

END OF EXAM

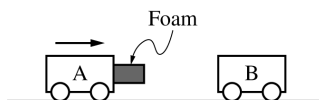
PHYSICS C: MECHANICS

SECTION II

Time—45 minutes

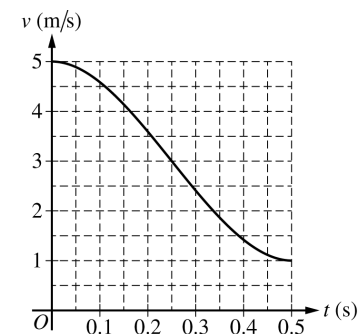
3 Questions

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.



Scientists have created a new type of lightweight foam and are performing experiments to investigate the properties of the foam. The mass of Cart A is 1000 kg and the mass of Cart B is 2000 kg. A piece of foam with negligible mass is attached to the front of Cart A, as shown. Cart A moves with a constant speed toward Cart B, which is initially at rest. At time $t = 0$ s, the foam connected to Cart A makes contact with Cart B. The foam remains in contact with Cart B for 0.5 s, after which the carts separate and both carts move with constant velocities.

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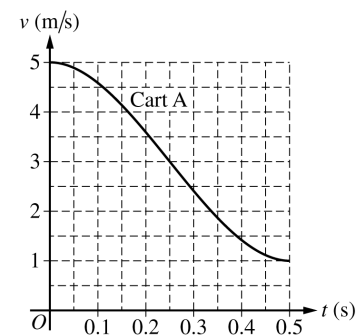
Continue your response to **QUESTION 1** on this page.

- (a) The graph shows the velocity v of Cart A as a function of time t for the time interval when the foam and Cart B are in contact.

i. What feature(s) of the graph could be used to estimate the displacement of Cart A during the collision?

ii. Using the information shown in the graph, determine the speed of Cart B at $t = 0.5$ s.

iii. On the following grid, draw a smooth curve of the velocity of Cart B as a function of time.



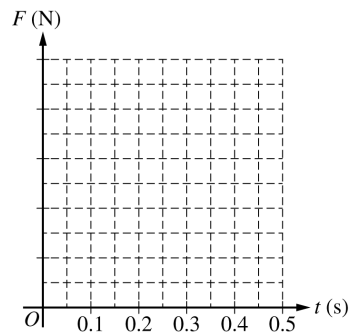
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Continue your response to **QUESTION 1** on this page.

(b) For $0 \leq t \leq 0.50$ s, the velocity v of Cart A can be described by the function $v(t) = 64t^3 - 48t^2 + 5$.

i. Calculate the magnitude of the maximum net force acting on Cart A during this interval.

ii. On the following grid, draw a smooth curve of the magnitude of the force acting on Cart A as a function of time. Clearly indicate the value of the maximum force on the vertical axis.



GO ON TO THE NEXT PAGE.

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

The foam is removed from the front of Cart A and the experiment is repeated. The carts collide, with both Cart A and Cart B having the same initial and final velocities as in the original collision. The time intervals during which the carts are in contact are different in the collision with the foam and the collision without the foam. In the collision without the foam, Cart A is in contact with Cart B for a shorter duration than in the original collision, when the foam was present.

For the original collision when the foam is present, the magnitude of the average net force exerted on Cart B is F_1 . For the collision without the foam, the magnitude of the average net force exerted on Cart B is F_2 .

(c) What is the relationship between the magnitude of the average net force F_1 exerted on Cart B for the collision with the foam and the magnitude of the average net force F_2 exerted on Cart B for the collision without the foam?

_____ $F_1 > F_2$ _____ $F_1 < F_2$ _____ $F_1 = F_2$

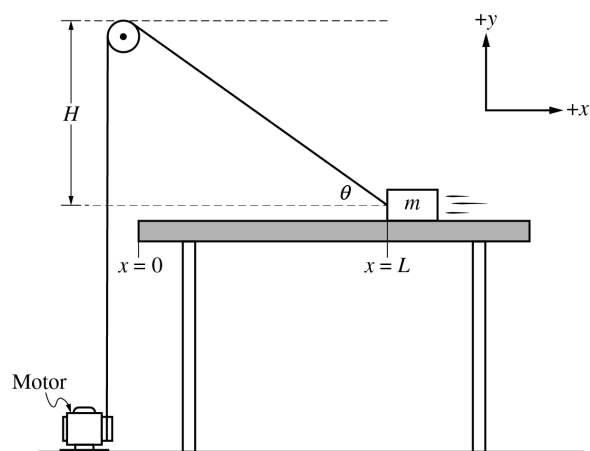
Justify your answer.

