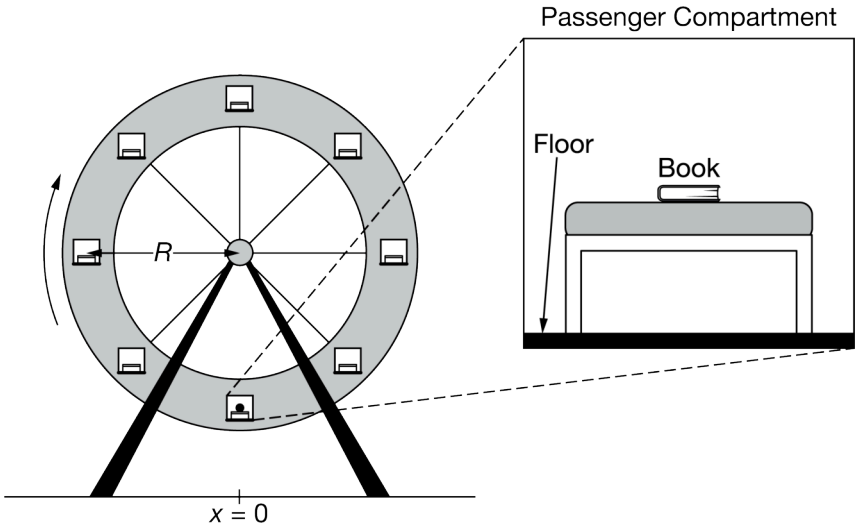
chapter2parta

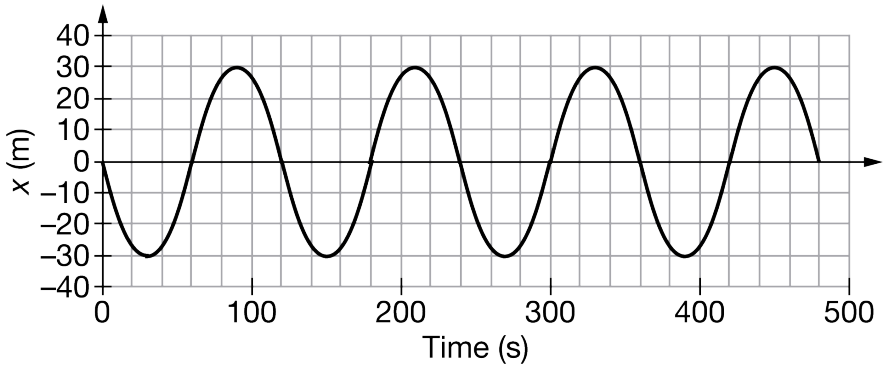
1. This question is a long free-response question. Show your work for each part of the question.

(12 points, suggested time 25 minutes)



A passenger compartment of a rotating amusement park ride contains a bench on which a book of mass m_b is placed, as indicated by the dot in the left figure above. The compartment moves with a constant angular speed about the center of the ride along a circular path of radius R. The bench remains horizontal throughout the compartment's motion. The right figure above shows a magnified view of the compartment.

The graph below shows the horizontal (x) component of the book's position as a function of time, where the $+x$ -direction is to the right.



(a)

i. Determine the period of revolution of the book.

ii. Calculate the tangential speed v_b (not the angular speed) of the book.

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(b)

i. On the dot below, which represents the book, draw and label the forces (not components) that act on the book at the lowest point of its circular path. Each force must be represented by a distinct arrow starting on, and pointing away from, the dot.



ii. At the lowest point of the circular path, the book is moving only in the horizontal direction. In what direction, if any, is the net vertical force on the book?

_____ Up _____ Down _____ No direction, since the net vertical force is equal to zero

Without deriving any equations, briefly explain your reasoning in terms of the book's motion.

(c) Derive an algebraic equation for the vertical force that the bench exerts on the book at the lowest point of the circular path in terms of the book's mass m_b, tangential speed v_b, radius R of the path, and physical constants, as appropriate. Do not substitute any numerical values for variables or physical constants.

(d) At the lowest point of the circular path, is the force that the bench exerts on the book greater than, less than, or equal to the weight of the book?

_____ Greater Than _____ Less Than _____ Equal to

Briefly explain how your answers in (b)ii and (c) support your selection.

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2. A student wants to determine the coefficient of static friction between a long, flat wood board and a small wood block.

a. Describe an experiment for determining the coefficient of static friction between the wood board and the wood block. Assume equipment usually found in a school physics laboratory is available.

i. Draw a diagram of the experimental setup of the board and block. In your diagram, indicate each quantity that would be measured and draw or state what equipment would be used to measure each quantity.

ii. Describe the overall procedure to be used, including any steps necessary to reduce experimental uncertainty. Give enough detail so that another student could replicate the experiment.

b. Derive an equation for the coefficient of static friction in terms of quantities measured in the procedure from part (a).

A physics class consisting of six lab groups wants to test the hypothesis that the coefficient of static friction between the board and the block equals the coefficient of kinetic friction between the board and the block. Each group determines the coefficients of kinetic and static friction between the board and the block. The groups' results are shown below, with the class averages indicated in the bottom row.

Lab Group Number	Coefficient of Kinetic Friction	Coefficient of Static Friction
1	0.45	0.54
2	0.46	0.52
3	0.42	0.56
4	0.43	0.55
5	0.74	0.23
6	0.44	0.54
Average	0.49	0.49

c. Based on these data, what conclusion should the students make about the hypothesis that the coefficients of static and kinetic friction are equal?

_____ The static and kinetic coefficients are equal.

_____ The static and kinetic coefficients are not equal.

Briefly justify your reasoning.

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d. A metal disk is glued to the top of the wood block. The mass of the block-disk system is twice the mass of the original block. Does the coefficient of static friction between the bottom of the block and the board increase, decrease, or remain the same when the disk is added to the block?

_____ Increase _____Decrease _____Remain he same

Briefly state your reasoning

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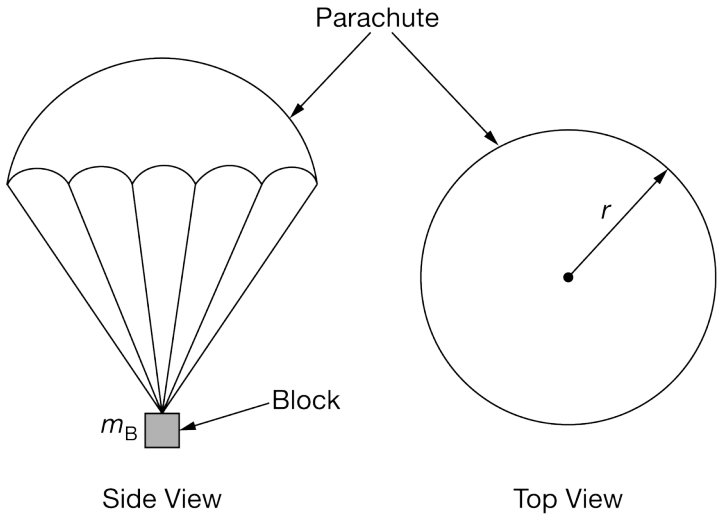
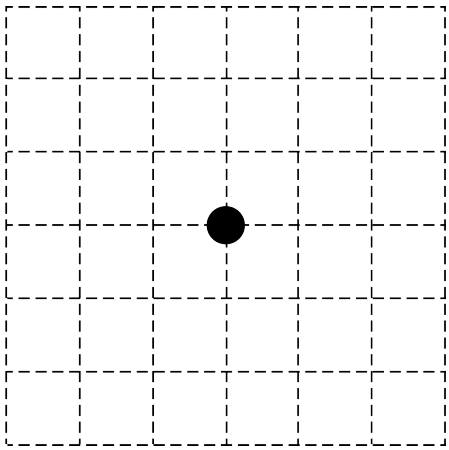
3. This question is a long free-response question. Show your work for each part of the question.



(12 points, suggested time 25 minutes)

A block of mass m_B can be attached to a parachute of negligible mass and radius r, as shown in the two views above. When falling, the parachute experiences an upward force of air resistance. This force increases as the speed of the parachute increases. The falling block and parachute speed up at first but eventually reach a constant speed called terminal speed.

(a) The dot below represents the block-parachute system when it has reached its terminal speed and is falling at this constant speed. On the dot, draw and label the forces (not components) acting on the system. Represent each force by a distinct arrow starting on, and pointing away from, the dot.
Note: Draw the relative lengths of all vectors to reflect the relative magnitudes of all the forces.



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A group of students has a collection of parachutes of different radii. They are curious about how the terminal speed depends on the radius of the parachute and find the following equation on the Internet.

$$F_{\text{air}} = Crv^2,$$

where F_{air} is the force exerted by air, r is the parachute's radius, v is the parachute's speed, and C is a constant that has appropriate units.

(b) Determine the units for C.

The units for C are _____ .

(c)

i. Based on the above equation for F_{air}, derive an equation for the system's constant terminal speed v_t in terms of r, C, physical constants, and other relevant quantities that can be measured with equipment usually found in a school physics laboratory, as appropriate. Assume the mass of the parachute is negligible and that the only nonnegligible forces acting on a block-parachute system are the block's weight $m_B g$ and the force of air resistance F_{air}.

ii. Indicate below what quantities could be measured and then graphed to determine whether the equation derived in part (c)(i) correctly relates the parachute's radius and the terminal speed of the block-parachute system.

Vertical axis: _____ Horizontal axis: _____

iii. On the axes below, sketch a graph showing the relationship between the two quantities indicated in part (c)(ii) and based on the equation derived in part (c)(i).



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(d) Design an experimental procedure the students could use to collect the data needed to test whether or not the relationship between the parachute's radius and the terminal speed is described by the graph drawn in part (c)(iii). Assume equipment usually found in a school physics laboratory is available.

In the table below, list the quantities that would be measured in your experiment. Define a symbol to represent each quantity, and also list the equipment that would be used to measure each quantity. You do not need to fill in every row. If you need additional rows, you may add them to the space just below the table.

Quantity to be Measured	Symbol for Quantity	Equipment for Measurement

Describe the overall procedure to be used, referring to the table. Provide enough detail so another student could replicate the experiment, including any steps necessary to reduce experimental uncertainty. As needed, use the symbols defined in the table. Include a simple diagram of the setup. As part of your description, be sure to explain how the students would know that they are measuring the constant terminal speed.

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Diagram of Experimental Setup Description of Experimental Procedure

(e) In another experiment, the students collect the following data showing the height of a block above the floor at different times, where the block is dropped from rest at time $t = 0$ with the attached parachute fully open.

Time (s)	Height of Block Above Floor (m)
0.00	1.35
0.10	1.30
0.20	1.18
0.30	1.01
0.40	0.82
0.50	0.63
0.60	0.43
0.70	0.23
0.80	0.03

Use the data shown above to determine the terminal speed of the block.

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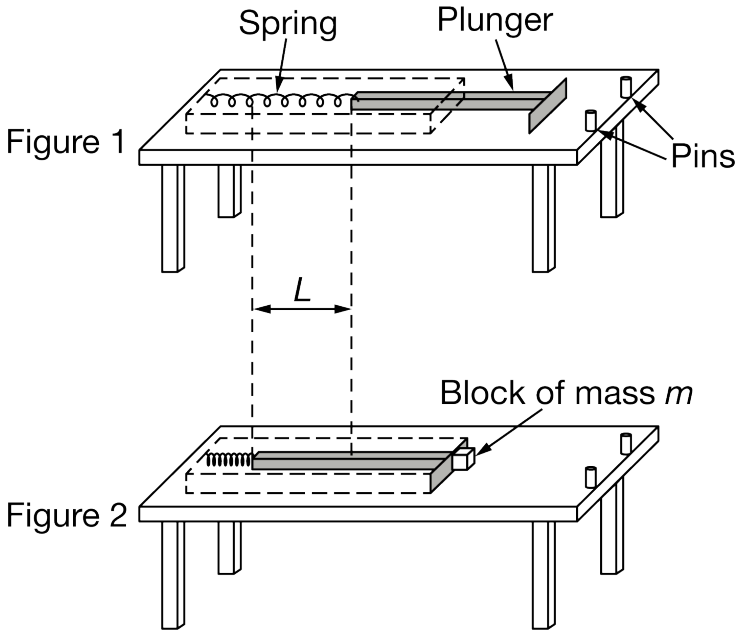
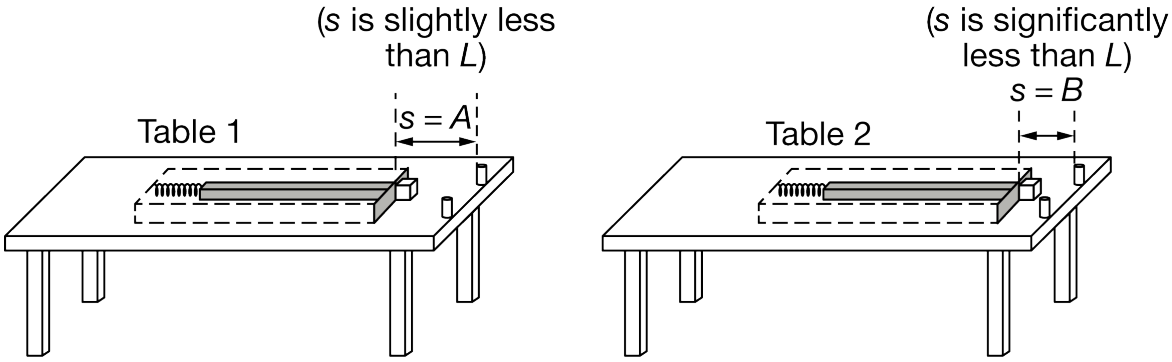
4. This question is a long free-response question. Show your work for each part of the question. (15 points, suggested time 25 minutes)



A spring-loaded launcher can be securely attached to a tabletop. When the spring is at its uncompressed length, the plunger is in the position shown above in Figure 1. A small wood block can be pressed against the end of the plunger, compressing the spring a distance L, as shown in Figure 2. When the block is released, the plunger pushes the block along the tabletop. Two pins are attached to the edge of the table to prevent the plunger from extending beyond the table. When the plunger hits the pins, the block then leaves the table. There is nonnegligible friction between the block and the tabletop.



The launcher can be moved closer to or farther from the edge of the tabletop. Students set up tables 1 and 2, as shown above, with tabletops that are made of the same material. On table 1, the launcher is positioned so that the distance $s = A$ between the launcher and the edge of the tabletop is slightly less than L. On table 2, the launcher is positioned so that the distance $s = B$ between the launcher and the edge of the tabletop is significantly less than L. On both tables, the block is released from rest and loses contact with the plunger at the moment the plunger reaches the pins. Tables 1 and 2 are the same height.

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k is the spring constant of the spring.
m is the mass of the block.
L is the distance the spring is compressed.
μ (mu) is the coefficient of kinetic friction between the block and the tabletop.
s is the distance between the launcher and the edge of the tabletop.

Assume the spring is ideal, the plunger has negligible mass, the block loses contact with the plunger immediately after it reaches the end of the table, and there is non-negligible friction between the tabletops and the blocks.

(a) Without manipulating equations, explain why the block launched from table 1 could land farther from the table than the block launched from table 2 does.

(b) Does the block launched from table 1 spend more, less, or the same amount of time in the air than the block launched from table 2 does? Explain your reasoning.

(c) Consider the Earth-block system. Determine the change, if any, in the total mechanical energy of the system from the instant the block leaves the table to the instant immediately before it reaches the ground.

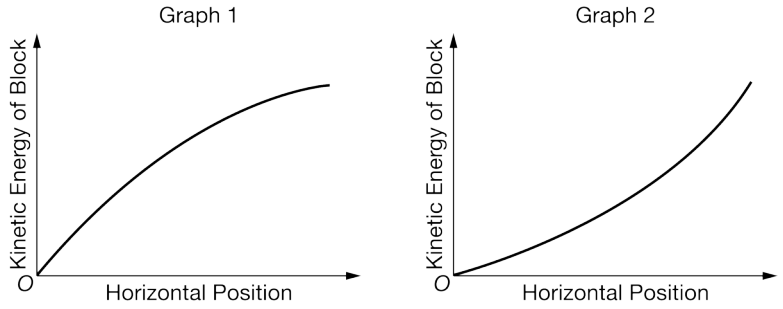
The students correctly derive an equation for the horizontal distance D from the edge of the tabletop that the block lands, in terms of s (the distance between the launcher and the edge of the tabletop):

$$D = t\sqrt{\frac{k}{m}(2Ls - s^2) - 2\mu g s},$$

where t is the time interval between the instant the block leaves the table and the instant immediately before it reaches the ground.

(d) Does this equation for D support your argument from part (a) that the block launched from table 1 could land farther from the table than the block launched from table 2? Briefly explain why or why not.

(e) The students now use the same setups to launch blocks that are identical to each other but more massive than the original blocks. The blocks are made of the same material as the original blocks. Does this change in the mass of the blocks make it more likely or less likely that the block launched from table 1 goes farther than the block launched from table 2 does? Briefly explain your reasoning.



(f) Two students each try to sketch a graph of the kinetic energy of the block as a function of its position from launch to the time the block reaches the edge of the table. Their graphs are shown above. Which graph best represents the kinetic energy of the block? Justify your selection.

