2026

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AP® Physics 1: Dynamics

Practice Free-Response Questions

Eight questions on forces, friction, pulleys, circular motion, and gravitation in two sets of four, written in the exam's four free-response formats, with scoring guidelines for every part.

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Online version: burketutoringinfremont.com/ap-physics-1-dynamics-frq/

PHYSICS 1: DYNAMICS
PRACTICE FREE-RESPONSE QUESTIONS
TIME: 95 MINUTES PER SET

Directions:

This booklet has eight free-response questions on Unit 2 of AP Physics 1. Questions 1 to 4 form Set A, and Questions 5 to 8 form Set B. Each set contains one question of each type used on the exam: mathematical routines, translation between representations, experimental design and analysis, and qualitative/quantitative translation.

Allow 95 minutes for each set. A steady pace is about 25 minutes each for the first three questions and 20 minutes for the fourth.

You may use a calculator, a ruler, and the AP Physics 1 reference information. Use $g = 9.8\ \text{m/s}^2$. Treat strings and pulleys as ideal and air resistance as negligible unless a question says otherwise.

Write your answers on separate paper, labeled with the part (A, B, C, D) and sub-part (i, ii, iii) they answer. Draw free-body diagrams, graphs, and best-fit lines directly on the figures in this booklet.

Show your work. Credit depends on choosing the right physics principles, writing derivations and explanations that someone else can follow, and giving units with numerical answers.

Scoring guidelines for all eight questions begin on page 18.

Reference information. The AP Physics 1 equation sheet is posted by College Board at apcentral.collegeboard.org/media/pdf/ap-physics-1-equations-sheet.pdf.

Review pages for these topics. AP Physics 1 dynamics study guide: burketutoringinfremont.com/ap-physics-1-dynamics-study-guide/
Pulley problems guide: burketutoringinfremont.com/ap-physics-1-pulley-problems/
Circular motion guide: burketutoringinfremont.com/ap-physics-1-circular-motion-problems/

Online version. Each scoring guide also sits under its question at burketutoringinfremont.com/ap-physics-1-dynamics-frq/.

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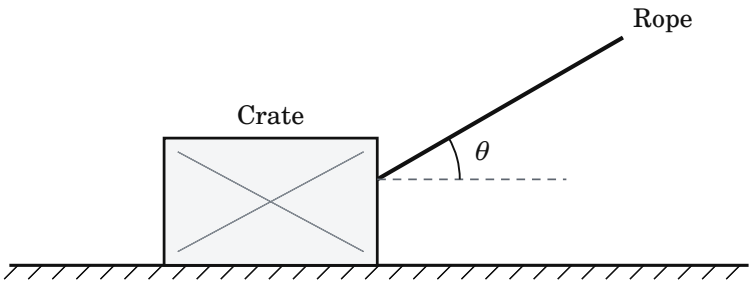
Question 1: Mathematical Routines

1. A worker slides a crate of mass M across a level warehouse floor. The coefficient of kinetic friction between the crate and the floor is μ_k. In Trip 1, the worker pulls the crate with a rope that makes an angle θ above the horizontal, as shown in Figure 1. The crate moves to the right at constant velocity. Air resistance is negligible.

Figure 1

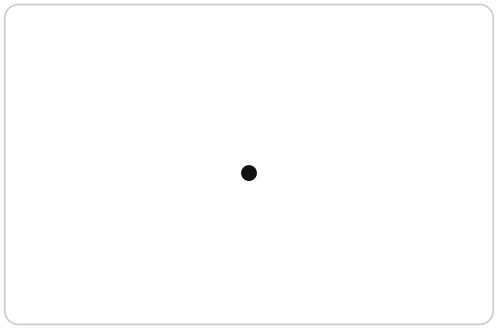


Note: Figure not drawn to scale.

Part A

i. The dot in Figure 2 represents the crate during Trip 1. On the dot, **draw** and **label** the forces (not components) exerted on the crate. Represent each force with a separate arrow that starts on the dot and points away from it. Draw the arrows so that their relative lengths show the relative magnitudes of the forces.