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Begin your response to QUESTION 1 on this page.

PHYSICS C: MECHANICS**SECTION II****Time—45 minutes****3 Questions**

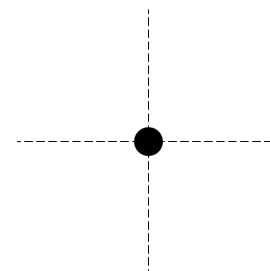
Directions: Answer all three questions. The suggested time is about 15 minutes for answering each of the questions, which are worth 15 points each. The parts within a question may not have equal weight. Show all your work in this booklet in the spaces provided after each part.



A block of mass m is pulled across a rough horizontal table by a string connected to a motor that is attached to the floor. The string passes over a pulley with negligible friction that is vertically aligned with the left edge of the table as shown. The string and pulley both have negligible mass. The pulley is at height H above the table. The motor exerts a constant force of tension F_T on the string, and the block remains in contact with the table at all times as the block slides across the table from $x = L$ to $x = 0$. The coefficient of kinetic friction between the table and the block is μ_k . Express all algebraic answers in terms of m , H , F_T , x , μ_k , L , and physical constants as appropriate.

GO ON TO THE NEXT PAGE.Continue your response to **QUESTION 1** on this page.

- (a) On the dot below that represents the block, draw and label the forces (not components) that act on the block when the block is at $x = L$. Each force must be represented by a distinct arrow starting on, and pointing away from, the dot.



- (b) Derive an expression for the angle θ that the string makes with the horizontal as a function of x .

GO ON TO THE NEXT PAGE.

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

(c)

i. Derive an expression for the normal force F_N exerted on the block by the table as a function of the block's position x .

ii. Derive an expression for the magnitude of the net horizontal force F_{net} exerted on the block as a function of the position x .

GO ON TO THE NEXT PAGE.

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

(d) Write, but do not solve, an integral expression that could be used to solve for the work W done by the string on the block as the block moves from $x = L$ to $x = 0$.

(e) Does the string do more, less, or the same amount of work on the block as the block moves from $x = L$ to $x = \frac{L}{2}$ compared to when the block moves from $x = \frac{L}{2}$ to $x = 0$?

_____ More work when the block moves from $x = L$ to $x = \frac{L}{2}$

_____ Less work when the block moves from $x = L$ to $x = \frac{L}{2}$

_____ The same amount of work when the block moves from $x = L$ to $x = \frac{L}{2}$

Justify your answer.

GO ON TO THE NEXT 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.

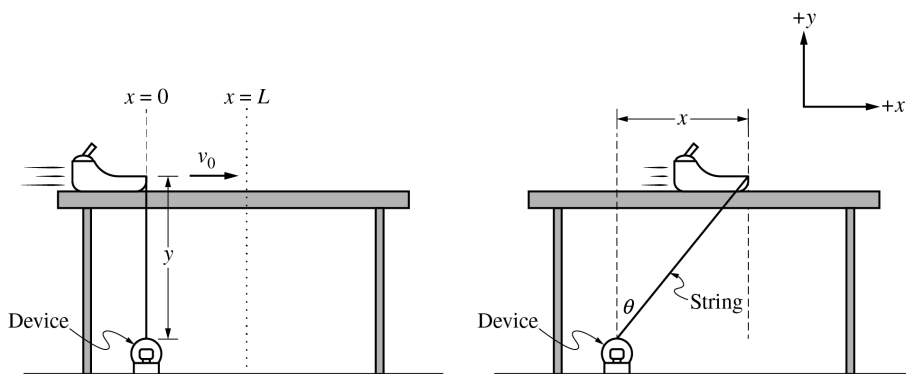


Figure 1

Figure 2

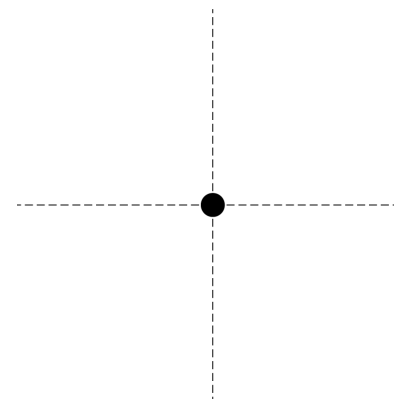
Note: Figures not drawn to scale.