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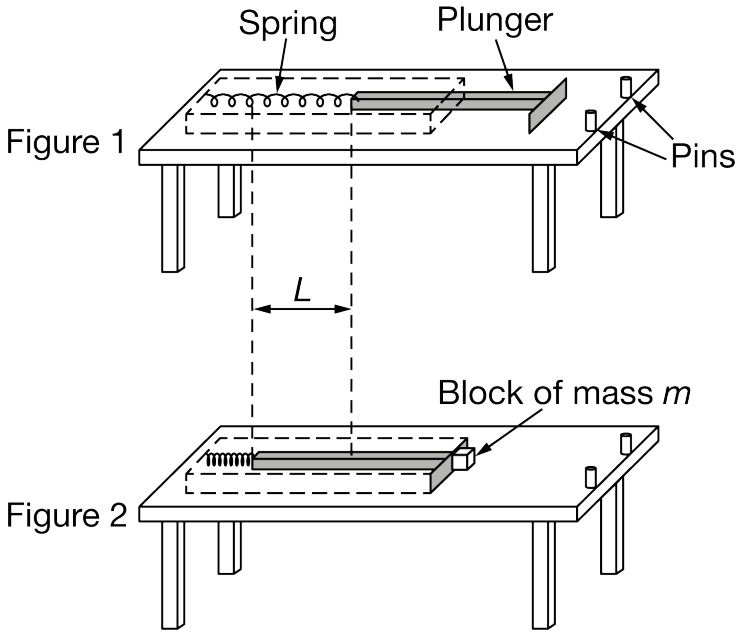
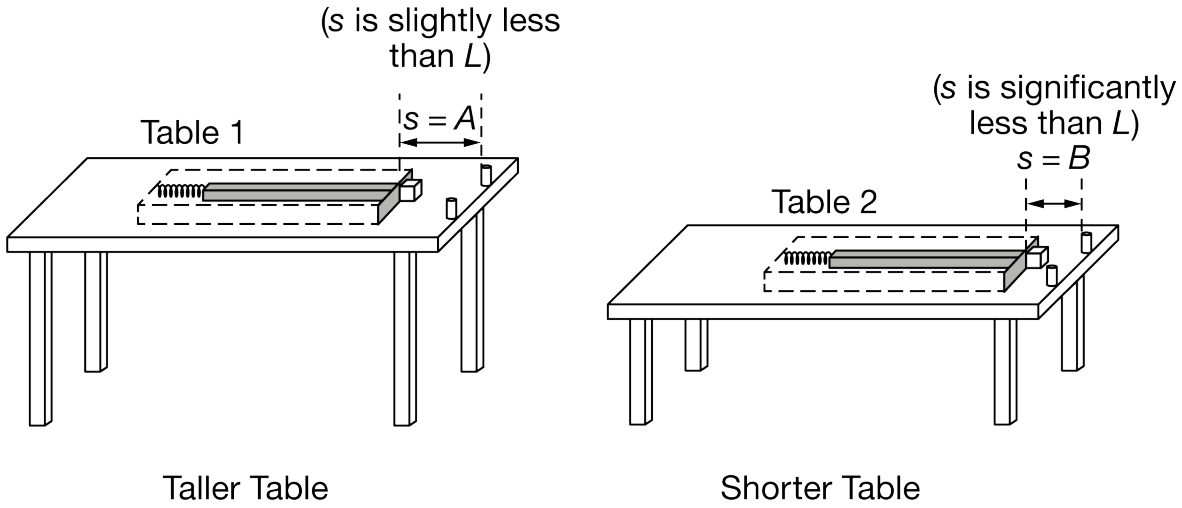
5. This question is a long free-response question. Show your work for each part of the question. (15 points, suggested time 25 minutes)



A spring-loaded launcher can be securely attached to a tabletop. When the spring is at its uncompressed length, the plunger is in the position shown above in Figure 1. A small wood block can be pressed against the end of the plunger, compressing the spring a distance L as shown in Figure 2. When the block is released, the plunger pushes the block along the tabletop. Two pins are attached to the edge of the table to prevent the plunger from extending beyond the table. When the plunger hits the pins, the block then leaves the table. There is nonnegligible friction between the block and the tabletop.



The launcher can be moved closer to or farther from the edge of the tabletop. Students set up tables 1 and 2, as shown above, with tabletops that are made of the same material. On table 1, which is taller than table 2, the

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launcher is positioned so that the distance $s = A$ between the launcher and the edge of the tabletop is slightly less than L. On table 2, the launcher is positioned so that the distance $s = B$ between the launcher and the edge of the tabletop is significantly less than L. On both tables, the block is released from rest and loses contact with the plunger at the moment the plunger reaches the pins.

k is the spring constant of the spring.
m is the mass of the block.
L is the distance the spring is compressed.
μ (mu) is the coefficient of kinetic friction between the block and the tabletop.
s is the distance between the launcher and the edge of the tabletop.

Assume the spring is ideal, the plunger has negligible mass, the block loses contact with the plunger immediately after it reaches the end of the table, and there is non-negligible friction between the tabletops and the blocks.

(a) Without manipulating equations, explain why the block launched from table 2 could have a greater speed when it leaves the table than the block launched from table 1 does.

(b) Does the block launched from table 2 spend more, less, or the same amount of time in the air than the block launched from table 1 does? Explain your reasoning.

(c) Consider the system consisting of only the block. Determine the change, if any, in the total mechanical energy of the system from the instant the block leaves the table to the instant immediately before it reaches the ground.

The students correctly derive an equation for the speed v of the block when it is at the edge of the tabletop, in terms of s (the distance between the launcher and the edge of the tabletop):

$v = \sqrt{\frac{k}{m}(2Ls - s^2) - 2\mu g s}$.

(d) Does this equation for v support your argument from part (a) that the block launched from table 2 could have a larger speed when it leaves the table than the block on table 1 does? Briefly explain why or why not.

(e) The students now repeat the scenario with identical setups except that the coefficient of kinetic friction between the blocks and the table is larger. Does this change in the coefficient of friction make it more likely or less likely that the block launched from table 1 has a greater speed when it leaves the table than the block on table 2 does? Briefly explain your reasoning.

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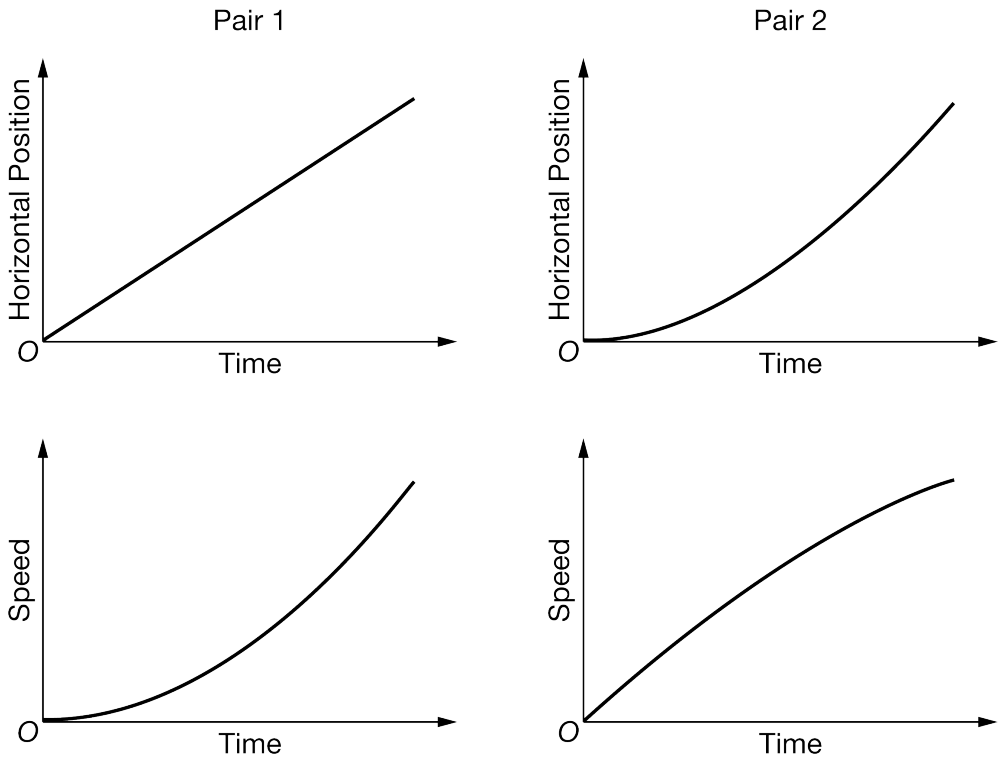

(f) Two students each try to sketch a graph of the horizontal position and speed of the block as a function of time while the block is being pushed by the plunger. Their graphs are shown above. In which pair of graphs are the two graphs consistent with each other? Justify your selection.

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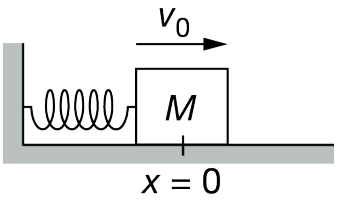
6. This question is a long free-response question. Show your work for each part of the question.

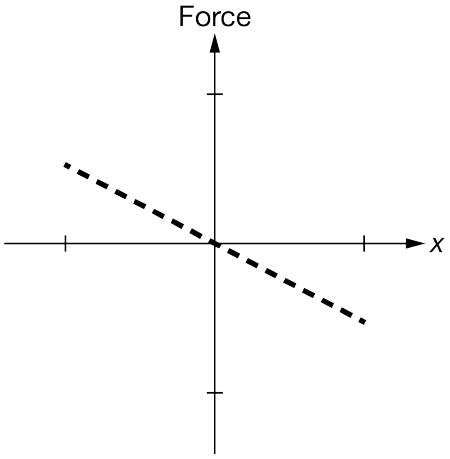


A block of mass M is attached to a spring of negligible mass and can slide on a horizontal surface along the x -direction, as shown above. There is friction present between the block and the surface. The spring exerts no force on the block when the center of the block is located at $x = 0$. At the instant shown above, the block is located at $x = 0$ and moving toward the right with speed $v = v_0$.

(a) For the instant shown above, with the block located at $x = 0$ and moving to the right, predict the direction of the net force on the block. If the net force is zero, select "The net force is zero."

____ To the left ____ The net force is zero ____ To the right

Briefly justify your prediction.



(b) The above graph indicates the force exerted on the block by the spring as a function of position x, with the positive direction toward the right. On the same graph, draw a graph of the net force on the block, as a function of position x, for situations where the block is moving toward the right.

(c) Is the graph you drew in part (b) consistent with your prediction in part (a) ?

____ Yes ____ No

Provide claims for why the answers to parts (a) and (b) are or are not consistent.

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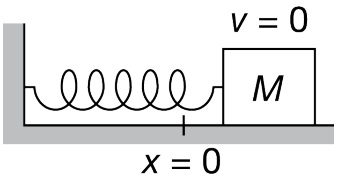

(d) In the figure above, the block of mass M has come to rest at a location to the right of the spring's equilibrium position. The spring has a spring constant k, and the coefficients of kinetic and static friction between the block and the surface are μ_k and μ_s, respectively.

i. On the dot below, which represents the block at rest and to the right of $x = 0$, draw and label the forces (not components) that act on the block. Each force must be represented by a distinct arrow starting on, and pointing away from, the dot.



ii. Derive an expression for the maximum displacement possible for the block that will allow the block to still remain at rest. Express your answer in terms of M, k, μ_k, μ_s, and physical constants, as appropriate.

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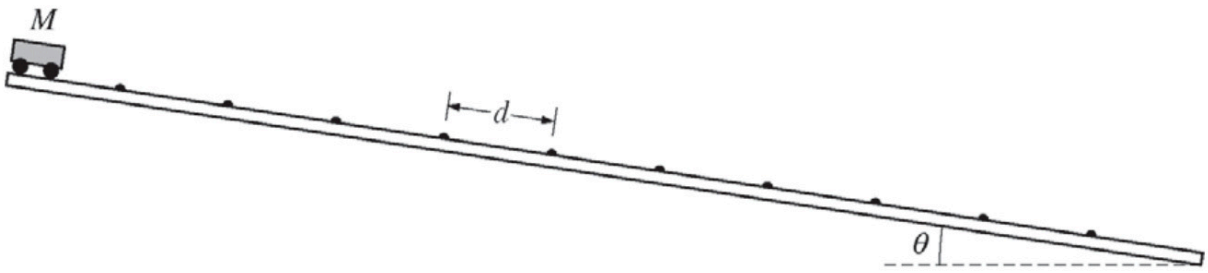
7.



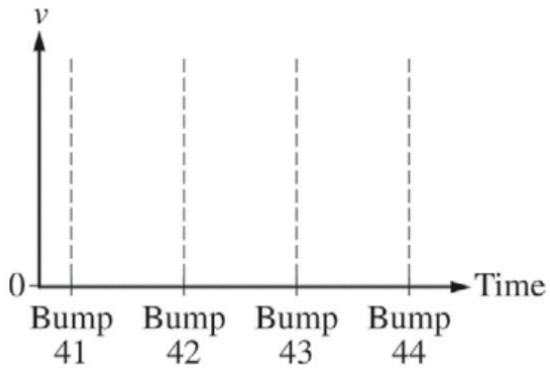
Note: Figure not drawn to scale.

A long track, inclined at an angle θ to the horizontal, has small speed bumps on it. The bumps are evenly spaced a distance d apart, as shown in the figure above. The track is actually much longer than shown, with over 100 bumps. A cart of mass M is released from rest at the top of the track. A student notices that after reaching the 40th bump the cart's average speed between successive bumps no longer increases, reaching a maximum value v_{avg}. This means the time interval taken to move from one bump to the next bump becomes constant.

a. Consider the cart's motion between bump 41 and bump 44.

   i. In the figure below, sketch a graph of the cart's velocity v as a function of time from the moment it reaches bump 41 until the moment it reaches bump 44.

   ii. Over the same time interval, draw a dashed horizontal line at $v = v_{avg}$. Label the line"v_{avg}"



b. Suppose the distance between the bumps is increased but everything else stays the same. Is the maximum speed of the cart now greater than, less than, or the same as it was with the bumps closer together?

   ____Greater than ____Less than ____The same as

   Briefly explain your reasoning.

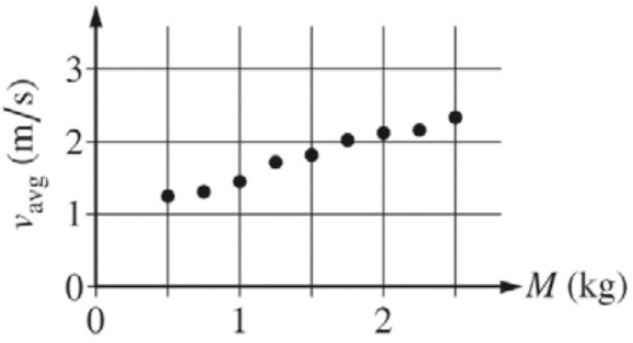
c. With the bumps returned to the original spacing, the track is tilted to a greater ramp angle θ. Is the maximum speed of the cart greater than, less than, or the same as it was when the ramp angle was smaller?

____Greater than ____Less than ____The same as

Briefly explain your reasoning.

d. Before deriving an equation for a quantity such as v_{avg} , it can be useful to come up with an equation that is intuitively expected to be true. That way, the derivation can be checked later to see if it makes sense physically. A student comes up with the following equation for the cart's maximum average speed: $v_{avg} = C\frac{Mg\sin\theta}{d}$, where C is a positive constant.

i. To test the equation, the student rolls a cart down the long track with speed bumps many times in front of a motion detector. The student varies the mass M of the cart with each trial but keeps everything else the same. The graph shown below is the student's plot of the data for v_{avg} as a function of M.



Are these data consistent with the student's equation?

____Yes ____No

Briefly explain your reasoning.

ii. Another student suggests that whether or not the data above are consistent with the equation, the equation could be incorrect for other reasons. Does the equation make physical sense?

____Yes ____No

Briefly explain your reasoning.

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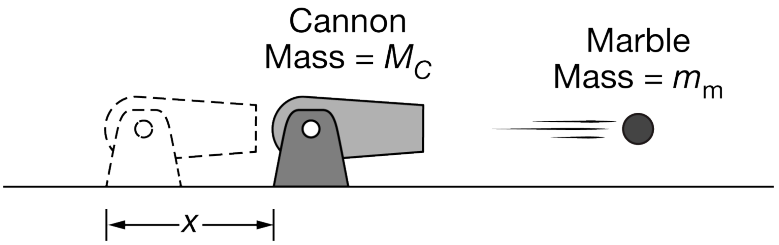
8. This question is a long free-response question. Show your work for each part of the question. (15 points, suggested time 25 minutes)



Note: Figure not drawn to scale.

Students launch marbles of mass m_{m} horizontally from a toy cannon of mass M_C, where M_C is always greater than m_{m}, as shown above. Each time a marble is launched, the cannon slides backward before coming to rest. The coefficient of kinetic friction between the cannon and the ground is μ (mu). For each launch, the students use a new marble with a different mass launched at the same speed v relative to the ground. The students record the distance x the cannon slides backward for each launch.

(a) Without manipulating equations, briefly describe what happens to the distance x that the cannon slides backward as students increase the mass of the marble. Explain your reasoning.

(b) Students find the following equation on the Internet to describe the distance x that the cannon slides backward: $x = \frac{m_{\mathrm{m}}^2 v^2}{2g\mu M_C^2}$. Whether or not the equation is correct, is it consistent with your prediction in part (a)? Briefly justify your answer.

(c) Without manipulating or stating equations, briefly describe whether it would take more work to stop the marble or to stop the cannon after the marble has been launched. Justify your answer.

(d) Students correctly derive the following equation relating the work W done on an object initially at rest, the momentum p of the object, and the mass m of the object: $W = \frac{p^2}{2m}$. Is this equation consistent with your description in part (c)? Justify your answer.

Students then discuss the mechanical energy of the marble-cannon system during the short time interval in which the marble is accelerated inside the cannon and make the following claims:

Student 1: The cannon is pushing the marble forward, and the marble is pushing back with equal and opposite force. Since the work done by the cannon cancels out the work done by the marble, the mechanical energy of the system is constant.

Student 2: The mechanical energy of the system increases while the marble is being accelerated. The marble gains kinetic energy to the right, and the cannon gains an equal amount of kinetic energy to the left.

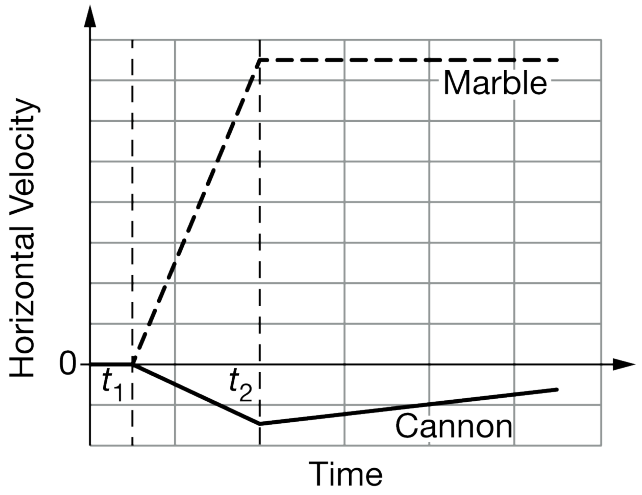
(e) Which underlined phrase or phrases in student 1's statement are ***correct***, if either? If neither phrase is ***correct***, write "none."

(f) Which underlined phrase or phrases in student 1's statement are ***incorrect***, if either? If neither phrase is

incorrect, write "none."

(g) Which underlined phrase or phrases in student 2's statement are ***correct***, if either? If neither phrase is ***correct***, write "none."

(h) Which underlined phrase or phrases in student 2's statement are ***incorrect***, if either? If neither phrase is ***incorrect***, write "none."



The graph above shows the horizontal component of the velocity of the marble (dashed line) and the cannon (solid line) relative to the ground. Before time t_1 the marble-cannon system is at rest. At time t_1 the marble begins accelerating within the cannon, and at time t_2 the marble leaves the cannon.

(i) Provide three pieces of evidence that together explain why the magnitude of the rate of change of the cannon's velocity is less than the magnitude of the rate of change of the marble's velocity during the time interval from t_1 to t_2.

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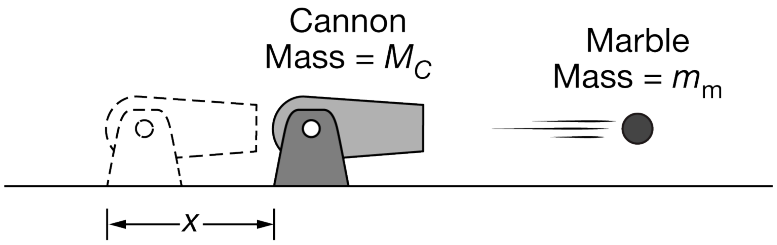
9. This question is a long free-response question. Show your work for each part of the question. (15 points, suggested time 25 minutes)



Note: Figure not drawn to scale.