Figure 2



ii. **Derive** an expression for the magnitude F_T of the force exerted on the crate by the rope during Trip 1. Express your answer in terms of M, θ, μ_k, and physical constants, as appropriate. Begin with a fundamental physics principle or an equation from the reference information, and show the steps that lead to your answer.

iii. The crate has mass $M = 45$ kg, the rope makes an angle $\theta = 30°$ with the horizontal, and $\mu_k = 0.40$. **Calculate** F_T.

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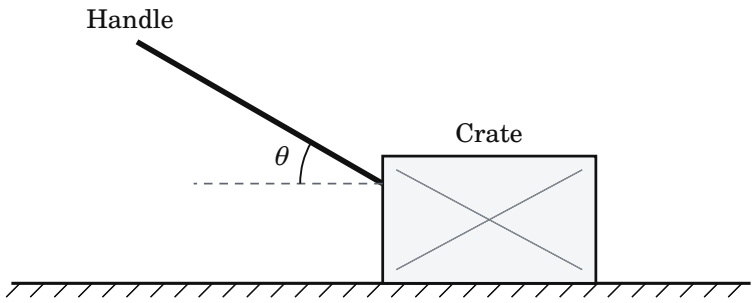
Part B

In Trip 2, the worker moves the same crate across the same floor at constant velocity by pushing on a handle with a force of magnitude F_P. The push is directed at the same angle θ below the horizontal, as shown in Figure 3.

Figure 3



Note: Figure not drawn to scale.

Indicate whether F_P is greater than, less than, or equal to F_T by writing one of the following.

- $F_P > F_T$
- $F_P < F_T$
- $F_P = F_T$

Justify your answer. Your justification must include reasoning in words, not only equations or derivations.

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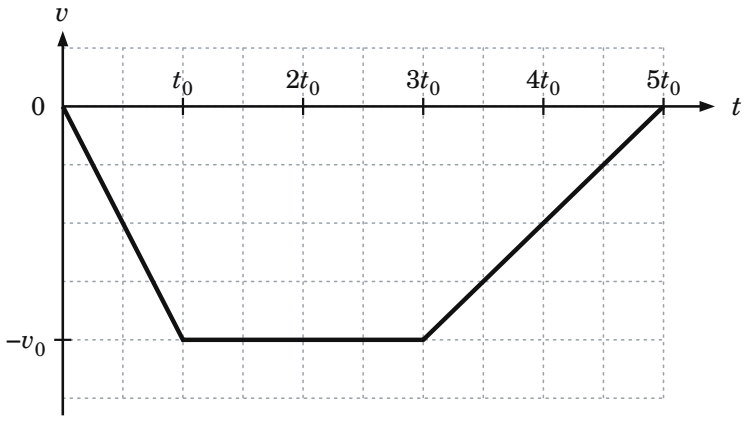
Question 2: Translation Between Representations

2. A student of mass m stands on a bathroom scale on the floor of an elevator. The elevator starts from rest, travels downward, and stops at a lower floor. Figure 1 shows the velocity v of the elevator as a function of time t from $t = 0$ to $t = 5t_0$, with upward as the positive direction. The scale reading F_{scale} is the magnitude of the force that the student exerts on the scale.