A small sled slides across a rough horizontal table with an initial velocity v_0 . The coefficient of kinetic friction between the sled and the table is μ_k . A string connects the sled to a device on the ground. The device maintains constant tension F_T in the string by unwinding the string as the sled slides to the right. The total mass of the sled is m . The string is attached to the device at $x = 0$ and at a height of y , as shown in Figure 1. The horizontal position of the sled is represented by x , as shown in Figure 2. Express all algebraic answers in terms of m , μ_k , F_T , x , y , and physical constants, as appropriate.

GO ON TO THE NEXT PAGE.

Continue your response to QUESTION 1 on this page.

- (a) On the dot below that represents the sled, draw and label the forces (not components) that are exerted on the sled a short time after $t = 0$ but before the sled has come to rest. Each force must be represented by a distinct arrow starting on, and pointing away from, the dot.



- (b) Determine an expression for the angle θ that the string makes with the vertical when the sled has traveled a horizontal distance x .

GO ON TO THE NEXT PAGE.

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

(c)

i. Derive an expression for the normal force F_N exerted on the sled by the table as a function of the position x .

ii. Derive an expression for the magnitude of the net horizontal force F_{net} exerted on the sled as a function of the position x .

GO ON TO THE NEXT PAGE.

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

(d) Derive an expression for the work W done by the string on the sled as the sled moves from $x = 0$ to $x = L$.

(e) The sled comes to rest after traveling a horizontal distance $x = 2L$. As the system slides from $x = 0$ to $x = L$, the energy dissipated by friction is E_1 . As the sled slides from $x = L$ to $x = 2L$, the energy dissipated by friction is E_2 . Is E_1 greater than, less than, or equal to E_2 ?

___ $E_1 > E_2$ ___ $E_1 < E_2$ ___ $E_1 = E_2$

Justify your answer.

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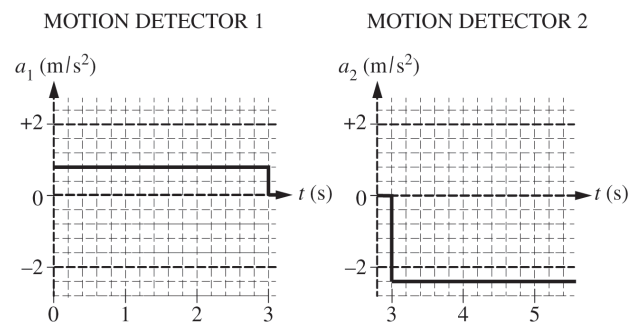
PHYSICS C: MECHANICS
SECTION II
Time—45 minutes
3 Questions

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.

1. A 0.50 kg fan cart is placed on a level, horizontal track of negligible friction, as shown. The fan is turned on, and the fan cart is released from rest and moves to the right. The cart travels along the horizontal track and then down an incline. Motion detector 1 measures the acceleration a of the cart from time $t = 0$ to $t = 3$ s. At $t = 3$ s, the cart makes a smooth transition to the incline, and motion detector 2 measures the acceleration of the cart after $t = 3$ s. The fan exerts the same magnitude of force on the cart during the entire motion. The graphs below show a as functions of t . For each motion detector, the positive direction is away from the detector.


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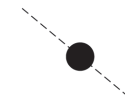
Use a pencil or pen with black or dark blue ink only. Do NOT write your name. Do NOT write outside the box.

- (a) On the dots below that represent the cart at two different locations, draw and label the forces (not components) that act on the cart at each location. Each force must be represented by a distinct arrow starting on, and pointing away from, the dot.

Cart on Horizontal Track



Cart on Incline



- (b) Calculate the magnitude of the net force exerted on the fan cart when it is on the horizontal track.

- (c) Calculate the angle θ of the incline.