Students launch identical marbles of mass m_m horizontally from a toy cannon of varying mass M_C, where M_C is always greater than m_m, as shown above. The students can attach weights to the cannon to change M_C. Each time a marble is launched, the cannon slides backward before coming to rest. The coefficient of kinetic friction between the cannon and the ground is μ (mu). For each launch, the students vary the mass of the cannon and launch a marble with the same speed v relative to the ground. The students record the distance x that the cannon slides backward.

(a) Without manipulating equations, explain how the distance x that the cannon slides backward changes, if at all, when marbles are launched from more massive cannons.

(b) Students find the following equation on the Internet to describe the distance x that the cannon slides backward: $x = \frac{m_m^2 v^2}{2g\mu M_C^2}$. Whether or not the equation is correct, is it consistent with your prediction in part (a)? Briefly justify your answer.

(c) If constant horizontal forces were exerted over the same distance on the cannon and on the marble after the launch, which object would require a force with a greater magnitude to completely stop it? Without manipulating or referencing equations, briefly explain your reasoning.

(d) Students correctly derive the following equation relating the force F exerted on an object initially at rest over a distance d, the mass m of the object, and the final momentum p of the object: $F = \frac{p^2}{2md}$. Is this equation consistent with your description in part (c)? Justify your answer.

Students then discuss the mechanical energy of the marble after it has been launched by the cannon but before it reaches the ground. Both students agree that air resistance is negligible and make the following claims.

Student 1: The mechanical energy of the marble is constant. There are no external forces exerted on the marble, so its energy does not change.

Student 2: The mechanical energy decreases as the marble falls. This happens because the gravitational force is doing work on the marble.

(e) Which underlined phrase or phrases in student 1's statement are ***correct***, if either? If neither phrase is ***correct***, write "none."

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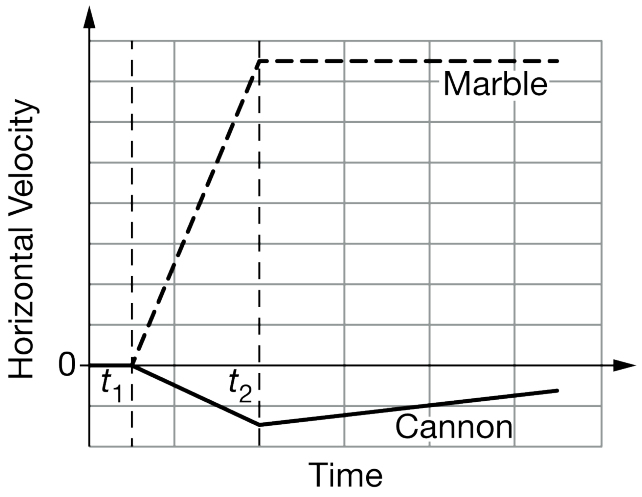
(f) Which underlined phrase or phrases in student 1's statement are ***incorrect***, if either? If neither phrase is ***incorrect***, write "none."

(g) Which underlined phrase or phrases in student 2's statement are ***correct***, if either? If neither phrase is ***correct***, write "none."

(h) Which underlined phrase or phrases in student 2's statement are ***incorrect***, if either? If neither phrase is ***incorrect***, write "none."



The graph above shows the horizontal component of the velocity of the marble (dashed line) and the cannon (solid line) relative to the ground. Before time t_1 the marble-cannon system is at rest. At time t_1 the marble begins accelerating within the cannon, and at time t_2 the marble leaves the cannon.

(i) Describe the motion of the center of mass of the marble-cannon system during the time interval from t_1 to t_2. Explain your reasoning.

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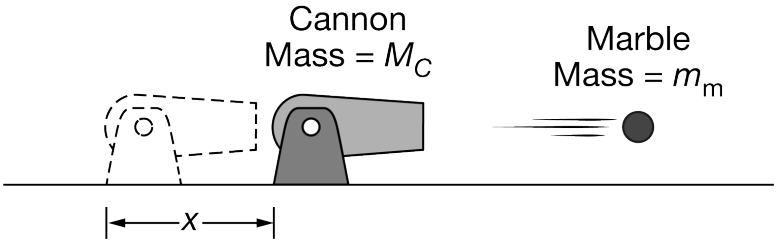
10. This question is a long free-response question. Show your work for each part of the question. (15 points, suggested time 25 minutes)



Note: Figure not drawn to scale.

Students launch identical marbles of mass m_m horizontally from a toy cannon of mass M_C, where $M_C > m_m$, as shown above. The cannon can be adjusted to change the launch speed v of the marble relative to the ground. Each time a marble is launched, the cannon slides backward before coming to rest. The coefficient of kinetic friction between the cannon and the ground is μ (mu). For each launch, the students vary the launch speed v and record the distance x the cannon slides backward for each launch speed.

(a) Without manipulating equations, briefly describe what happens to the distance x that the cannon slides backward as students increase the launch speed. Explain your reasoning.

(b) Students find the following equation on the Internet to describe the distance x that the cannon slides backward: $x = \frac{m_m^2 v^2}{2g\mu M_C^2}$. Whether or not the equation is correct, is it consistent with your prediction in part (a)? Briefly justify your answer.

(c) Without manipulating or stating equations, briefly describe whether the cannon or the marble has more kinetic energy immediately after the marble leaves the cannon. Justify your answer.

(d) Students correctly derive an equation relating the kinetic energy K, the momentum p, and the mass m of an object: $K = \frac{p^2}{2m}$. Is this equation consistent with your description in part (c)? Justify your answer.

Students then discuss the mechanical energy of the marble after it has been launched by the cannon but before it reaches the ground. Both students agree that air resistance is negligible and make the following claims.

Student 1: There are two external forces exerted on the marble while it is in the air, the gravitational force and the force exerted by the cannon. Therefore, the mechanical energy of the marble changes while it is in the air.

Student 2: The cannon does not exert a force on the marble after the launch. Therefore, the mechanical energy of the marble is constant.

(e) Which underlined phrase or phrases in student 1's statement are ***correct***, if either? If neither phrase is ***correct***, write "none."

(f) Which underlined phrase or phrases in student 1's statement are ***incorrect***, if either? If neither phrase is ***incorrect***, write "none."

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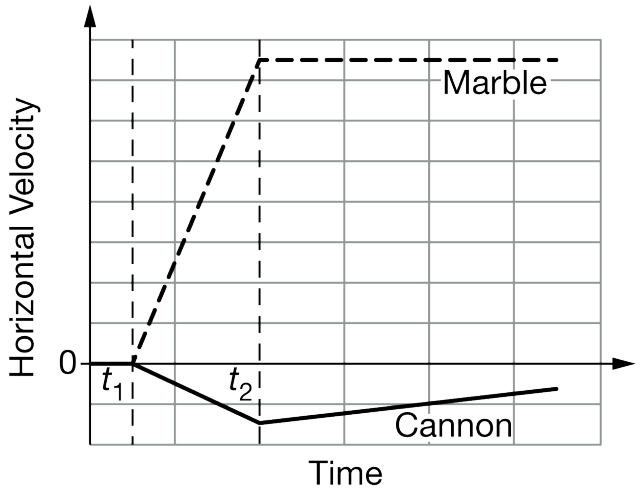
(g) Which underlined phrase or phrases in student 2's statement are ***correct***, if either? If neither phrase is ***correct***, write "none."

(h) Which underlined phrase or phrases in student 2's statement are ***incorrect***, if either? If neither phrase is ***incorrect***, write "none."



The graph above shows the horizontal component of the velocity for the marble (dashed line) and the cannon (solid line) relative to the ground. Before time t_1 the marble-cannon system is at rest. At time t_1 the marble begins accelerating within the cannon, and at time t_2 the marble leaves the cannon.

(i) Describe how to find the change in the distance between the center of mass of the cannon and the center of mass of the marble from time t_1 to time t_2. Assume that before time t_1 the center of mass of the marble is at the same position as the center of mass of the cannon.

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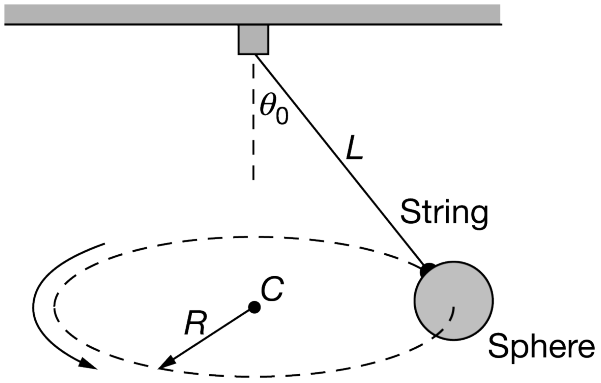
11. This question is a long free-response question. Show your work for each part of the question.



(12 points, suggested time 25 minutes)

A small sphere of mass M is suspended by a string of length L. The sphere is made to move in a horizontal circle of radius R at a constant speed, as shown above. The center of the circle is labeled point C, and the string makes an θ_0 with the vertical.

(a) Two students are discussing the motion of the sphere and make the following statements.

Student 1: None of the forces exerted on the sphere are in the direction of point C, the center of the circular path. Therefore, I don't see how there can be a centripetal force exerted on the sphere to make it move in a circle.

Student 2: I see another problem. The tension force exerted by the string is at an angle from the vertical. Therefore, its vertical component must be less than the weight Mg of the sphere. That means the net force on the sphere has a downward vertical component, and the sphere should move downward as well as moving around in a circle.

i. What is one aspect of Student 1's reasoning that is incorrect?

ii. What is one aspect of Student 2's reasoning that is incorrect?

(b)

i. Derive an equation for the magnitude of the net force exerted on the sphere. Express your answer in terms of M, θ_0, and physical constants, as appropriate.

ii. Describe one aspect or step in your derivation of part (b)(i) that can be correctly linked to your answer to either part (a)(i) or part (a)(ii).

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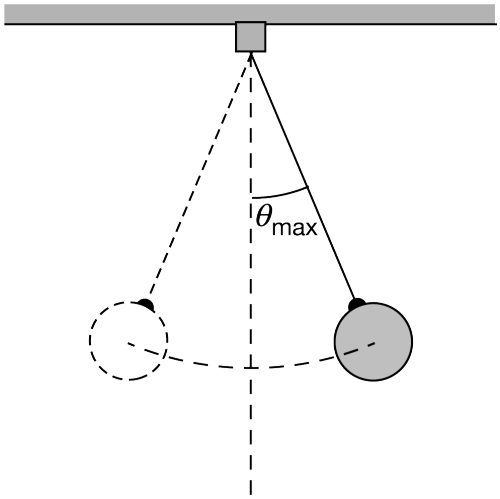
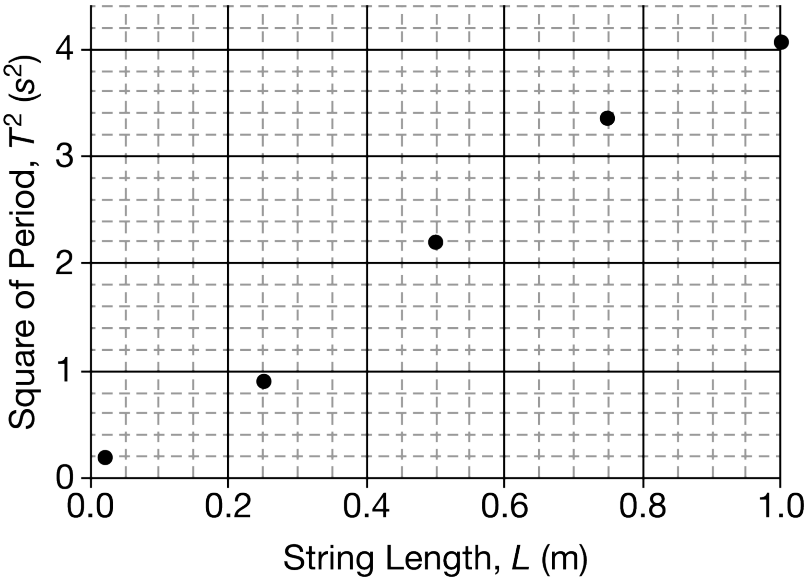


Instead of moving in a horizontal circle, the sphere now moves in a vertical plane so that it is a simple pendulum, as shown above. The maximum angle θ_{max} that the string makes from the vertical can be assumed to be small. The graph below shows data for the square of the pendulum period T as a function of string length L.



(c) On the graph above, draw a best-fit line for the data. Then use the line to calculate a numerical value for the gravitational acceleration g.

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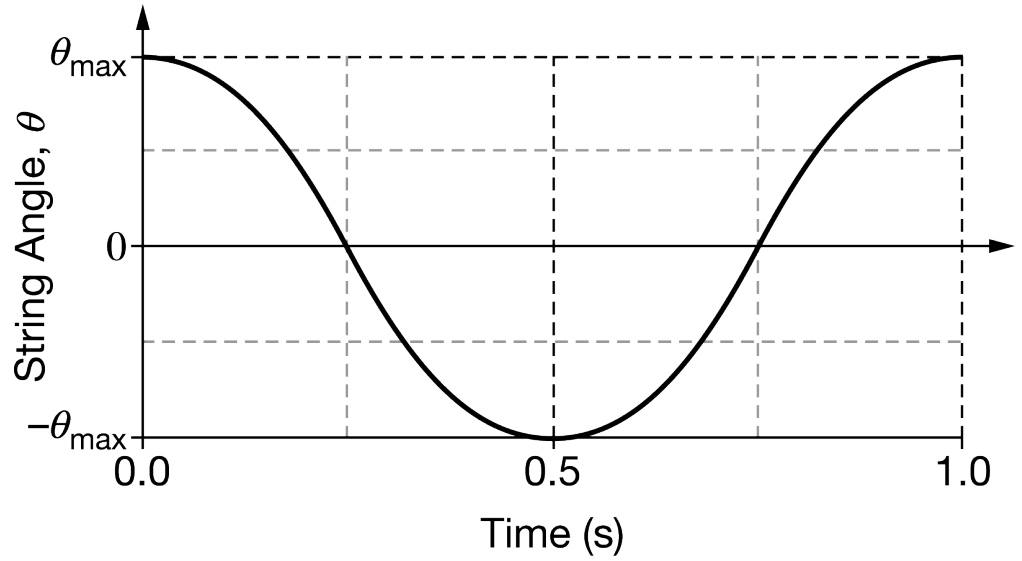
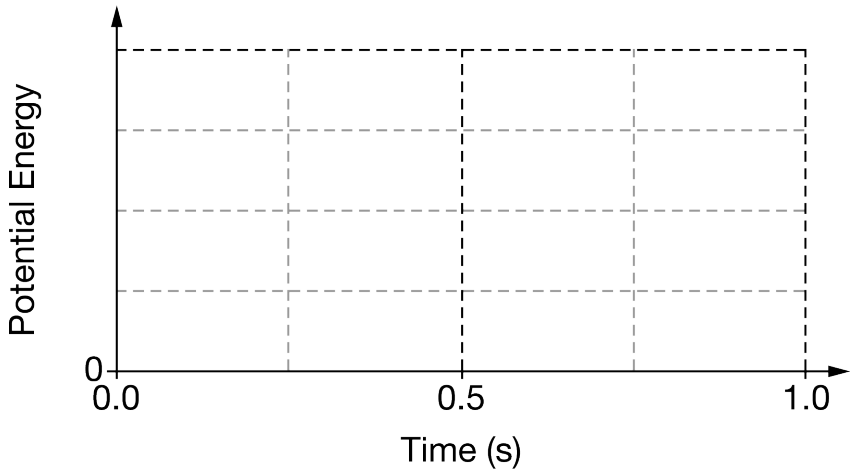


(d) The graph above shows the angle θ from the vertical as a function of time for the pendulum. On the axes below, sketch a graph of the gravitational potential energy of the sphere-Earth system for the same time interval. Take the zero of potential energy to be when the potential energy has its minimum value.



(e) As the sphere swings back and forth, it must also rotate a small amount during each swing. The figures below indicate the direction that the sphere rotates as it is swinging in each direction.

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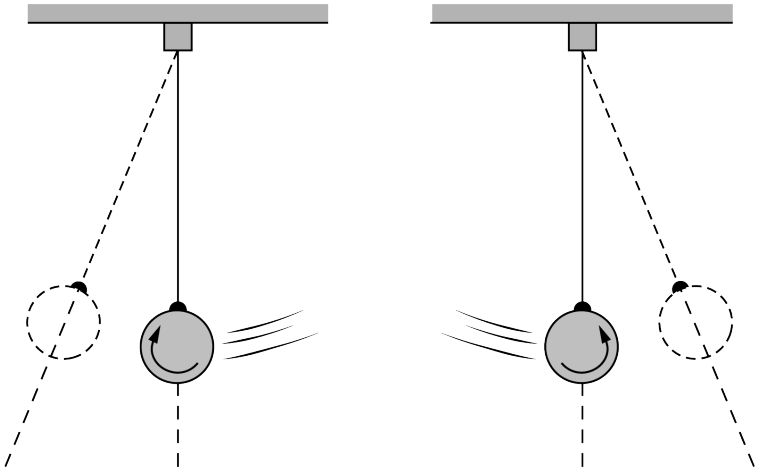

In order for the sphere's rotation to change direction, a torque must be exerted on the sphere. When the sphere is at its maximum rightward displacement, what is the direction of the torque exerted on the sphere with respect to the point of attachment between the sphere and string?

_____ Clockwise _____ Counterclockwise

Briefly state why the torque is in the direction you indicated.

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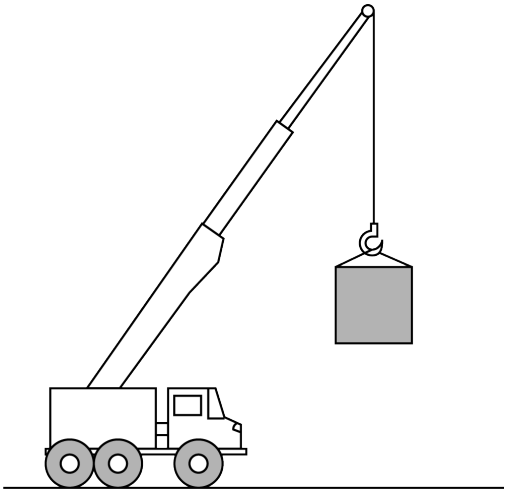
12. This question is a long free-response question. Show your work for each part of the question.