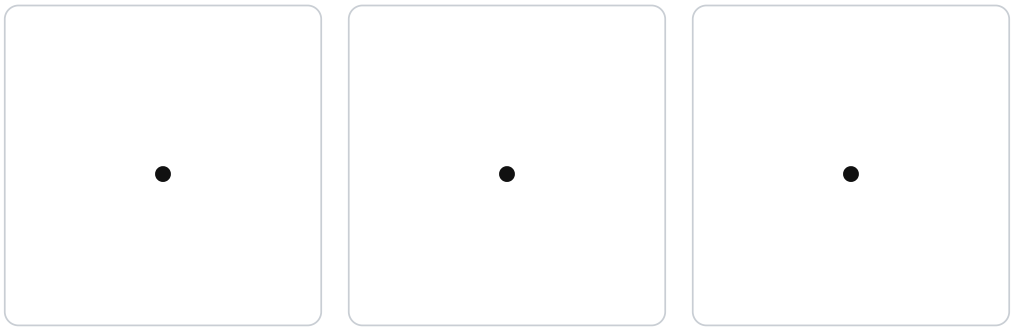
Figure 1



Part A

The dots in Figure 2 represent the student at times $t = 0.5t_0$, $t = 2t_0$, and $t = 4t_0$. On each dot, **draw** and **label** the forces (not components) exerted on the student. Represent each force with a separate arrow that starts on the dot and points away from it. Use the same scale for all three diagrams, so that the arrow lengths can be compared within each diagram and from one diagram to another.

Figure 2



$t = 0.5t_0$ $t = 2t_0$ $t = 4t_0$

Part B

Derive an expression for F_{scale} from $t = 0$ to $t = t_0$. Express your answer in terms of m, v_0, t_0, and physical constants, as appropriate. Begin with a fundamental physics principle or an equation from the reference information, and show the steps that lead to your answer.

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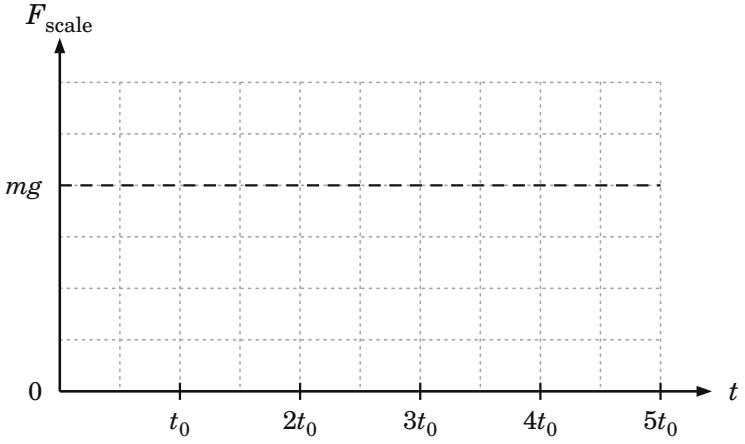
Part C

On the axes in Figure 3, **sketch** a graph of F_{scale} as a function of time t from $t = 0$ to $t = 5t_0$. The dashed line shows the value mg.

Figure 3



Part D

Indicate whether the magnitude of the force exerted on the scale by the student at $t = 4t_0$ is greater than, less than, or equal to the magnitude of the gravitational force exerted on the student by Earth.

- Greater than
- Less than
- Equal to

Justify your answer by referring to Figure 1 and to Newton's third law.

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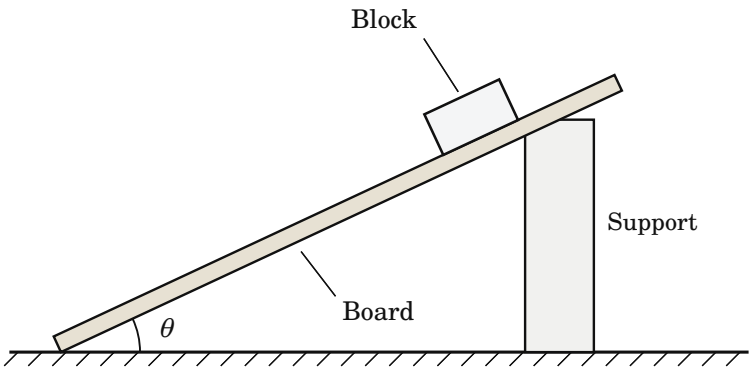
Question 3: Experimental Design and Analysis

The following information applies to Parts A and B.