- (d) Suppose careful measurement determines the angle of the incline to be 3° larger than that calculated in part (c). Consider the following explanation.

“The scale used to measure the mass of the fan cart was not calibrated properly before the measurement, and this could account for the observed difference in the angle.”

Does the explanation sufficiently account for the observed discrepancy?

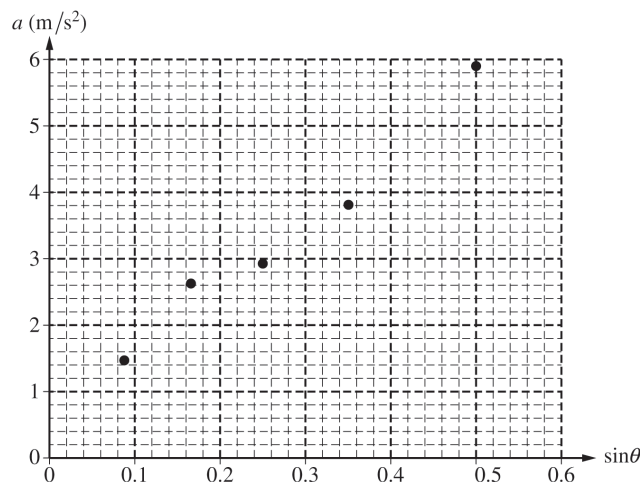
_____ Yes _____ No

Justify your answer.

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

The experiment is repeated for several trials, each with a different angle for the incline. The acceleration of the cart down the incline is measured for each angle. The graph below shows the plot of the acceleration a of the cart as a function of the sine of the angle $\sin \theta$.



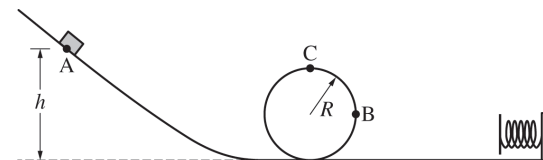
(e)

- Draw a best-fit line for the data.
- Using the straight line, calculate an experimental value for the acceleration due to gravity g .

(f) If the cart were replaced with a second cart of mass 1.0 kg that has a fan that exerts the same magnitude of force as the original fan, explain how the graph given in part (e) would change.

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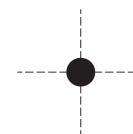
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Note: Figure not drawn to scale.

2. A block of mass m starts from rest at point A and travels with negligible friction through the loop onto a horizontal surface, where the block makes contact with a spring of spring constant $k = \frac{mg}{2R}$. All motion of the spring is in the horizontal direction. Point C is the highest point on the loop, and point B is the rightmost point on the loop. Express all algebraic answers in terms of m , h , R , and physical constants, as appropriate.

(a) On the dot below, which represents the block, draw an arrow that represents the direction of the acceleration of the block at point B in the figure above. The arrow must start on and point away from the dot.



Justify your answer.

(b)

- Derive an expression for the speed v of the block at point B.
- Derive an expression for the magnitude of the net force F on the block at point B.

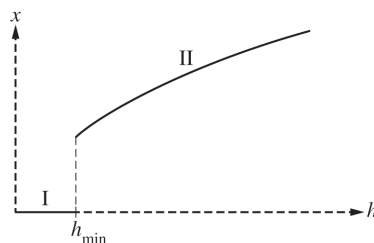
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Use a pencil or pen with black or dark blue ink only. Do NOT write your name. Do NOT write outside the box.

(c) In terms of R , derive an expression for the minimum height $h_{\min}$ necessary for the block to maintain contact with the track through point C.

(d) It is determined that $h = 0.30$ m and $R = 0.10$ m. If the block is released from a height greater than that found in part (c), what would be the maximum compression x_{MAX} of the spring?

(e) A graph of the maximum compression of the spring as a function of height is shown below. The height $h_{\min}$ is the height calculated in part (c).



i. Explain why section I appears as a horizontal line segment on the horizontal axis.

ii. Explain the reason for the shape of section II on the graph.