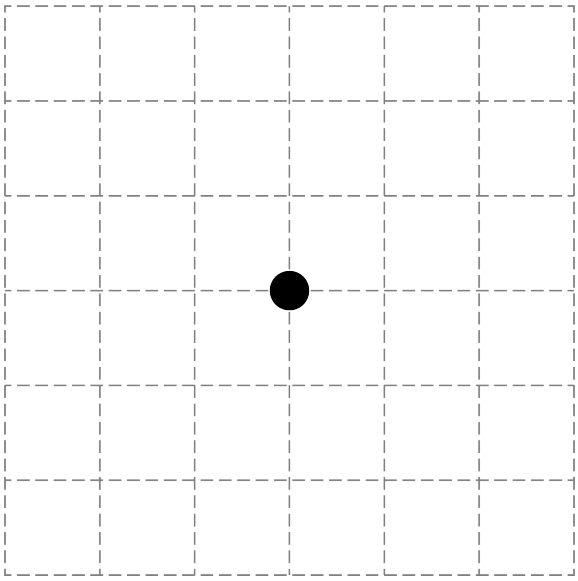


(12 points, suggested time 25 minutes)

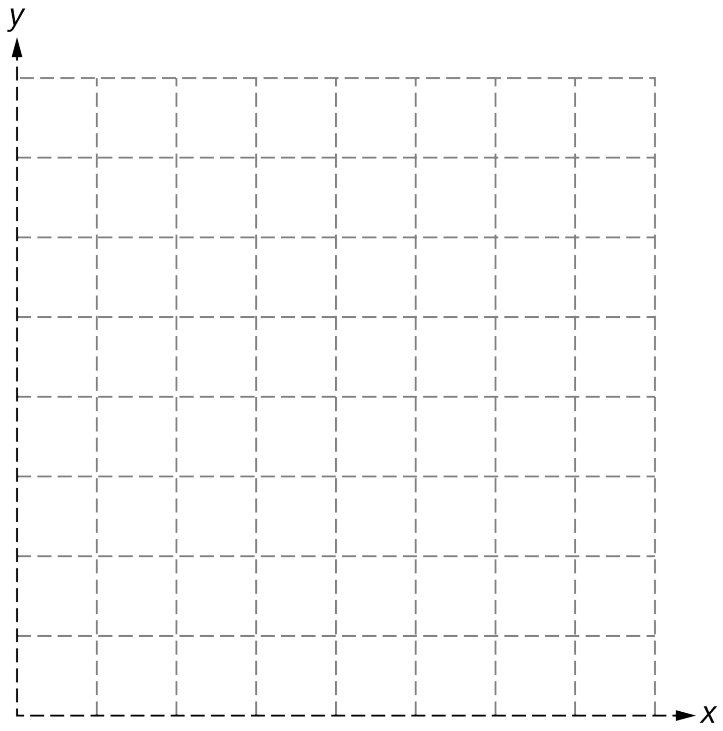
A crane and box are both initially at rest. At time $t = 0\ \text{s}$, the crane begins to drive forward at a constant speed of $0.5\ \frac{\text{m}}{\text{s}}$, while also lifting the box with an upward acceleration of $1\ \frac{\text{m}}{\text{s}^2}$. The box does not swing while being lifted by the crane.

(a) On the dot below, which represents the box, draw and label the forces (not components) that are exerted on the box during the scenario described above. Represent each force by a distinct arrow starting on, and pointing away from, the dot.

Note: Draw the relative lengths of all vectors to reflect the relative magnitudes of all the forces.



(b) On the grid below, sketch the shape of the path taken by the box as it is lifted by the crane as viewed by a stationary observer.



Justify the shape of the path you drew above.

(c) Assume that, at $t = 0$ s, the horizontal position of the box is $x = 0$ and it has a vertical position of $y = 0$. Derive an equation that describes the vertical position y of the box as a function of the horizontal position x of the box.

(d) Does your equation from part (c) agree with your sketch in part (b)? Justify your response.

At time $t = t_1$, the crane begins to accelerate forward, reaching a new constant velocity at time $t = t_2$. The box accelerates upward during the entire time interval $t_1 < t < t_2$.

(e) The dot below represents the box during the time interval $t_1 < t < t_2$. On the dot, draw an arrow indicating the direction of the net force exerted on the block during this interval. The arrow should start on, and point away from, the dot.

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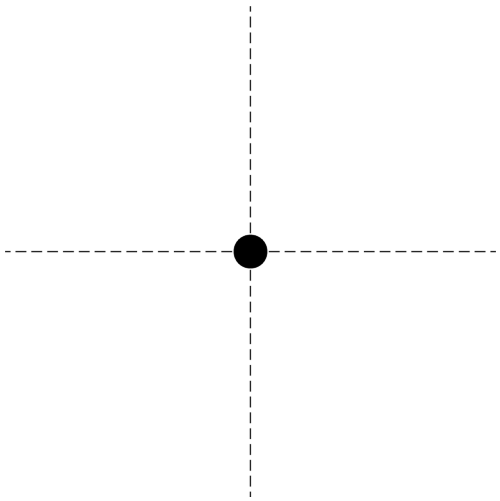

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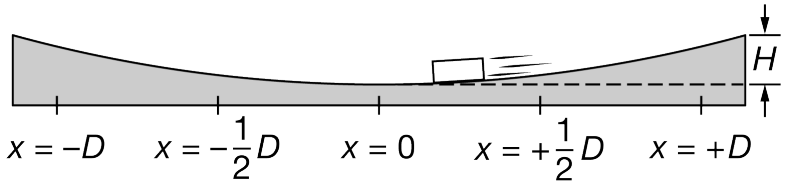
13. This question is a long free-response question. Show your work for each part of the question. (15 points, suggested time 25 minutes)

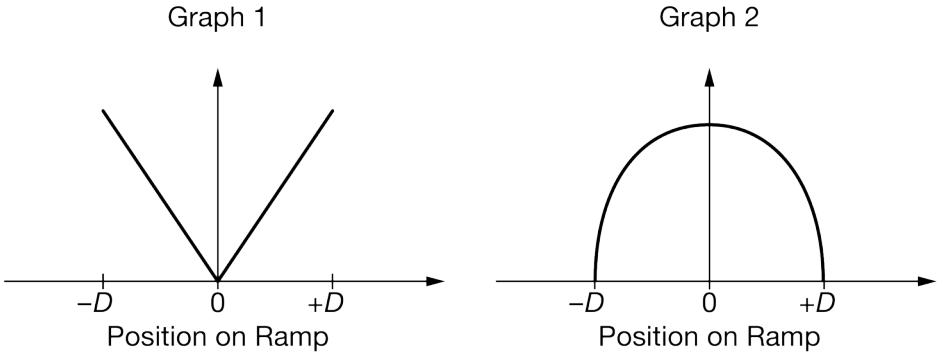


Track 1

Note: Figure not drawn to scale.

A block slides back and forth without any appreciable loss of energy on a track with a slight circular curvature, as shown above. The maximum height H of the track at each end is much smaller than D.

The center of mass of the block oscillates between $x = -D$ and $x = +D$. The curve is so gradual that the total distance traveled along the curved portion of the track by the center of mass of the block can be considered to be $2D$. The block undergoes two full oscillations in 8.0 seconds.



(a) Which of the graphs above, Graph 1 or Graph 2, could represent the magnitude of the horizontal component of the block's acceleration as a function of its position on the ramp, and which graph could represent the magnitude of the block's momentum as a function of its position on the ramp? Justify both your choices with physics principles.

(b) For the system consisting of only the block, describe how the mechanical energy of the system changes, if at all, as the block moves from $x = 0$ to $x = -D$. Justify your answer.

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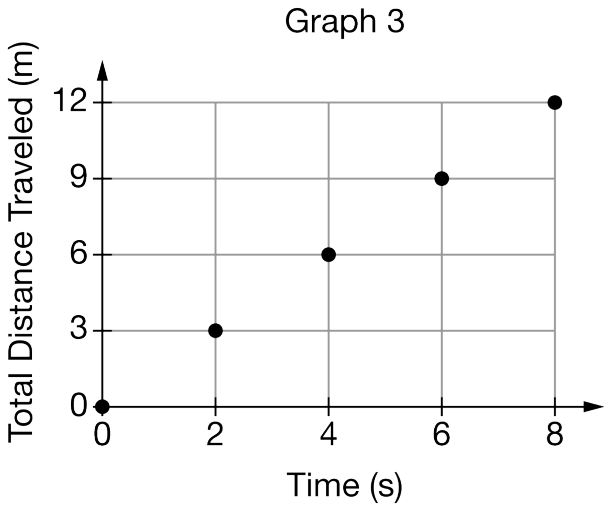
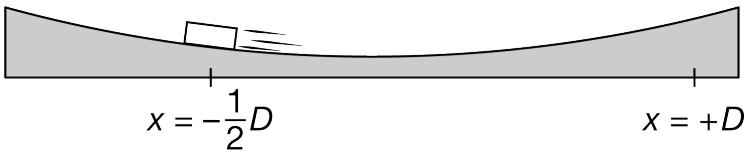


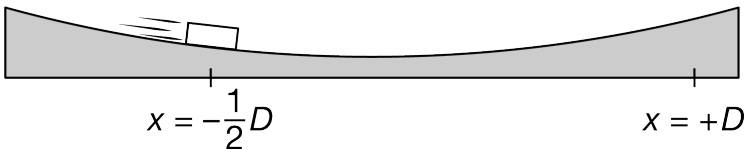
(c) Graph 3 above shows the total horizontal distance traveled by the block as a function of time as it completes two oscillations. Using the graph, determine the distance D between the midpoint of the ramp and the maximum position of the block on the ramp. Explain how you arrived at your answer.

(d) Suppose the entire setup was moved to the Moon, where the gravitational field strength is less than that on Earth. The center of mass of the block again oscillates between $x = -D$ and $x = +D$. Would the period of the block's oscillation on the Moon be greater than, less than, or equal to the period of oscillation on Earth? Justify your answer.

(e) A student derives the following equation for the period T of the block's oscillation: $T = 2\pi\sqrt{\frac{D^2}{2Hg}}$. Whether or not this equation is correct, is the equation consistent with your answer to part (d)?



Block on Track 2 at Time $t = T_1$



Block on Track 2 at Time $t = T_2$

Note: Figures not drawn to scale.

(f) Track 2 is identical to Track 1 except there is nonnegligible friction between the block and Track 2. The block

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is released from rest on Track 2 at position $x = +D$. At time $t = T_1$, the block moves to the left, passing through position $x = -\frac{1}{2}D$, as shown above. After the block reverses direction near $x = -D$, the block moves to the right, passing through position $x = -\frac{1}{2}D$ at time $t = T_2$. At which time, T_1 or T_2, if either, is the magnitude of the tangential acceleration of the block greater? Justify your answer.

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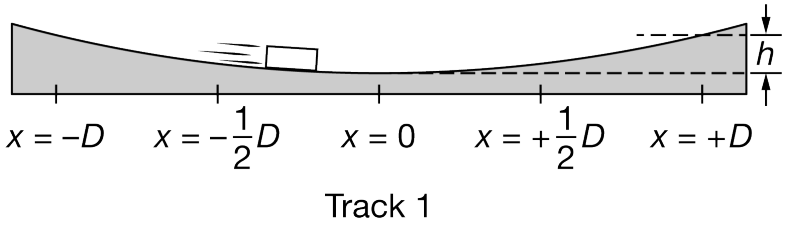
14. This question is a long free-response question. Show your work for each part of the question. (15 points, suggested time 25 minutes)

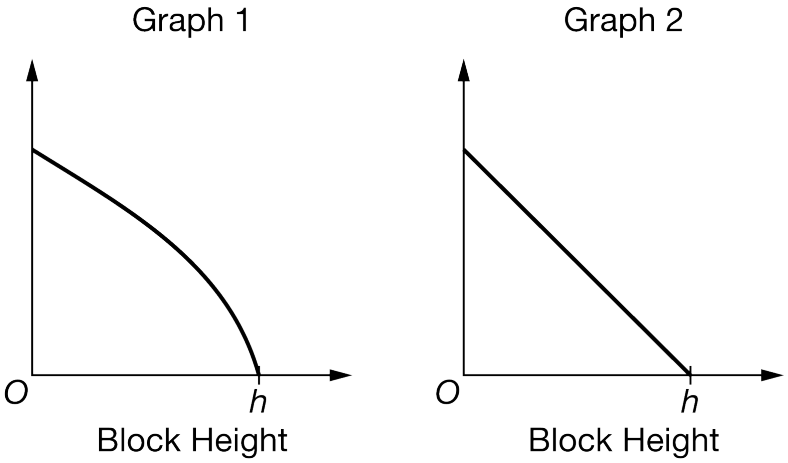


Track 1

Note: Figure not drawn to scale.

A block slides back and forth on a track with a slight circular curvature, where friction is negligible, as shown above. The maximum height h of the track at each end is much smaller than D.

The center of mass of the block oscillates between $x = -D$ and $x = +D$, reaching a maximum height h every time the block is at $x = +D$ or $x = -D$. The curve is so gradual that the total distance traveled along the curved portion of the track by the center of mass of the block can be considered to be $2D$. At time $t = 0$, the speed of the block is zero. The next time that the block's speed is zero is at time $t = 2.0$ s.



(a) Which of the graphs above, Graph 1 or Graph 2, could represent the kinetic energy of the block as a function of its height on the track, and which graph could represent the speed as a function of the block's height on the track? Justify both of your choices with physics principles.

(b) For the system consisting of the block and Earth, describe how the mechanical energy of the system changes, if at all, as the block moves from $x = +D$ to $x = 0$. Justify your answer.

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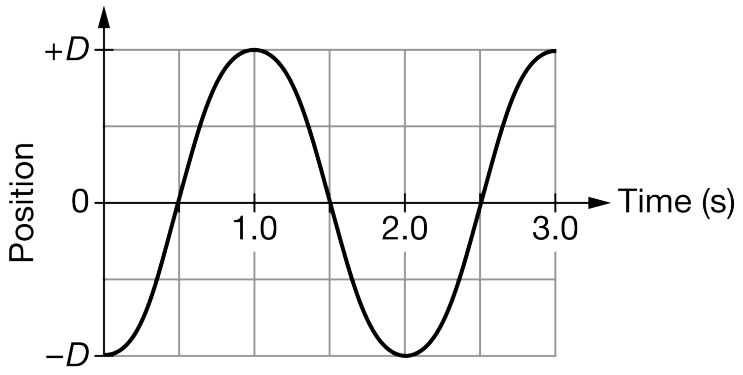
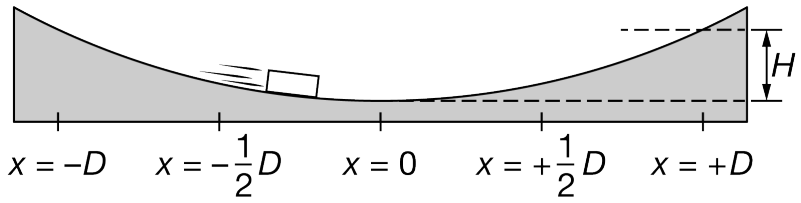
Graph 3



(c) Graph 3 above incorrectly represents the horizontal position of the block as a function of time. Identify a feature of the graph that does not correctly represent the motion of the block. Justify your answer.



Track 2

Note: Figure not drawn to scale.

(d) Track 2 is similar to Track 1, but the maximum height H on Track 2 is greater than h and is still much smaller than D, as shown above. The center of mass of the block oscillates between $x = -D$ and $x = +D$, the same as on Track 1. How does the period of the block's oscillation on Track 2 compare to the period of the block's oscillation on Track 1? Justify your answer.

(e) A student derives the following equation for the period T of the block's oscillation: $T = 2\pi\sqrt{\frac{H^2}{2Dg}}$. Whether or not this equation is correct, is the equation consistent with your answer to part (d)?

(f) When the block reaches $x = 0$ at the bottom of the circular track, is the force exerted by the track on the block greater than, less than, or equal to the weight of the block? Justify your answer.

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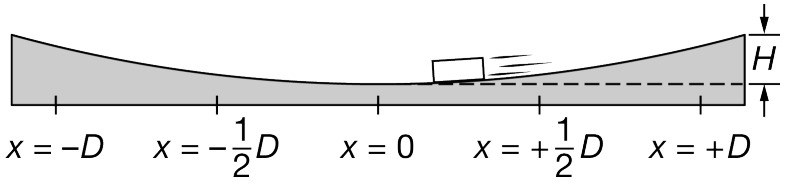
15. This question is a long free-response question. Show your work for each part of the question. (15 points, suggested time 25 minutes)



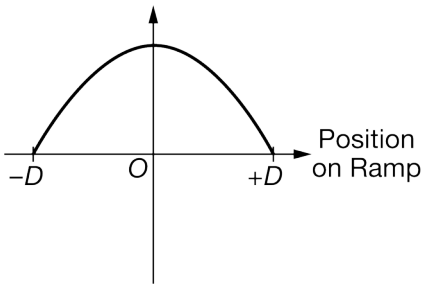
Track 1

Note: Figure not drawn to scale.

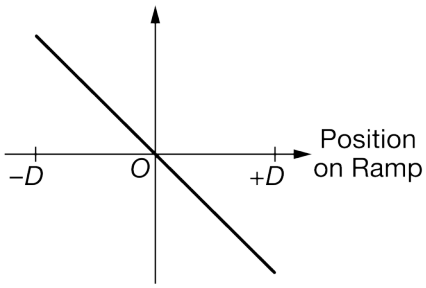
A block slides back and forth on a track with a slight circular curvature, where friction is negligible, as shown above. The maximum height H of the track at each end is much smaller than D.

The center of mass of the block oscillates between $x = -D$ and $x = +D$. The curve is so gradual that the total distance traveled along the curved portion of the track by the center of mass of the block can be considered to be $2D$. At time $t = 0$ the block is released from rest at position $x = +D$. The period of the block's oscillation is 2.0 seconds.

Graph 1



Graph 2



(a) Which of the graphs above, Graph 1 or Graph 2, could represent the block's kinetic energy as a function of its position on the circular track, and which graph could represent the horizontal component of the net force acting on the block as a function of its position on the track? Justify both of your choices with physics principles.

(b) Choose one of the graphs in part (a) above and explain how the graph shows evidence that a restoring force is acting on the block.

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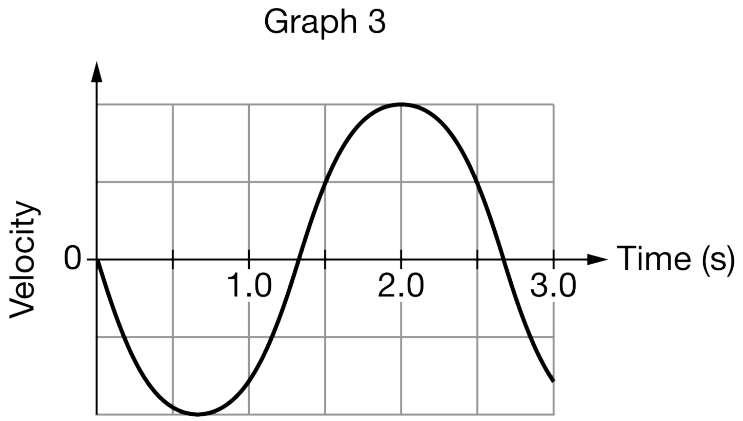
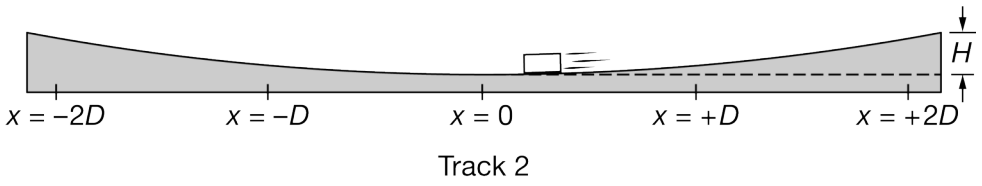


(c) Graph 3 above incorrectly shows the horizontal velocity of the block as a function of time. Identify a feature of the graph that does not correctly represent the motion of the block. Justify your answer.