3. Students want to determine the coefficient of kinetic friction μ_k between a wooden block and a long board. One end of the board can be raised so that the board makes an adjustable angle θ with the horizontal, as shown in Figure 1. The students have a protractor, a meterstick, and a stopwatch. When the angle is large enough, the block slides down the board with constant acceleration after it is released from rest.

Figure 1



Note: Figure not drawn to scale.

Part A

i. **Describe** a procedure the students could follow to collect data that would let them determine μ_k from a linear graph. Identify each quantity they would measure and the equipment they would use to measure it.

ii. Briefly **describe** one way the students could reduce the experimental uncertainty in their results.

Part B

When the board is at small angles, the block stays at rest after it is placed on the board.

i. **Describe** how the students could use the same equipment to determine the coefficient of static friction μ_s between the block and the board.

ii. **Indicate** how μ_s is related to the quantity measured in Part B(i).

The following information applies to Parts C and D.

The students release the block from rest with the board at five different angles. For each angle, they determine the magnitude a of the block's acceleration, as shown in Table 1. The students correctly

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determine that a and θ are related by $a = g \sin \theta - \mu_k g \cos \theta$. They make a graph with $a/\cos \theta$ plotted on the horizontal axis.

Table 1

θ (degrees)	a (m/s^2)		
30	2.40		
35	3.15		
40	4.09		
45	4.82		
50	5.68		

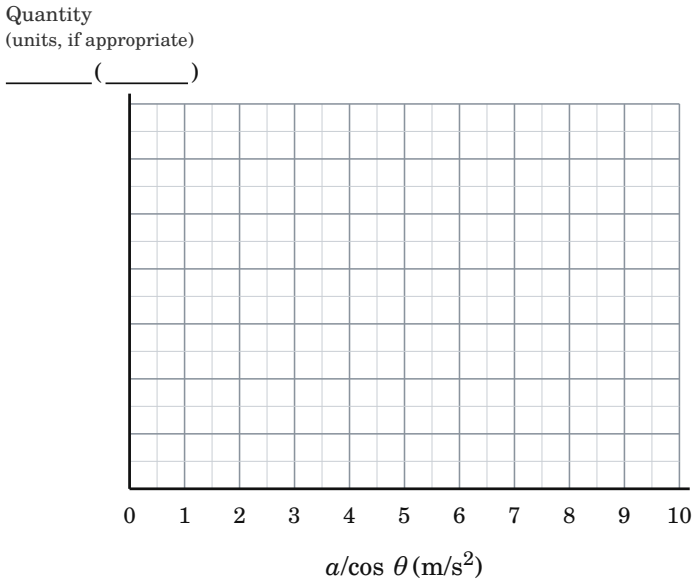
Part C

i. **Label** the vertical axis of Figure 2 with a measured or calculated quantity, with units if it has any. Choose a quantity that makes the graph linear and that can be used to determine μ_k.

ii. On the grid in Figure 2, make a graph that can be used to determine μ_k.

- Add a numerical scale to the vertical axis.
- **Plot** the data points.
- Table 1 gives space for calculations and is not scored.

Figure 2



iii. **Draw** a best-fit line through the data you plotted in Part C(ii).

Part D

Use your best-fit line from Part C(iii) to **calculate** an experimental value for μ_k.

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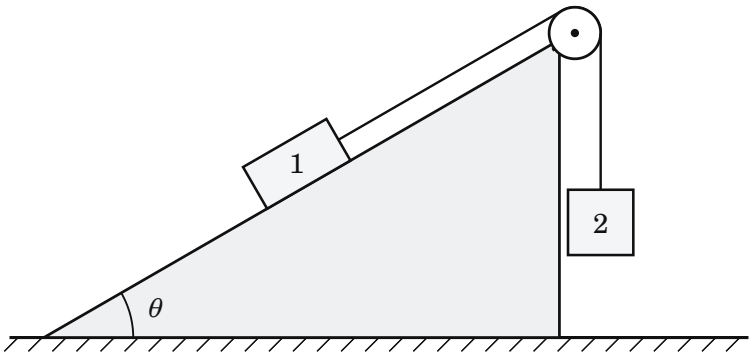
Question 4: Qualitative/Quantitative Translation