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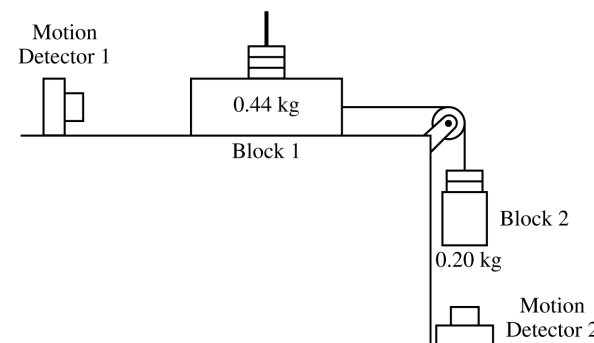
PHYSICS C: MECHANICS

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.



Students design an experiment using blocks of adjustable mass to investigate friction using the setup shown. Block 1 of initial mass 0.44 kg is placed on a rough horizontal surface and connected by a string to block 2 of initial mass 0.20 kg. The string extends over a pulley that has negligible mass and friction.

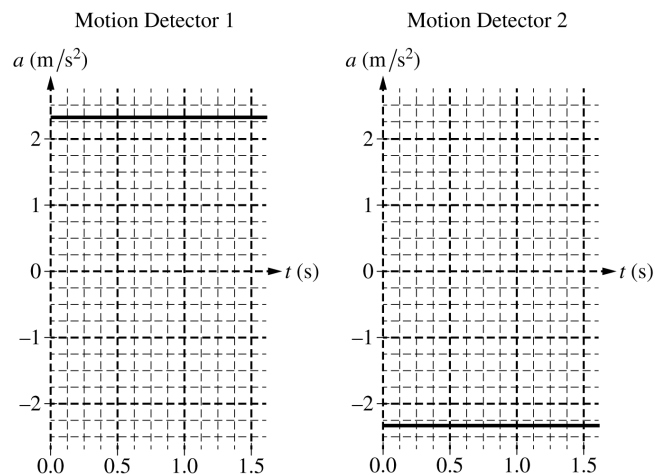
(a) Calculate the minimum value of the coefficient of static friction μ_s that would keep the two-block system at rest.

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

Write your responses to questions 1 through 5 on this page.

The coefficient of friction is such that when block 2 is released from rest, block 1 travels across the surface. The acceleration a of each block is recorded with motion detectors 1 and 2, as shown in the figure. The data for the motion detectors as functions of time t are shown on the graphs. For each motion detector, the positive direction is away from the detector.



(b) On the dots below, which represent the blocks, draw and label the forces (not components) that act on each block. Each force must be represented by a distinct arrow starting on, and pointing away from, the dot.

Block 1



Block 2



(c) Calculate the coefficient of kinetic friction μ_k between block 1 and the table.

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

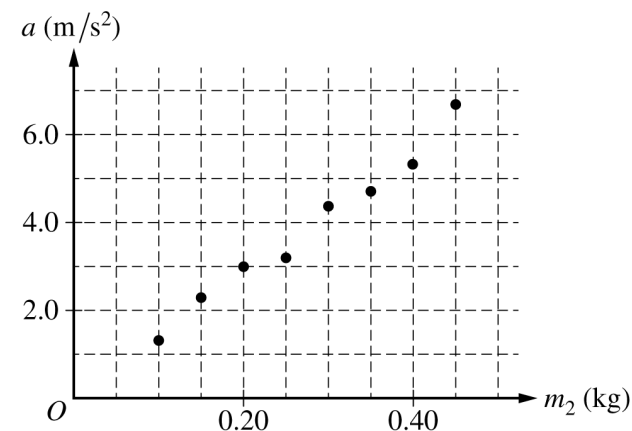
(d) Careful measurements determine that the coefficient of kinetic friction is larger than the value calculated in part (c). Does the following explanation sufficiently account for the observed discrepancy?

“The horizontal table was not perfectly level before the experiment was conducted. The observed difference in the angle accounts for the difference in the expected and calculated values of μ_k .”

☐ Yes ☐ No

Justify your answer.

The experiment is moved to a surface with negligible friction and run for eight trials. In each trial, the students vary the masses m_1 and m_2 of blocks 1 and 2, respectively, while keeping the total mass $(m_1 + m_2) = 0.64$ kg constant. The data for the acceleration a of block 1 as a function of m_2 are shown on the graph below.



(e)

- Draw a best-fit line for the data points.
- Using the straight line, calculate an experimental value for the acceleration due to gravity g .