Track 2

Note: Figure not drawn to scale.

(d) Track 2, shown above, has a horizontal length that is greater than that of Track 1 and the same maximum height H. The block is released from rest at position $x = +2D$ Is the period of the block's oscillation on Track 2 greater than, less than, or equal to the period of oscillation on Track 1? Justify your answer.

(e) A student derives the following equation for the period T of the block's oscillation: $T = 2\pi\sqrt{\frac{h^2}{2dg}}$, where d is the maximum displacement of the block from equilibrium and h is the height of the track at $x = d$. Whether or not this equation is correct, is the equation consistent with your answer to part (d)?

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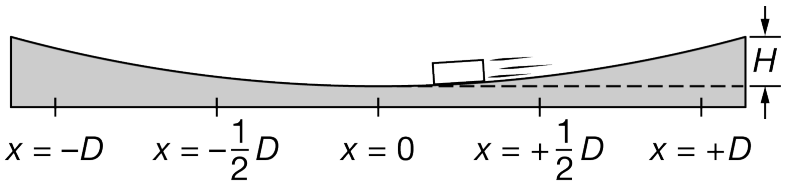
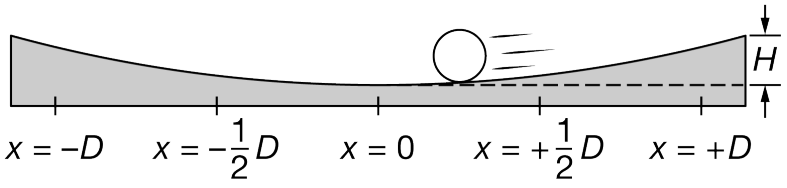


Track 1



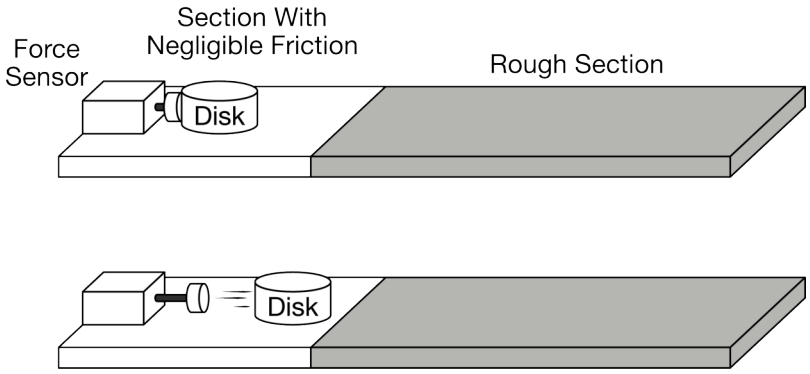
Track 3

Note: Figures not drawn to scale.

(f) On Track 1, shown above again for reference, friction is negligible and the center of mass of the block oscillates between a horizontal position of $+D$ and $-D$ with a period of 2.0 seconds. If a sphere with a mass equal to that of the block were to roll without slipping between $+D$ and $-D$ along Track 3 shown above, which is identical to Track 1 but has nonnegligible friction, would the period of the motion of the sphere be greater than, less than, or equal to 2.0 seconds? Justify your answer.

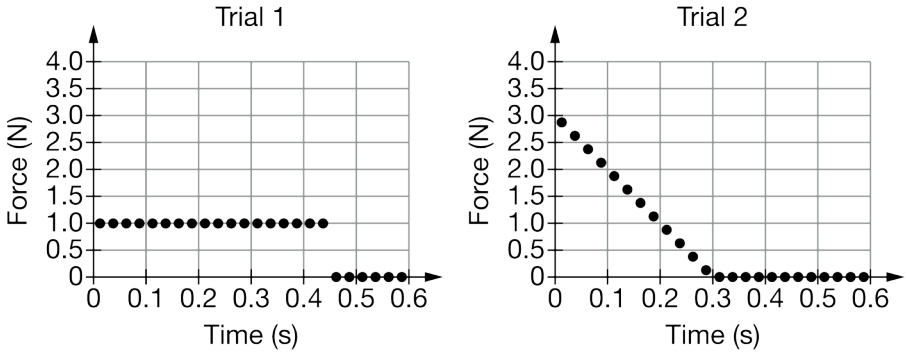
chapter2parta

16. This question is a long free-response question. Show your work for each part of the question. (15 points, suggested time 25 minutes)



Students use a force sensor to push a disk of mass m across a horizontal table. The force sensor pushes the disk over a short time interval. The magnitude of the force and the duration of the time interval can be set by the students. After being pushed by the sensor, the disk first slides along a surface with negligible friction and then enters a rough section where friction is not negligible, as shown above.

The students perform two trials in which the magnitude of the force exerted by the force sensor and the time interval are different. They create the graphs of force as a function of time shown below. The disk enters the rough section in each trial after $t = 0.5$ s.



(a) In which of the two trials, if either, is the change in momentum of the disk between 0 seconds and 0.5 seconds greater? Explain your reasoning.

(b) In both trials, the disk comes to rest in the rough section before reaching the edge of the table. In which trial, if either, does the disk travel a greater distance in the rough section? Explain your reasoning.

(c) The students repeat Trial 1 with a disk that is made from the same material as the original disk and has the same mass as the original disk but that has a larger radius (and therefore more surface area is in contact with the surface). The same force is exerted on the new disk over the same time interval as in Trial 1. Would the distance traveled in the rough section by the new disk be greater than, less than, or the same as the distance traveled by the original disk in Trial 1? Explain your reasoning.

Students derive the following equation, which may or may not be correct, to describe the distance D traveled by

the original disk on the rough section: $D = \frac{(F_{\text{avg}}{}^2)t^2}{2\mu mg}$, where F_{avg} is the average force exerted by the sensor, t is the time that the disk is in contact with the sensor, μ (mu) is the coefficient of kinetic friction, and m is the mass of the disk.

(d) Without algebraic manipulation of equations or attempting to derive this equation, indicate whether the above equation is consistent with your answer in part (b). Explain your reasoning.

A student measures the distance x_0 that the disk travels while in contact with the force sensor in Trial 1. The disk then travels a distance D along the rough section. The student claims that if a force with twice the magnitude of the original force was exerted on the disk for a distance x_0, the disk would travel a distance $2D$ in the rough section.

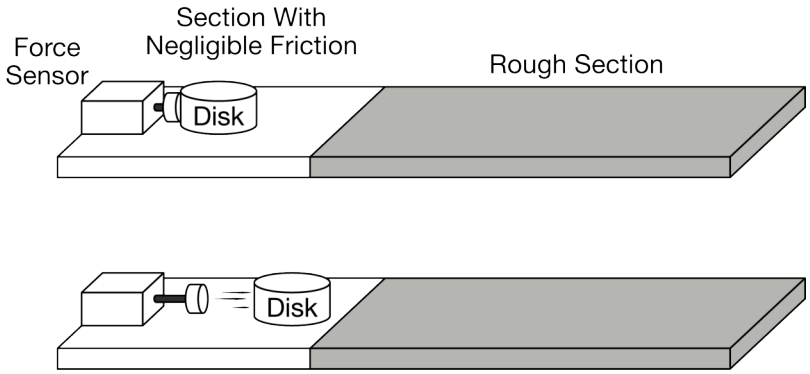
(e) Is the above claim correct or incorrect? Justify your answer without citing or manipulating equations.

The student finds the following equation on the Internet describing the relationship between the magnitude F of the force exerted on the disk, the distance x the disk is pushed, and the distance D it slides in the rough section: $D = C\frac{Fx}{\mu mg}$, where C is a constant with appropriate units.

(f) Indicate whether or not the equation above is consistent with your statement in part (e) relating D and x. Explain your reasoning.

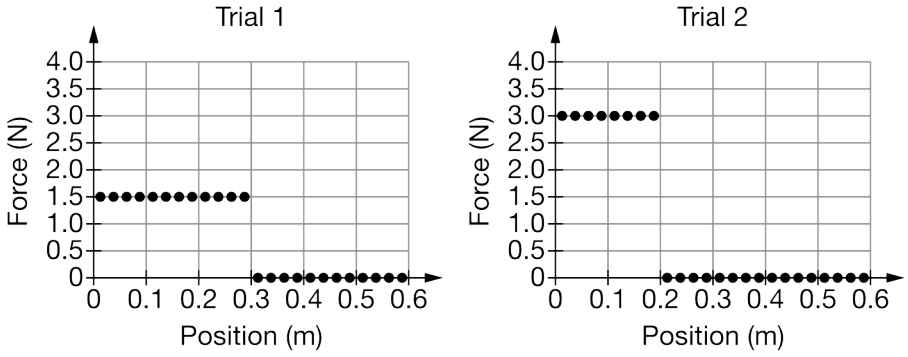
chapter2parta

17. This question is a long free-response question. Show your work for each part of the question. (15 points, suggested time 25 minutes)



Students use a force sensor to push a disk of mass m across a horizontal table. The force sensor pushes the disk over a short distance. The magnitude of the force and the distance the disk is pushed can be set by the students. After being pushed by the sensor, the disk first slides along a surface with negligible friction and then enters a rough section where friction is not negligible, as shown above.

The students perform two trials in which the magnitude of the force exerted by the force sensor and the distance the disk is pushed are different. They create the graphs of force as a function of position shown below. The disk enters the rough surface in each trial after moving 0.6 meters.



(a) In which of the two trials, if either, is the change in energy of the disk the greatest during the interval shown in the graphs? Explain your reasoning.

(b) In both trials, the disk comes to rest in the rough section before reaching the edge of the table. In which trial, if either, does the disk travel a shorter distance in the rough section? Explain your reasoning.

(c) The students repeat Trial 2 with a disk that is made from the same material as the original disk but that is less massive. The same constant force is exerted on the less massive disk over the same distance as in Trial 2. Would the distance traveled in the rough section by the less massive disk be greater than, less than, or the same as the distance traveled in the rough section by the original disk in Trial 2? Explain your reasoning.

Students derive the following equation, which may or may not be correct, to describe the distance D traveled by the original disk in Trial 2 on the rough section: $D = \frac{Fx}{\mu mg}$, where F is the force exerted by the sensor, x is the

distance over which the sensor exerts a force on the disk, μ (mu) is the coefficient of kinetic friction, and m is the mass of the disk.

(d) Without algebraic manipulation of equations or attempting to derive this equation, indicate whether the equation is consistent with your answer in part (b). Explain your reasoning.

A student measures the time t that the disk is in contact with the force sensor in Trial 2. The disk then travels a distance D along the rough section. The student claims that if the same force is exerted on the disk for a time $2t$, the disk would travel a distance $2D$ in the rough section.

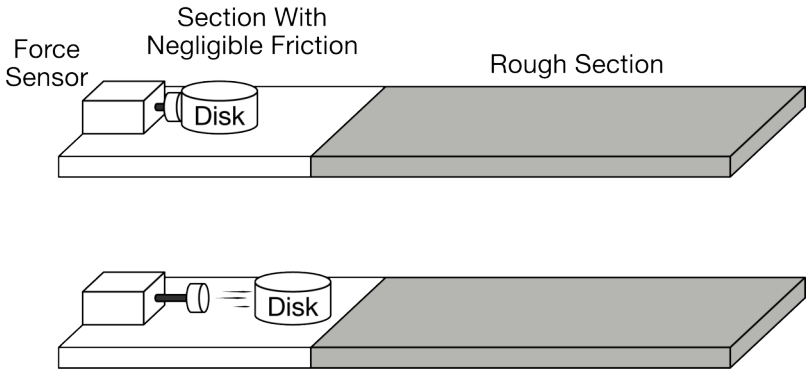
(e) Is the above claim correct or incorrect? Justify your answer without citing or manipulating equations.

The student finds the following equation on the Internet describing the relationship between the time t the disk is pushed and the distance D it slides in the rough section: $D = C\frac{F^2t^2}{2\mu m^2 g}$, where C is a constant with appropriate units.

(f) Indicate whether or not the above equation is consistent with your statement in part (e) relating D and t. Explain your reasoning.

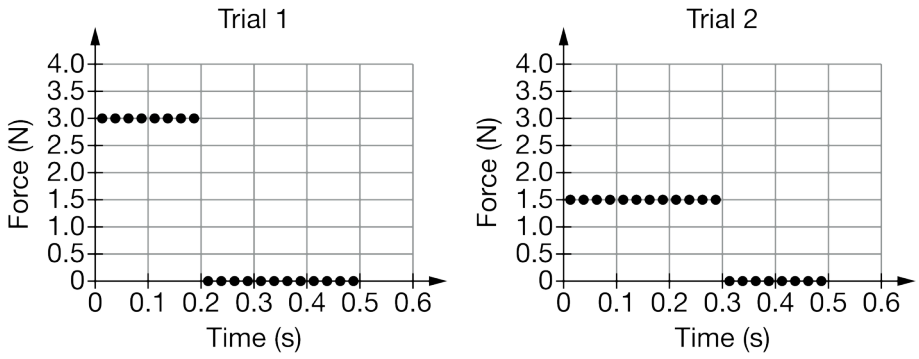
chapter2parta

18. This question is a long free-response question. Show your work for each part of the question. (15 points, suggested time 25 minutes)



Students use a force sensor to push a disk of mass m across a horizontal table. The force sensor pushes the disk with a force of constant magnitude over a short time interval. The magnitude of the force and the duration of the time interval can be set by the students. After being pushed by the sensor, the disk first slides along a surface with negligible friction and then enters a rough section where friction is not negligible, as shown above.

The students perform two trials in which the magnitude of the force exerted by the force sensor and the time interval are different. They create the graphs of force as a function of time shown below. The disk enters the rough surface in each trial after $t = 0.5$ s.



(a) In which of the two trials, if either, is the speed of the disk the greatest at time 0.5 seconds? Explain your reasoning.

(b) In both trials, the disk comes to rest in the rough section before reaching the edge of the table. In which trial, if either, does the disk travel a greater distance in the rough section? Explain your reasoning.

(c) The students repeat Trial 1 with a disk that is made from the same material as the original disk but that is more massive. The same force is exerted on the more massive disk over the same time interval as in Trial 1. Would the distance traveled in the rough section by the more massive disk be greater than, less than, or the same as the distance traveled by the original disk in Trial 1? Explain your reasoning.

Students derive the following equation, which may or may not be correct, to describe the distance D traveled by the original disk on the rough section: $D = \frac{F^2 t^2}{2\mu m g}$, where F is the force exerted by the sensor, t is the time that

the disk is in contact with the sensor, μ (mu) is the coefficient of kinetic friction, and m is the mass of the disk.

(d) Without algebraic manipulation of equations or attempting to derive this equation, indicate whether the above equation is consistent with your answer in part (b). Explain your reasoning.

A student measures the distance x_0 that the disk travels while in contact with the force sensor in Trial 1. The disk then travels a distance D along the rough section. The student claims that if the same force is exerted on the disk for a distance $2x_0$, the disk would travel a distance $2D$ in the rough section.

(e) Is the above claim correct or incorrect? Justify your answer without citing or manipulating equations.

The student finds the following equation on the Internet describing the relationship between the distance x the disk is pushed and the distance D it slides in the rough section: $D = C\frac{Fx^2}{\mu mg}$, where C is a constant with appropriate units.

(f) Indicate whether or not the equation above is consistent with your statement in part (e) relating D and x. Explain your reasoning.

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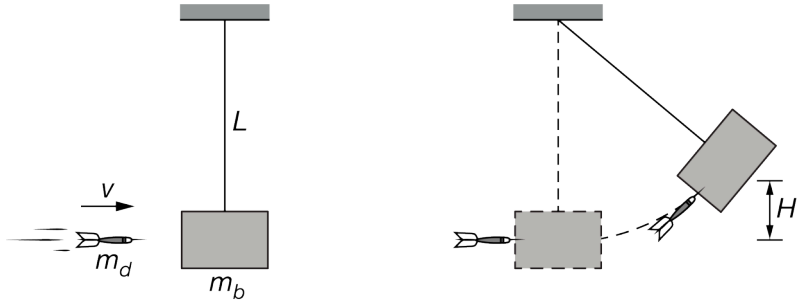
19. This question is a long free-response question. Show your work for each part of the question. (15 points, suggested time 25 minutes)



A dart with mass m_d is launched toward a block of mass m_b that is suspended from a string of length *L*, as shown at left above. The dart is moving horizontally with speed *v* immediately before it strikes the block and remains embedded. The dart-block system then swings up to a point at which its center of mass reaches a maximum height *H* above its starting position, as shown at right above. The block's mass m_b is greater than the dart's mass m_d.

(a) Indicate which object, if either, experiences a net horizontal force of larger magnitude during the collision. If the net horizontal force is the same magnitude for both objects, state this explicitly. Briefly explain your reasoning.

(b) If the experiment was repeated with a dart with the same horizontal speed but with mass smaller than m_d, how would the maximum height reached by the center of mass of the dart-block system compare to *H* ? Explain your response without deriving or manipulating equations.

Two students are discussing the motion of the dart-block system at the instant it first reaches a height of $H/2$, and they make the following statements:

Student 1: When the dart-block system is at a height of $H/2$, the kinetic energy of the system is half of its maximum value, and therefore the speed of the system is half of its maximum speed.

Student 2: When the dart-block system reaches a height of $H/2$, the centripetal force is equal to the tension in the string. Therefore, the acceleration of the system must point toward the fixed end of the string.

(c) Which underlined phrase or phrases, if either, are ***correct*** about student 1's statement? If neither phrase is ***correct***, write "none."

(d) Which underlined phrase or phrases, if either, are ***incorrect*** about student 1's statement? If neither phrase is ***incorrect***, write "none."

(e) Which underlined phrase or phrases, if either, are ***correct*** about student 2's statement? If neither phrase is ***correct***, write "none."

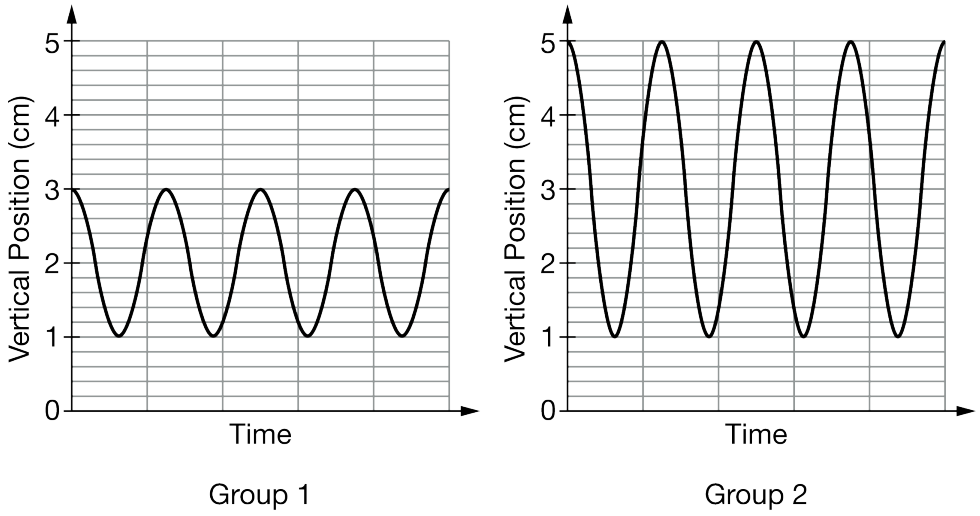
(f) Which underlined phrase or phrases, if either, are ***incorrect*** about student 2's statement? If neither phrase is ***incorrect***, write "none."

(g) The students correctly derive an equation for the maximum height: $H = \frac{1}{2g}\left(\frac{v}{1+\frac{m_b}{m_d}}\right)^2$. Explain how this

equation supports your claim in part (b).

(h) Could the masses of the dart and block both be changed so that the maximum height *H* reached by the dart-block system would remain the same as in the original setup? Justify your answer by referring to the equation in part (g).

After the collision, the dart-block system is then allowed to swing freely, and the students produce the graph shown below at left, labeled Group 1, of the vertical position of the center of mass of the dart-block system as a function of time. A second group of students makes a single change to the setup and then repeats the experiment. Their graph, labeled Group 2, of the vertical position of the center of mass of the dart-block system as a function of time is shown below at right.



Note: The time scale is the same for both graphs.

(i) Indicate the single difference in either the dart mass or the string length between group 1's setup and group 2's setup that could lead to the difference between the two graphs. Justify your answer.

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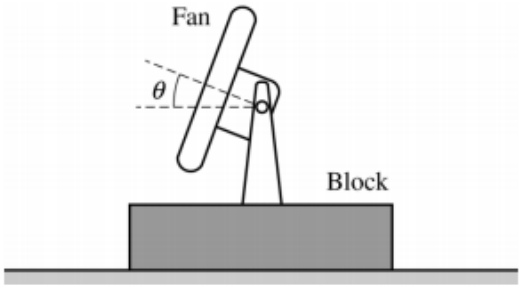
20.



A student in a physics lab has a block with a fan attached to it, as shown in the figure above. The fan has a pivot so that the angle θ it makes with the horizontal can be adjusted between 0° and 90°. When the fan is pointed horizontally so that θ = 0°, the block accelerates from rest along a track, even though there is friction between the block and the track. For the following questions, assume that the student has access to equipment that would usually be found in a school physics laboratory.

a. Describe an experimental procedure that the student could use to measure the force F that the air exerts on the fan-block system when the fan is turned on. Assume that the magnitude of this force is the same for all angles θ.

    i. What quantities would be measured?

    ii. What equipment would be used for the measurements, and how would that equipment be used? Include a labeled diagram of the experimental setup.

    iii. Describe the overall procedure to be used. Give enough detail so that another student could replicate the experiment.

    iv. Describe how the force can be determined from the measurements described in parts (a)i–iii.

b. Describe an experimental procedure that would allow the student to use the fan-block system, with the **fan turned on**, to find the coefficient of kinetic friction between the block and the track.

    i. What quantities would be measured?

    ii. What equipment would be used for the measurements, and how would that equipment be used? Include a labeled diagram of the experimental setup.

    iii. Describe the overall procedure to be used. Give enough detail so that another student could replicate the experiment.

    iv. On the dot to the right, which represents the fan-block system, draw and label the forces (not components) that are exerted on the system during the experiment described in parts (b)i–iii. Represent each force by a distinct arrow starting on, and pointing away from, the dot.

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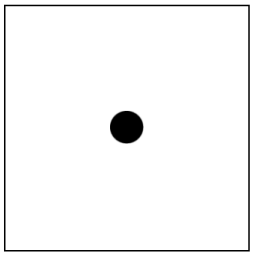
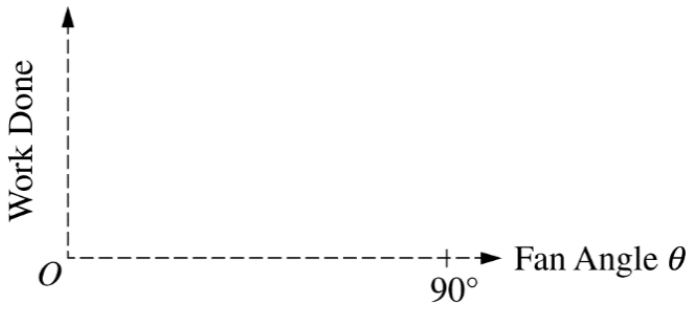


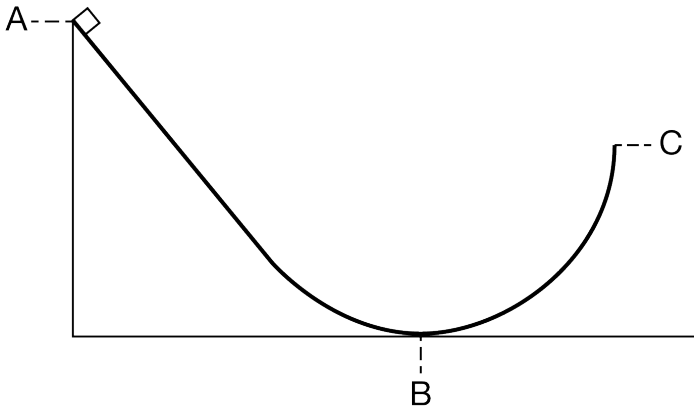
c. Describe how to analyze the data from the experiment described in parts (b)i–iii in order to determine the coefficient of kinetic friction between the block and the track. Your analysis may include the force F exerted by the air on the fan-block system. Do not add to the free-body diagram in part (b)iv.

d. In a different experiment, the student attaches the block to the top of a low-friction cart. On the axes below, sketch a graph of the work done by air on the fan-block-cart system as a function of q when the system travels a fixed distance D



chapter2parta

21. This question is a short free-response question. Show your work for each part of the question. (10 points, suggested time 15 minutes)



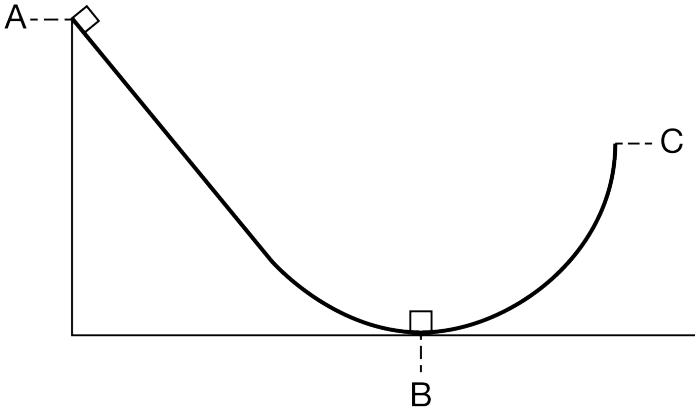
The figure above shows a track consisting of a straight section that connects to a circular section. The bottommost point of the track is at location B, and the track ends at location C, where the track is vertical. A block is released from rest at location A. There is negligible friction between the track and the box.

(a) Is the magnitude of the normal force exerted on the block by the track when the block is at location B greater than, less than, or equal to the normal force immediately before the block reaches location C? Justify your answer.

(b) In a coherent, paragraph-length response, describe the relative angle between the direction of the normal force exerted on the block by the track and the direction of the block's acceleration at the following times.

Immediately after the block is released at location A
When the block is at location B
Immediately before the block reaches location C

Specifically, indicate whether the normal force is parallel to the acceleration, perpendicular to the acceleration, or neither, at each location. Use physical principles to justify your responses.



(c) The scenario is repeated, but an identical block is at rest at location B, as shown above. When the block at location A is released from rest, it slides down the track and collides with and sticks to the identical block. The

two blocks then continue sliding up the ramp. Is the maximum height reached by the two blocks greater than, less than, or equal to the maximum height reached by the block in the original scenario? Briefly explain your answer.

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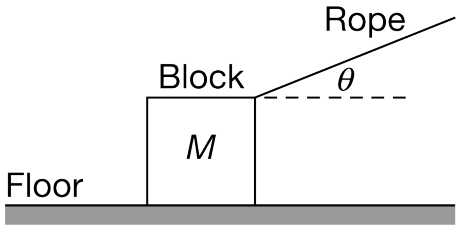
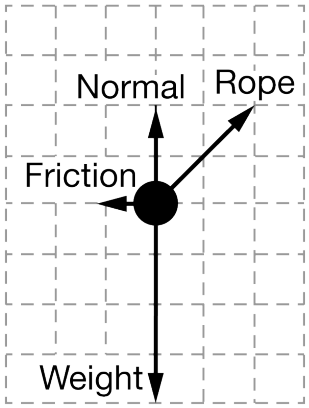
22. This question is a long free-response question. Show your work for each part of the question. (15 points, suggested time 25 minutes)

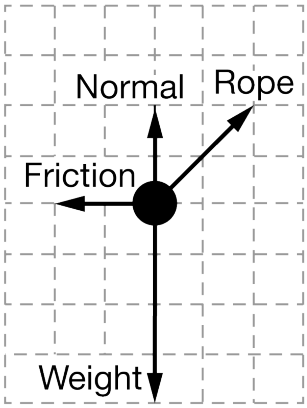


A block of mass M is pulled by a rope that makes an angle θ (theta) above the horizontal, as shown above. The coefficient of kinetic friction between the block and floor is μ (mu).

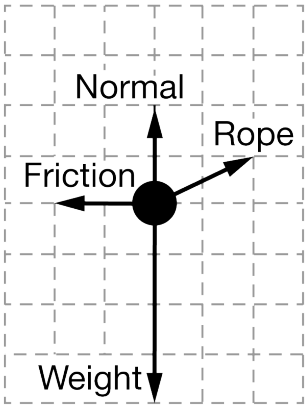
The block is initially at rest and starts accelerating to the right along the floor. Three students each draw a diagram to indicate all of the forces that are exerted on the block as it moves. In the students' diagrams, which are shown below, the lengths of the arrows indicate the relative magnitudes of the forces.



Student 1's Diagram



Student 2's Diagram



Student 3's Diagram

Only one of the students has drawn a diagram that could correctly represent the forces. The other two students' diagrams are incorrect.

(a) Which student has drawn a diagram that could correctly represent the forces exerted on the block?

(b) For the incorrect student diagrams, explain why the diagram could not represent the forces exerted on the block. If there is more than one specific reason a diagram is incorrect, identify each of the reasons.

(c) Briefly explain why slightly increasing the angle θ (without changing the magnitude of the force exerted by the rope) could cause a decrease in the block's acceleration.

Suppose the rope is pulled with a force that has a magnitude that is one-third the weight of the block, or $\frac{Mg}{3}$. In this case, when the block accelerates, its acceleration is $a = g\left(\frac{1}{3}\cos\theta + \frac{\mu}{3}\sin\theta - \mu\right)$.

(d) Explain why the above equation is consistent with the claim that an increase in the angle θ could cause a decrease in the acceleration.

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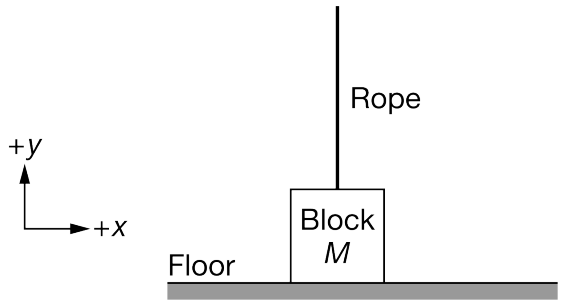
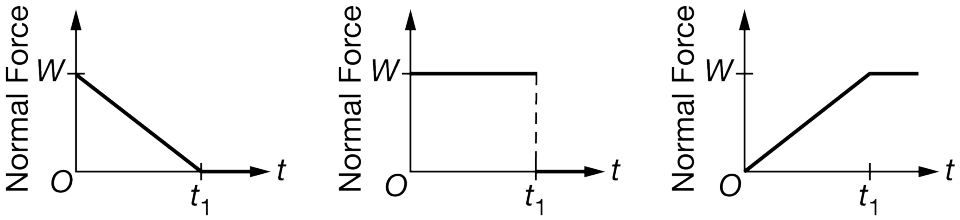


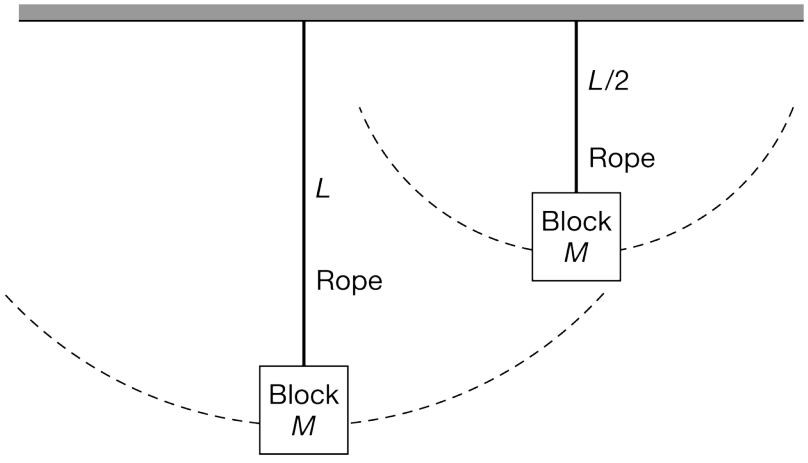
The rope is now attached to the center of the top of the block, as shown above. The force exerted by the rope is initially zero newtons at time $t = 0$. The force steadily increases, becomes equal to the block's weight W at time t_1, and continues to increase further. Three students sketch the graphs shown below to represent the normal force exerted by the floor on the block as a function of time t. One of the graphs is consistent with this scenario, while the other graphs are not consistent with this scenario.



Graph 1 Graph 2 Graph 3

(e) Which graph is consistent with the scenario in which the force exerted by the rope on the block steadily increases?

(f) Identify all features of the other two graphs that make them inconsistent with this scenario. Explain your reasoning.



Note: Figure not drawn to scale.

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With one end of the rope still attached to the block, the other end of the rope is attached to a ceiling to create a pendulum with length L, where L is much greater than the dimensions of the block. A second pendulum is made from an identical block and a rope of length $\frac{L}{2}$, as shown above. Both pendulums are displaced by the same small angle and released from rest.

(g) Does the longer pendulum or the shorter pendulum have a greater period of oscillation? Briefly explain your choice without reference to equations, but by describing the restoring forces exerted on and motion of each block.

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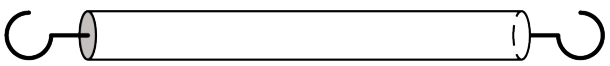
23. This question is a long free-response question. Show your work for each part of the question.



(12 points, suggested time 25 minutes)

A group of students is investigating how the thickness of a plastic rod affects the maximum force F_{max} with which the rod can be pulled without breaking. Two students are discussing models to represent how F_{max} depends on rod thickness.
Student A claims that F_{max} is directly proportional to the radius of the rod.
Student B claims that F_{max} is directly proportional to the cross-sectional area of the rod—the area of the base of the cylinder, shaded gray in the figure above.

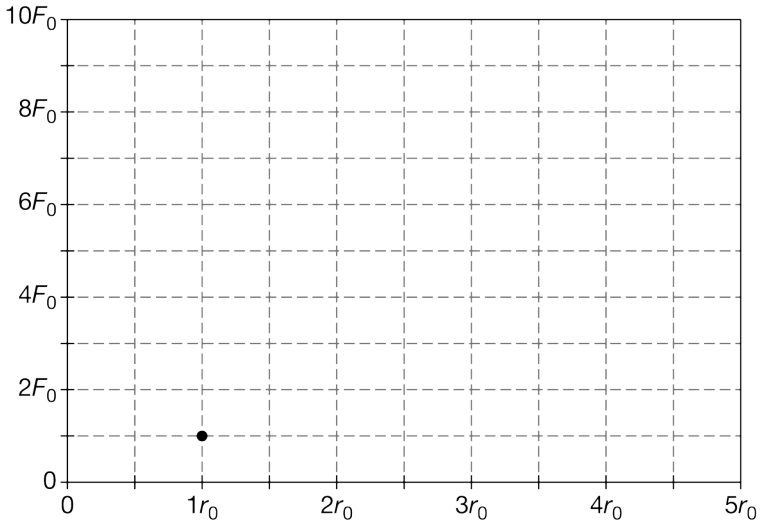
(a) The students have a collection of many rods of the same material. The rods are all the same length but come in a range of six different thicknesses. Design an experimental procedure to determine which student's model, if either, correctly represents how F_{max} depends on rod thickness.

In the table below, list the quantities that would be measured in your experiment. Define a symbol to represent each quantity, and also list the equipment that would be used to measure each quantity. You do not need to fill in every row. If you need additional rows, you may add them to the space just below the table.

Quantity to be Measured	Symbol for Quantity	Equipment for Measurement

Describe the overall procedure to be used, referring to the table. Provide enough detail so that another student could replicate the experiment, including any steps necessary to reduce experimental uncertainty. As needed, use the symbols defined in the table and/or include a simple diagram of the setup.

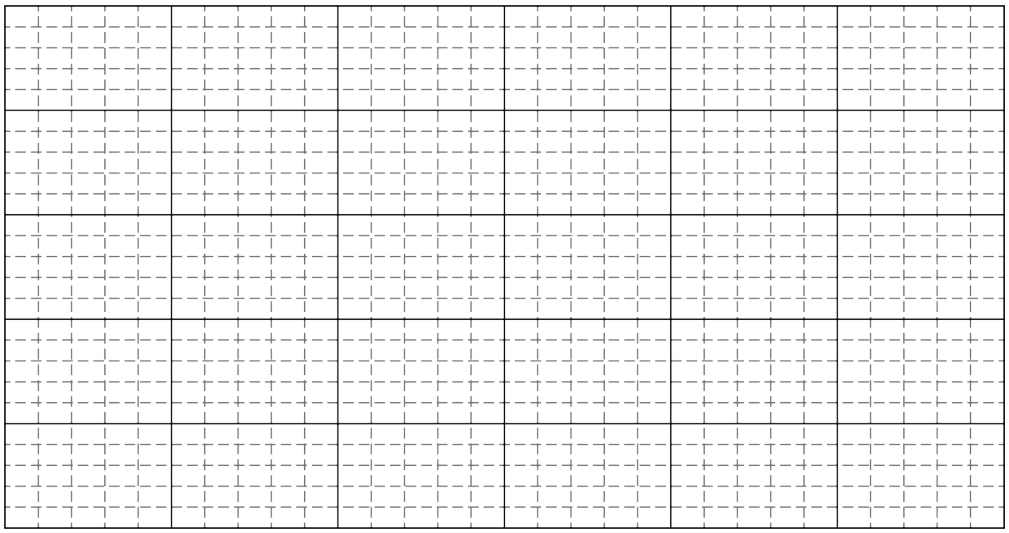
(b) For a rod of radius r_0, it is determined that $F_{\max}$ is F_0, as indicated by the dot on the grid below. On the grid, draw and label graphs corresponding to the two students' models of the dependence of $F_{\max}$ on rod radius. Clearly label each graph "A" or "B," corresponding to the appropriate model.