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

Begin your response to QUESTION 3 on this page.

- (f) The students lift the left end of the surface so that the surface is inclined at an angle to the horizontal, and the experiment for $m_2 = 0.20 \text{ kg}$ is repeated. Would the acceleration of the system be greater than, less than, or equal to the acceleration of the system in the original experiment?

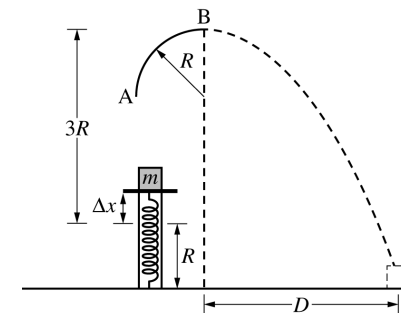
_____ Greater than _____ Less than _____ Equal to

Justify your claim.

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

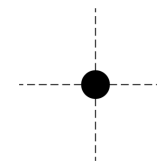
Begin your response to QUESTION 3 on this page.



Note: Figure not drawn to scale.

3. A block of mass m is placed on top of an ideal spring of spring constant k . The block is pushed against the spring, compressing the spring a distance Δx . The block is released from rest, leaves the spring at the position shown in the figure, travels upward, and enters a track with a constant radius of curvature R that has negligible friction. The block enters the track at point A, maintains contact with the track, and exits horizontally at point B, a distance $3R$ above the point the block was released. The block then falls to the ground and lands a horizontal distance D from the end of the track. Express all algebraic answers in terms of m , k , Δx , R , and physical constants, as appropriate. The size of the block is much smaller than the radius of curvature of the track.

- (a) On the dot below, which represents the block, draw and label the forces (not components) that act on the block while still in contact with the track at point B. Each force must be represented by a distinct arrow starting on, and pointing away from, the dot.



Justify your choice of vectors.

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

(b)

- Derive an expression for the speed v of the block at point B.
- Derive an expression for the magnitude of the net force F on the block at point B.

(c) Derive an expression for the minimum value of $\Delta x_{\min}$ required in order for the block to maintain contact with the track through point B.

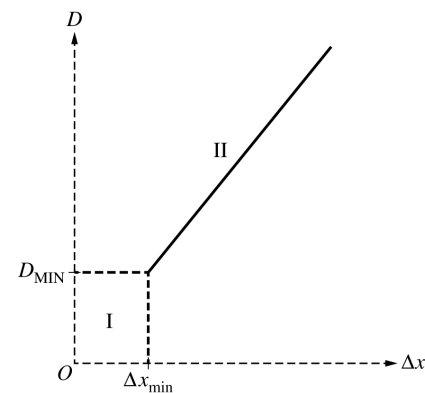
The procedure is repeated several times with the distance $\Delta x > \Delta x_{\min}$.

- Calculate the distance D that the block travels.

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

(e) The graph below shows the best-fit line drawn by the students through their data of D as a function of Δx .



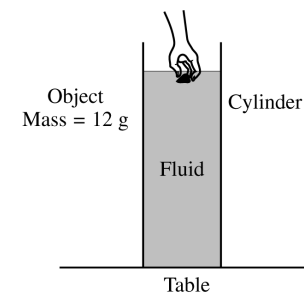
- Explain why there are no data for section I of the graph.
- Explain the reason for the shape and minimum value of section II on the graph.

GO ON TO THE NEXT PAGE.

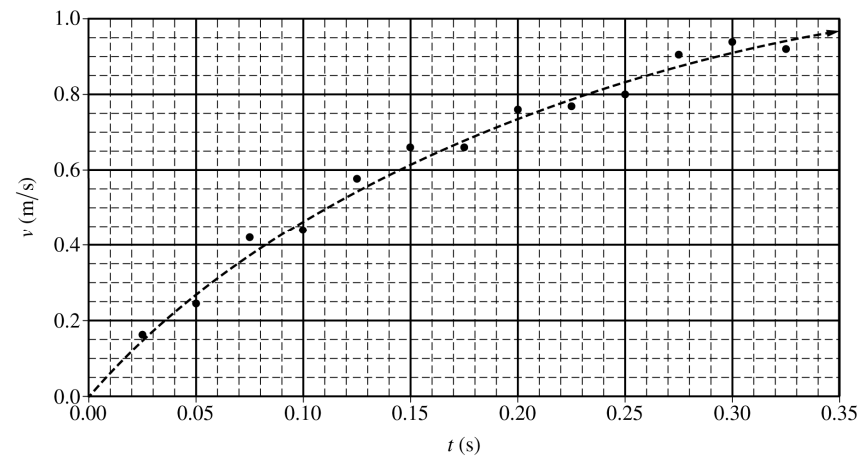
Use a pencil or pen with black or dark blue ink only. Do NOT write your name. Do NOT write outside the box.