The table below shows results of measurements taken by another group of students for rods of different thicknesses.

Rod radius (mm)	0.5	1.0	1.5	2.0	2.5
$F_{\max}$ (N)	40	120	320	520	900

(c) On the grid below, plot the data points from the table. Clearly scale and label all axes, including units. Draw either a straight line or a curve that best represents the data.



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(d) Which student's model is more closely represented by the evidence shown in the graph you drew in part (c) ?

____ Student A's model: F_{max} is directly proportional to the radius of the rod.

____ Student B's model: F_{max} is directly proportional to the cross-sectional area of the rod.

Explain your reasoning.

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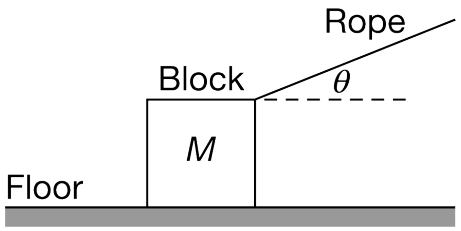
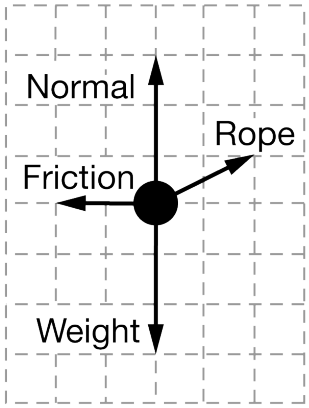
24. This question is a long free-response question. Show your work for each part of the question. (15 points, suggested time 25 minutes)

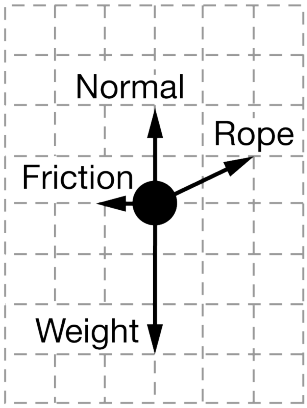


A block of mass M is pulled by a rope that makes an angle θ (theta) above the horizontal, as shown above. The coefficient of kinetic friction between the block and floor is μ (mu).

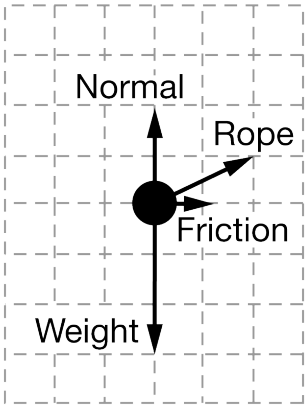
The block is initially at rest and starts accelerating to the right along the floor. Three students each draw a diagram to indicate all of the forces that are exerted on the block as it moves. In the students' diagrams, which are shown below, the lengths of the arrows indicate the relative magnitudes of the forces.



Student 1's Diagram



Student 2's Diagram



Student 3's Diagram

Only one of the students has drawn a diagram that could correctly represent the forces. The other two students' diagrams are incorrect.

(a) Which student has drawn a diagram that could correctly represent the forces exerted on the block?

(b) For the incorrect student diagrams, explain why the diagram could not represent the forces exerted on the block. If there is more than one specific reason a diagram is incorrect, identify each of the reasons.

(c) Briefly explain why slightly increasing the force F exerted by the rope on the block (without changing the angle θ) would cause a decrease in the friction force.

(d) The friction force f is $f = \mu(W - F\sin\theta)$, where W is the weight of the block and F is the force exerted by the rope. Explain why this equation is consistent with the claim that an increase in F would cause a decrease in the friction force.

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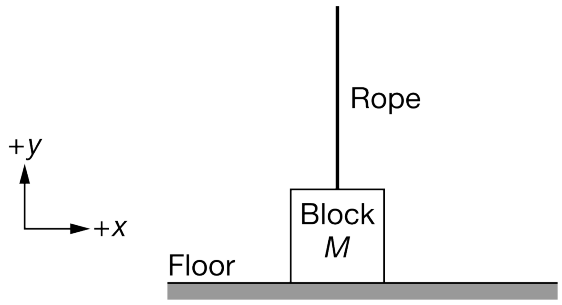
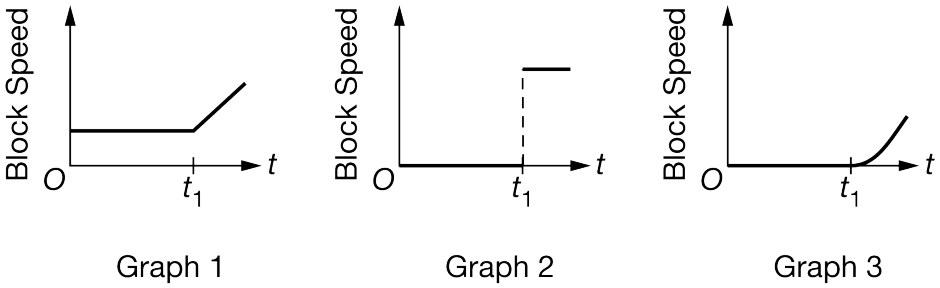
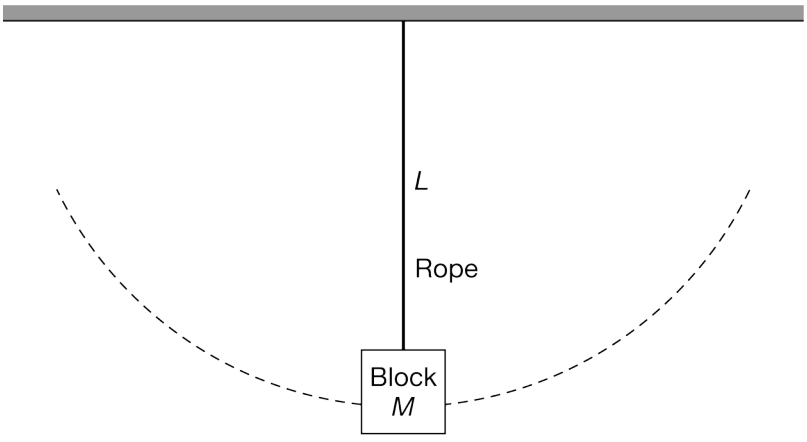


The rope is now attached to the center of the top of the block, as shown above. The force exerted by the rope is initially zero newtons at time $t = 0$. The force steadily increases, becomes equal to the block's weight W at time t_1, and continues to increase further. Three students sketch the graphs shown below to represent the speed of the block as a function of time t. One of the graphs is consistent with this scenario, while the other graphs are not consistent with this scenario.



(e) Which graph is consistent with the scenario in which the force exerted by the rope on the block steadily increases?

(f) Identify all features of the other two graphs that make them inconsistent with this scenario. Explain your reasoning.



Note: Figure not drawn to scale.

With one end of the rope still attached to the block, the other end of the rope is attached to a ceiling to create a

pendulum with length L, where L is much greater than the dimensions of the block. A second identical pendulum is located on the Moon, where the acceleration due to gravity is less than that on Earth. Both pendulums are displaced by the same small angle and released from rest.

(g) Does the pendulum on Earth or the pendulum on the Moon have a greater period of oscillation? Briefly explain your choice without reference to equations, but by describing the restoring forces exerted on and motion of each block.

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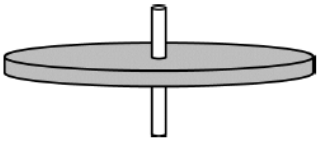
25.

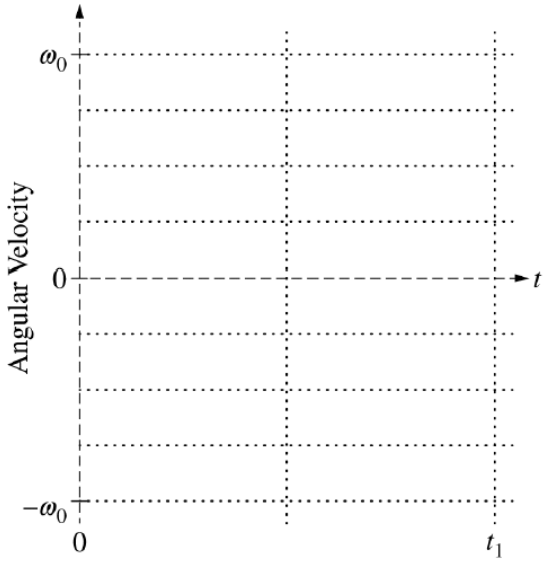


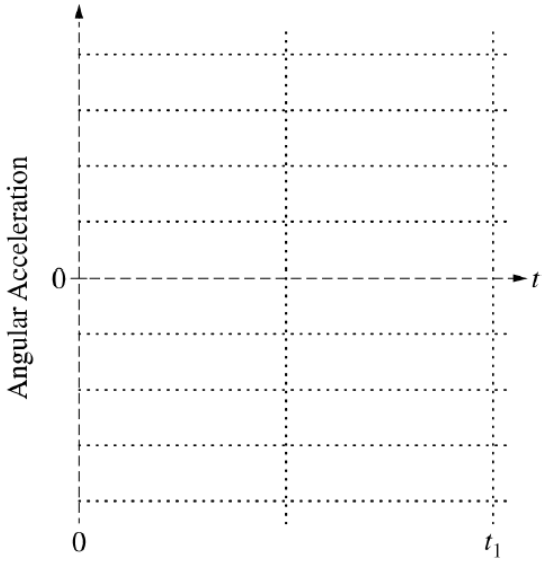
The disk shown above spins about the axle at its center. A student's experiments reveal that, while the disk is spinning, friction between the axle and the disk exerts a constant torque on the disk.

a. At time $t = 0$ the disk has an initial counterclockwise (positive) angular velocity ω_0.The disk later comes to rest at time $t = t_1$.

   i. On the grid at left below, sketch a graph that could represent the disk's angular velocity as a function of time t from $t = 0$ until the disk comes to rest at time $t = t_1$.

   ii. On the grid at right below, sketch the disk's angular acceleration as a function of time t from $t = 0$ until the disk comes to rest at time $t = t_1$.





b. The magnitude of the frictional torque exerted on the disk is τ_0. Derive an equation for the rotational inertia I of the disk in terms of τ_0, ω_0, t_1, and physical constants, as appropriate.

c. In another experiment, the disk again has an initial positive angular velocity ω_0 at time $t = 0$. At time $t = \frac{1}{2}t_1$, the student starts dripping oil on the contact surface between the axle and the disk to reduce the friction. As time passes, more and more oil reaches that contact surface, reducing the friction even further.

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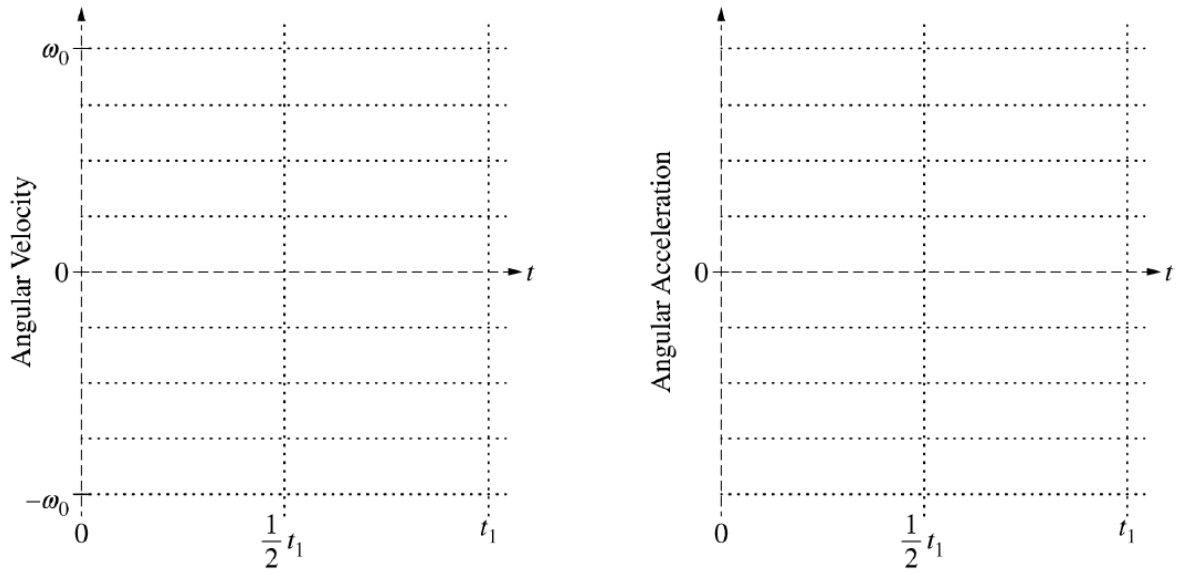
i. On the grid at left below, sketch a graph that could represent the disk's angular velocity as a function of time from $t = 0$ to $t = t_1$, which is the time at which the disk came to rest in part (a).

ii. On the grid at right below, sketch the disk's angular acceleration as a function of time from $t = 0$ to $t = t_1$.



d. The student is trying to mathematically model the magnitude τ of the torque exerted by the axle on the disk when the oil is present at times $t > \frac{1}{2}t_1$. The student writes down the following two equations, each of which includes a positive constant (C_1 or C_2) with appropriate units.

$$(1)\ \tau = C_1\left(t - \tfrac{1}{2}t_1\right) \text{ (for } t > \tfrac{1}{2}t_1\text{)}$$
$$(2)\ \tau = \frac{C_2}{\left(t + \frac{1}{2}t_1\right)} \text{ (for } t > \tfrac{1}{2}t_1\text{)}$$

Which equation better mathematically models this experiment?

____Equation (1) ____Equation (2)

Briefly explain why the equation you selected is plausible and why the other equation is not plausible.

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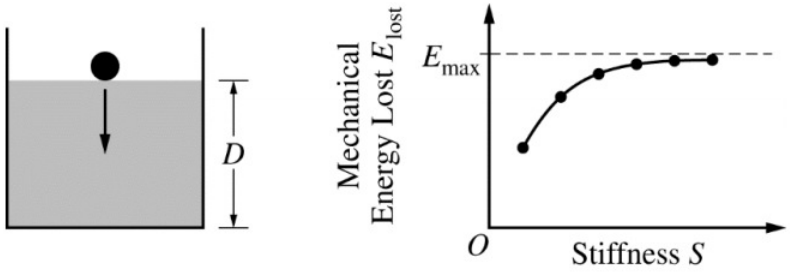
26.



Food scientists have created a new oil. At room temperature, the oil is a liquid. As the oil gets colder, however, it stiffens (thickens) into a sticky gel. To explore the properties of the oil, the scientists fill a container with the oil to a height D, as shown in the figure above on the left. They drop a small steel ball of mass M from rest at the top of the oil. Using video to capture the ball's motion, the scientists calculate E_{lost} , the mechanical energy lost by the ball-Earth system from the time the ball enters the oil to the time just before the ball strikes the bottom of the container. The scientists also define the "stiffness" S of the oil as a quantity proportional to the force required to move a rod through the oil at a standard constant speed. The scientists calculate E_{lost} and S at several different temperatures, ranging from room temperature to the lowest temperature at which the ball still falls through the oil. The graph above on the right shows E_{lost} as a function of S for the calculated data points and a best-fit curve.

a. Give a physical reason why the curve in the graph would not reach the vertical (E_{lost}) axis even if the scientists had taken data over a broader range of temperatures.

b. As S increases, E_{lost} approaches a maximum value labeled E_{max} on the graph above. Write an equation for E_{max} in terms of *M, D*, and physical constants, as appropriate.

   Justify your answer.

c. One of the scientists, in trying to represent the relationship between the oil stiffness and the mechanical energy lost, writes down the equation $2\ E_{\text{lost}} = CS^2$, where *C* is a constant with appropriate units. Another scientist points out that this equation cannot be correct. Give two reasons why the equation cannot be correct.

d. Further attempting to model the ball's motion, the scientists write the following equation for the time t the ball takes to fall through the oil: $t = Z/S$, where Z is a constant with appropriate units. Is this equation plausible—in other words, does it make physical sense?

   ____ Plausible ____ Not plausible

   Briefly explain your reasoning.

e. ΔK is the change in kinetic energy of the ball between the time it is released from rest and the time just before the ball strikes the bottom of the container. On the axes below, sketch ΔK as a function of S, the oil stiffness.

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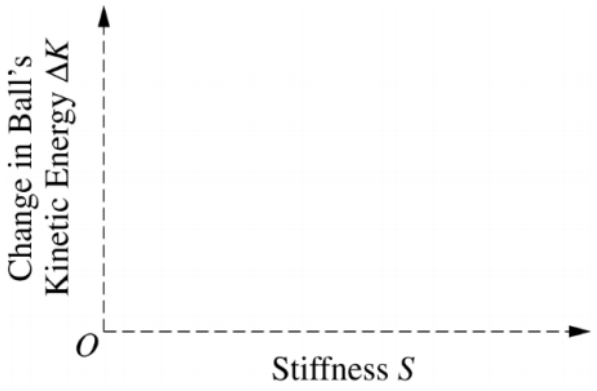

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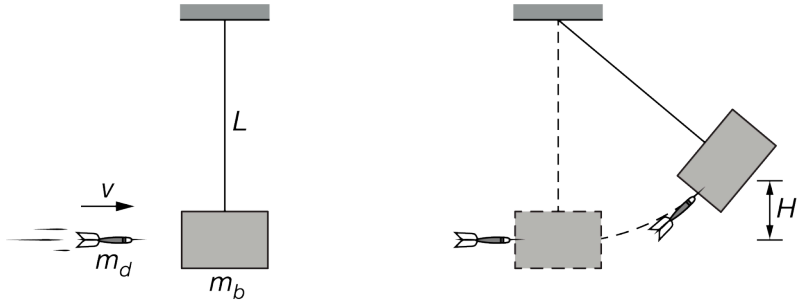
27. This question is a long free-response question. Show your work for each part of the question. (15 points, suggested time 25 minutes)



A dart with mass m_d is launched toward a block of mass m_b that is suspended from a string of length *L*, as shown above at left. The dart is moving horizontally with speed *v* immediately before it strikes the block and remains embedded. The dart-block system then swings up to a point at which its center of mass reaches a maximum height *H* above its starting position, as shown above at right. The block's mass m_b is greater than the dart's mass m_d.

(a) Indicate which object, if either, experiences an acceleration of larger magnitude during the collision. If the acceleration is the same magnitude for both objects, state this explicitly. Briefly explain your reasoning.

(b) If the experiment were repeated with a block with mass greater than m_b, how would the maximum height reached by the center of mass of the dart-block system compare to *H* ? Explain your response without deriving or manipulating equations.

Two students are discussing the tension in the string at the moment immediately after the collision and state the following:

Student 1: The tension in the string immediately after the collision is greater than the weight of the dart-block system because the acceleration is upward at that instant.

Student 2: The tension in the string is equal to the weight of the block-dart system because there is no vertical acceleration immediately after the collision.

(c) Which underlined phrase or phrases, if any, are ***correct*** about student 1's statement? If neither phrase is ***correct***, write "none."

(d) Which underlined phrase or phrases, if any, are ***incorrect*** about student 1's statement? If neither phrase is ***incorrect***, write "none."

(e) Which underlined phrase or phrases, if any, are ***correct*** about student 2's statement? If neither phrase is ***correct***, write "none."

(f) Which underlined phrase or phrases, if any, are ***incorrect*** about student 2's statement? If neither phrase is ***incorrect***, write "none."

(g) The students correctly derive an equation for the maximum height: $H = \frac{1}{2g}\left(\frac{m_d v}{m_d + m_b}\right)^2$. Explain how this equation supports your claim in part (b).

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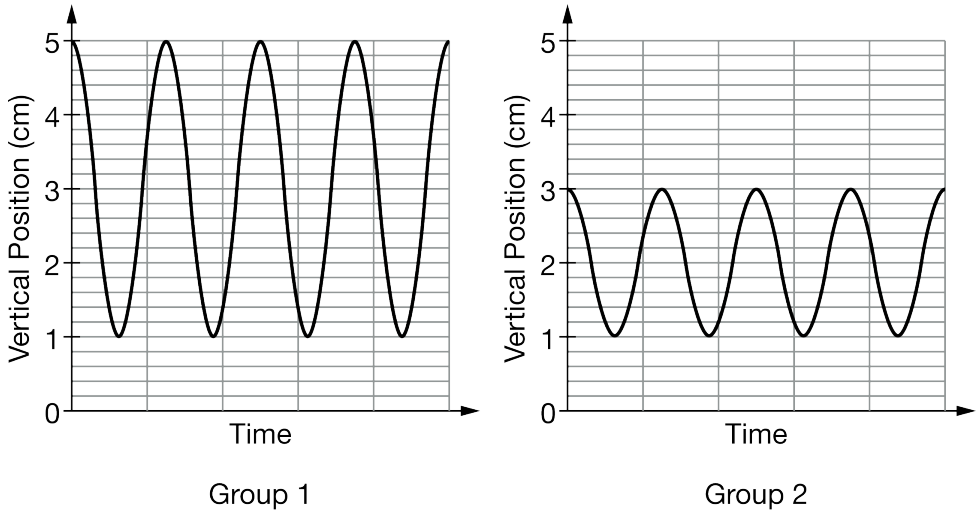
(h) Consider the case in which the collision between the dart and the block is perfectly elastic (the dart bounces off the block to the left). In this case, is the speed of the block immediately after the collision greater than, less than, or the same as the speed of the block in the original case? Justify your answer.

After the collision, the dart-block system is then allowed to swing freely, and the students produce the graph shown below at left, labeled Group 1, of the vertical position of the center of mass of the dart-block system as a function of time. A second group of students makes a single change to the setup and then repeats the experiment. Their graph, labeled Group 2, of the vertical position of the center of mass of the dart-block system as a function of time is shown below at right.



Note: The time scale is the same for both graphs.

(i) Indicate the single difference in either the dart speed or the string length between group 1's setup and group 2's setup that could lead to the difference between the two graphs. Justify your answer.

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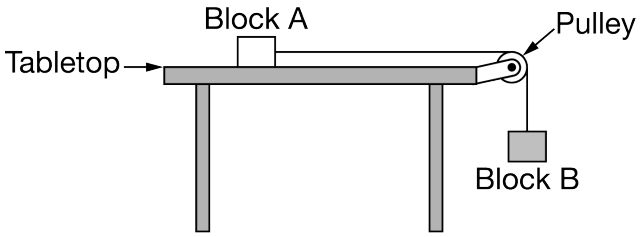
28. This question is a long free-response question. Show your work for each part of the question.



(12 points, suggested time 25 minutes)

This problem explores how the relative masses of two blocks affect the acceleration of the blocks. Block A, of mass m_A, rests on a horizontal tabletop. There is negligible friction between block A and the tabletop. Block B, of mass m_B, hangs from a light string that runs over a pulley and attaches to block A, as shown above. The pulley has negligible mass and spins with negligible friction about its axle. The blocks are released from rest.

(a)

i. Suppose the mass of block A is much greater than the mass of block B. Estimate the magnitude of the acceleration of the blocks after release.

Briefly explain your reasoning without deriving or using equations.

ii. Now suppose the mass of block A is much less than the mass of block B. Estimate the magnitude of the acceleration of the blocks after release.

Briefly explain your reasoning without deriving or using equations.

(b) Now suppose neither block's mass is much greater than the other, but that they are not necessarily equal. The dots below represent block A and block B, as indicated by the labels. On each dot, draw and label the forces (not components) exerted on that block after release. Represent each force by a distinct arrow starting on, and pointing away from, the dot.



(c) Derive an equation for the acceleration of the blocks after release in terms of m_A, m_B, and physical constants, as appropriate. If you need to draw anything other than what you have shown in part (b) to assist in your solution, use the space below. Do NOT add anything to the figure in part (b).

(d) Consider the scenario from part (a)(ii), where the mass of block A is much less than the mass of block B. Does your equation for the acceleration of the blocks from part (c) agree with your reasoning in part (a)(ii)?

_____ Yes _____ No

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Briefly explain your reasoning by addressing why, according to your equation, the acceleration becomes (or approaches) a certain value when m_A is much less than m_B.

(e) While the blocks are accelerating, the tension in the vertical portion of the string is T_1. Next, the pulley of negligible mass is replaced with a second pulley whose mass is not negligible. When the blocks are accelerating in this scenario, the tension in the vertical portion of the string is T_2. How do the two tensions compare to each other?

_____ $T_2 > T_1$ _____ $T_2 = T_1$ _____ $T_2 < T_1$

Briefly explain your reasoning.

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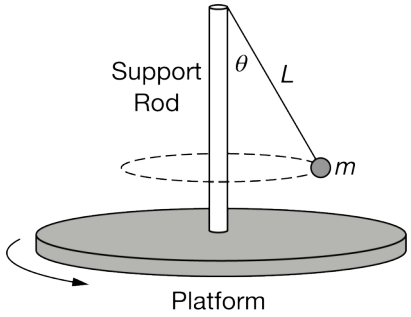
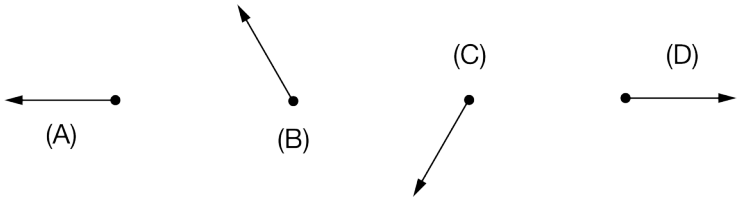
29. This question is a long free-response question. Show your work for each part of the question. (15 points, suggested time 25 minutes)



A vertical support rod is fixed at the center of a platform. A light string of length L is attached to the top of the support rod, and the other end of the string is attached to a sphere of mass m, as shown above. The platform rotates with an angular speed that can be varied. When the platform rotates with a constant angular speed ω (omega), the string makes an angle θ (theta) with the rod.



(a) Identify which of the above vectors represents the net force exerted on the sphere at the moment shown above. Briefly justify your answer.

(b) Is the magnitude of the tension in the string greater than, less than, or equal to the weight of the sphere? Explain your reasoning.

(c) The string can never be completely horizontal no matter how fast the platform is rotating. Without writing any equations or formulas, explain why.

One of the following two equations for the square of the tangential speed v of the sphere as a function of θ is consistent with the statement in part (c) that the string can never be horizontal as the platform is rotating.

Equation 1: $v^2 = \frac{gL(\sin^2\theta)}{(\cos\theta)}$ **Equation 2:** $v^2 = \frac{gL(\cos^2\theta)}{(\sin\theta)}$

(d) Indicate which equation is consistent with the statement in part (c), and explain why. Also explain why the other equation is not consistent with the statement in part (c).

(e) In a series of experimental trials, a group of students changes L and adjusts v to keep θ constant. They record L and v for each trial. Based on the equation in part (d) that you indicated as consistent with the statement in part (c), what quantities could the students graph to yield a straight line whose slope could be used to find the acceleration due to gravity, g ?

(f) Let I be the rotational inertia of the sphere-rod-platform system about a vertical axis through the center of the

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support rod. Does I increase, decrease, or stay the same when L increases (but θ stays constant)? Briefly explain your reasoning.

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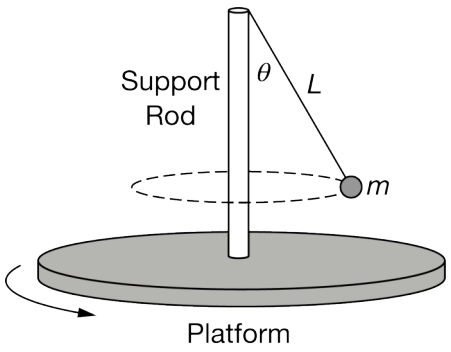
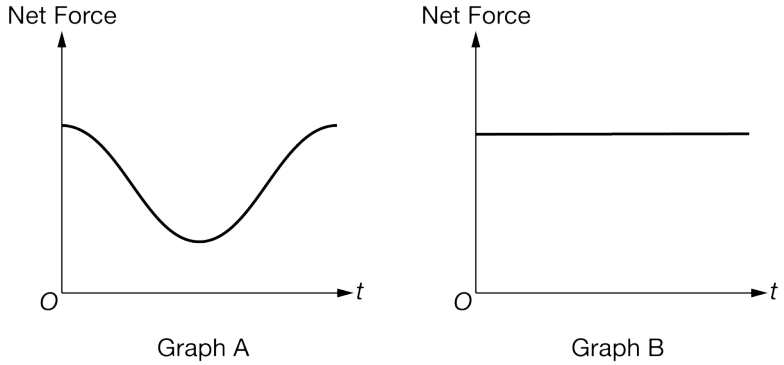
30. This question is a long free-response question. Show your work for each part of the question. (15 points, suggested time 25 minutes)



A vertical support rod is fixed at the center of a platform. A light string of length L is attached to the top of the support rod, and the other end of the string is attached to a sphere of mass m, as shown above. The platform rotates with an angular speed that can be varied. When the platform rotates with a constant angular speed ω (omega), the string makes an angle θ (theta) with the rod.



(a) The platform rotates with a constant angular speed. Which of the above graphs correctly shows the magnitude of the net force exerted on the sphere as a function of time t ? Briefly justify your answer.

(b) Is the magnitude of the tension in the string greater than, less than, or equal to the centripetal force exerted on the sphere? Explain your reasoning.

(c) The string is nearly vertical when the sphere's tangential speed is very small. Without writing any equations or formulas, explain why.

(d) A student derives an equation for the square of the tangential speed v of the sphere as a function of θ : $v^2 = gL(\tan\theta)(\sin\theta)$. Indicate whether the equation is consistent with the statement in part (c) and explain why.

(e) In a series of experimental trials, a group of students adjusts v and measures θ while keeping all other variables constant. They record v and θ for each trial. If the students use the equation given in part (d), what quantities could they graph to yield a straight line whose slope could be used to find the acceleration due to gravity, g ?

(f) Let I be the rotational inertia of the sphere-rod-platform system about a vertical axis through the center of the

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support rod. Does I increase, decrease, or stay the same when θ decreases? Briefly explain your reasoning.

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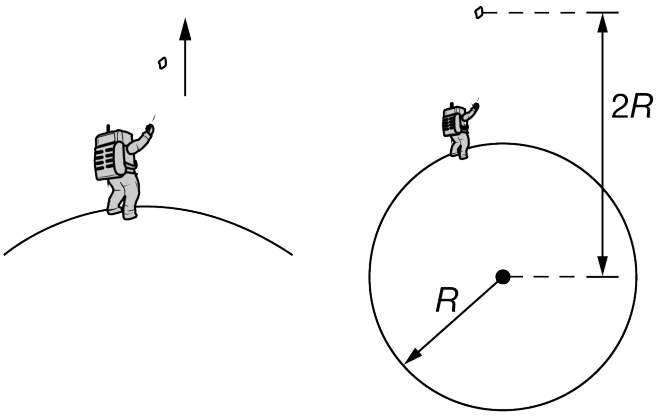
31. This question is a short free-response question. Show your work for each part of the question.

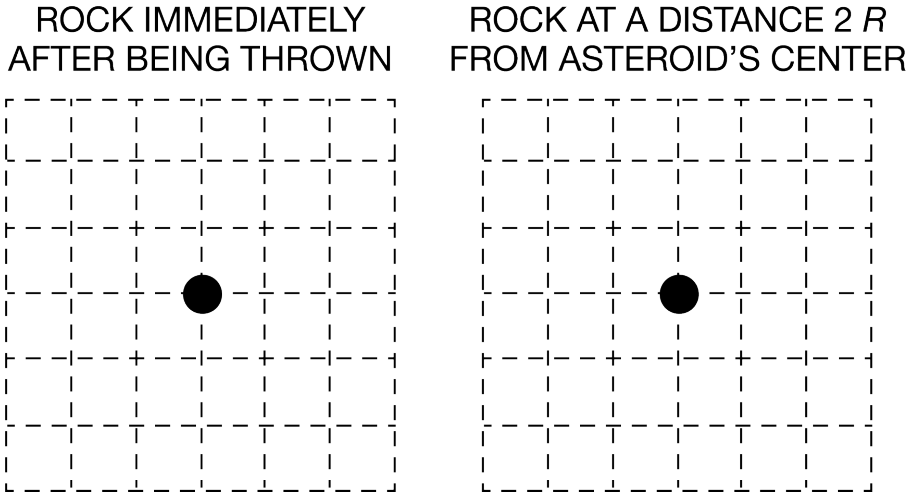


Note: Figures not drawn to scale.

An astronaut stands on the surface of a spherical asteroid that has a weak gravitational field but no atmosphere. The astronaut throws a small rock straight upward, as shown at left above. The rock travels upward until it reaches a distance of $2R$ from the center of the asteroid, where R is the asteroid's radius, and then falls back down to the asteroid's surface.

(a) The dots below represent the rock immediately after being thrown and when it is a distance $2R$ from the asteroid's center. On each dot, draw and label the forces (not components) exerted on the rock at the indicated time. Each force must be represented by a distinct arrow starting on, and pointing away from, the appropriate dot.

Note: Draw the relative lengths of all vectors to reflect the relative magnitudes of all the forces at both times.



(b) The graph at left below shows the rock's velocity as a function of time after being thrown upward with an initial velocity v_{01}. The dashed line shows what the velocity would be if the rock experienced a constant acceleration, and the solid curve shows the rock's actual velocity.

After the rock lands back on the surface, the astronaut then throws the rock straight upward a second time but with

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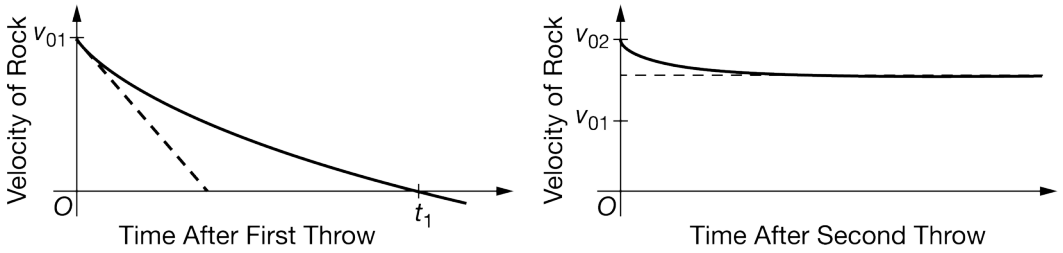
a greater force so that the rock's initial speed v_{02} is greater than initial speed v_{01} for the first throw. The graph at right below shows the rock's velocity as a function of time after being thrown upward the second time.



In a clear, coherent, paragraph-length response that may also contain equations and/or drawings, make claims for the following aspects of the rock's motion.

For the first throw, state a claim for what is happening at time t_1.
State a claim about the strength of the gravitational force exerted on the rock as the rock gets farther from the asteroid.
For the first throw, state a claim about the relationship about the strength of the gravitational force exerted on the rock as the rock gets farther from the asteroid and the behavior indicated between time 0 and t_1 in the velocity-time graph.
For the second throw, state a claim about why there is a horizontal asymptote for the velocity.

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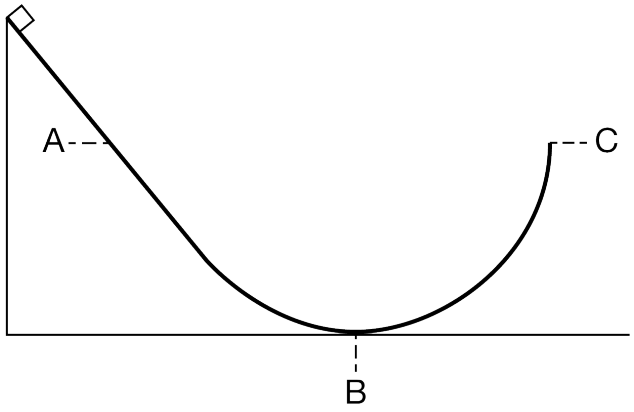
32. This question is a short free-response question. Show your work for each part of the question. (10 points, suggested time 15 minutes)



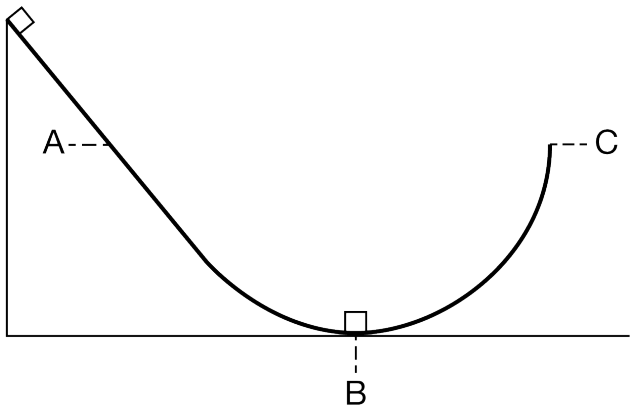
The figure above shows a track consisting of a straight section that connects to a circular section. Three locations are indicated: location A on the straight section of the track, location B at the bottommost point of the track, and location C at the point where the track is vertical. Locations A and C are at the same height. A block is released from rest at the top of the straight section of the track. There is negligible friction between the track and the block.

(a) Is the magnitude of the normal force exerted on the block by the track at location A greater than, less than, or equal to the normal force at location B? Justify your answer.

(b) In a coherent, paragraph-length response, describe the relative angle between the direction of the block's velocity and the direction of the block's acceleration at the following times.

When the block is at location A
When the block is at location B
Immediately before the block reaches location C

Specifically, indicate whether the velocity is parallel to the acceleration, perpendicular to the acceleration, or neither, at each location. Use physical principles to justify your responses.



(c) The scenario is repeated, but an identical block is at rest at location B, as shown above. When the block at the

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top of the straight section of the track is released from rest, it slides down the track and collides elastically with the identical block and comes to rest. The identical block then begins sliding up the ramp. Is the maximum height reached by the identical block greater than, less than, or equal to the maximum height reached by the block in the original scenario? Briefly explain your answer.