STOP**END OF EXAM****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.



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

☐ Increase ☐ Decrease ☐ Remain the same

- ii. In a brief statement, describe the direction of the object's acceleration and how the magnitude of this acceleration changed as the object fell.
- iii. Using the graph, calculate an approximate value for the magnitude of the acceleration of the object at $t = 0.20$ s.

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 $A = 1.18$ m/s and $B = 5$ s⁻¹.

(b) Use the above equation to:

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

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.

(c)

- i. Determine the constant speed of the object.
Justify your answer.
- ii. Determine the force exerted by the fluid on the object at this time.
Justify your answer.

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.

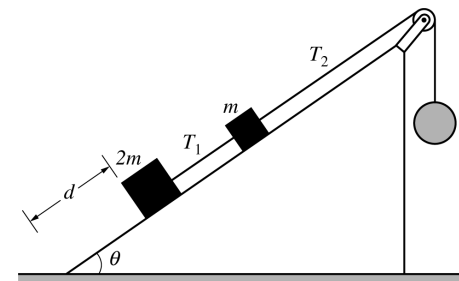
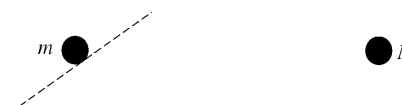


Figure 1

1. Blocks of mass m and $2m$ are connected by a light string and placed on a frictionless inclined plane that makes an angle θ with the horizontal, as shown in Figure 1 above. Another light string connecting the block of mass m to a hanging sphere of mass M passes over a pulley of negligible mass and negligible friction. The entire system is initially at rest and in equilibrium.
- (a) On the dots below that represent the block of mass m and the sphere of mass M , draw and label the forces (not components) that act on each of the objects shown. Each force must be represented by a distinct arrow starting on and pointing away from the dot.



- (b) Derive expressions for the magnitude of each of the following. If you need to draw anything other than what you have shown in part (a) to assist in your solution, use the space below. Do NOT add anything to the figures in part (a).
- The force T_2 exerted on the block of mass m by the string. Express your answers in terms of m , θ , and physical constants, as appropriate.
 - The mass M for which the system can remain in equilibrium. Express your answers in terms of m , θ , and physical constants, as appropriate.
- (c) Now suppose that mass M is large enough to descend and that the sphere reaches the floor before the blocks reach the pulley. Answer the following for the moment immediately after the sphere reaches the floor.
- Does the tension T_1 increase, decrease to a nonzero value, decrease to zero, or stay the same?
____ Increase ____ Decrease to a nonzero value
____ Decrease to zero ____ Stay the same
 - Is the velocity of the block of mass m up the ramp, down the ramp, or zero?
____ Up the ramp ____ Down the ramp ____ Zero
 - Is the acceleration of the block of mass m up the ramp, down the ramp, or zero?
____ Up the ramp ____ Down the ramp ____ Zero
- (d) Consider the initial setup in Figure 1. Now suppose the surface of the incline is rough and the coefficient of static friction between the blocks and the inclined plane is μ_s . Derive an expression for the minimum possible value of M that will keep the blocks from moving down the incline. Express your answer in terms of m , μ_s , θ , and fundamental constants, as appropriate.
- (e) The string connecting block m and the sphere of mass M then breaks, and the blocks begin to move from rest down the incline. The lower block starts a distance d from the bottom of the incline, as shown in Figure 1. The coefficient of kinetic friction between the blocks and the inclined plane is μ_k . Derive an expression for the speed of the blocks when the lower block reaches the bottom of the incline. Express your answer in terms of m , d , μ_k , θ , and fundamental constants, as appropriate.