4. Block 1 of mass m_1 rests on a ramp inclined at an angle θ above the horizontal. A light string attached to block 1 runs parallel to the ramp, passes over an ideal pulley at the top of the ramp, and is attached to block 2, which hangs freely, as shown in Figure 1. The coefficient of static friction between block 1 and the ramp is μ_s. If block 2 were removed, block 1 would slide down the ramp. A student finds that both blocks remain at rest when the mass m_2 of block 2 has any value from a minimum value m_{min} to a maximum value m_{max}.

Figure 1



Note: Figure not drawn to scale.

Part A

Without deriving or using equations, **explain** why the blocks can remain at rest for a range of values of m_2 rather than for only one value. Your explanation should describe the direction of the static friction force exerted on block 1 when $m_2 = m_{min}$ and when $m_2 = m_{max}$.

Part B

Derive expressions for m_{min} and m_{max}. Express your answers in terms of m_1, θ, μ_s, and physical constants, as appropriate. Begin with a fundamental physics principle or an equation from the reference information, and show the steps that lead to your answer.

Part C

Explain how your expressions from Part B are consistent with your reasoning in Part A.

END OF SET A

Set B begins with Question 5.

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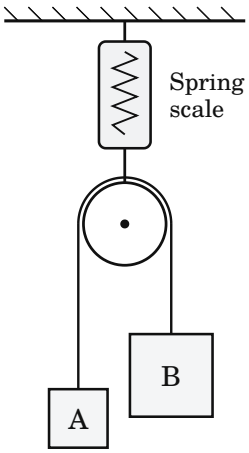
Question 5: Mathematical Routines

5. Block A of mass m and block B of mass $3m$ hang from the ends of a light string that passes over an ideal pulley, as shown in Figure 1. The axle of the pulley hangs from a spring scale attached to the ceiling. The masses of the pulley and the scale are negligible. The blocks are released from rest, and block B moves downward.

Figure 1

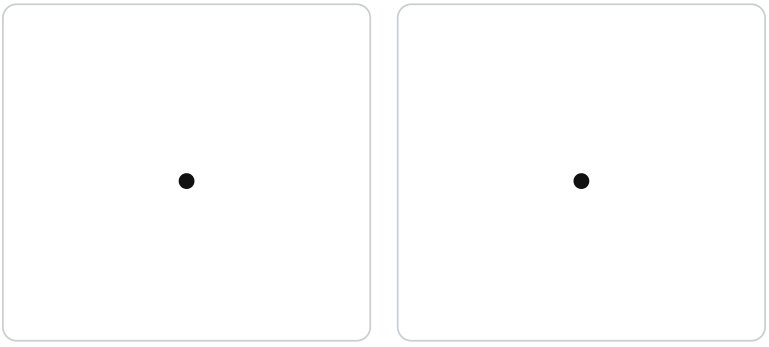


Note: Figure not drawn to scale.

Part A

i. The dots in Figure 2 represent block A and block B. On each dot, **draw** and **label** the forces (not components) exerted on that block. Represent each force with a separate arrow that starts on the dot and points away from it. Use the same scale for both diagrams.

Figure 2



Block A Block B

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ii. **Derive** an expression for the magnitude a of the acceleration of the blocks. Express your answer in terms of m and physical constants, as appropriate. Begin with a fundamental physics principle or an equation from the reference information, and show the steps that lead to your answer.

iii. **Derive** an expression for the tension F_T in the string. Express your answer in terms of m and physical constants, as appropriate.

Part B

Indicate whether the reading of the spring scale while the blocks are moving is greater than, less than, or equal to $4mg$, the combined weight of the two blocks.

- Greater than $4mg$
- Less than $4mg$
- Equal to $4mg$

Justify your answer.

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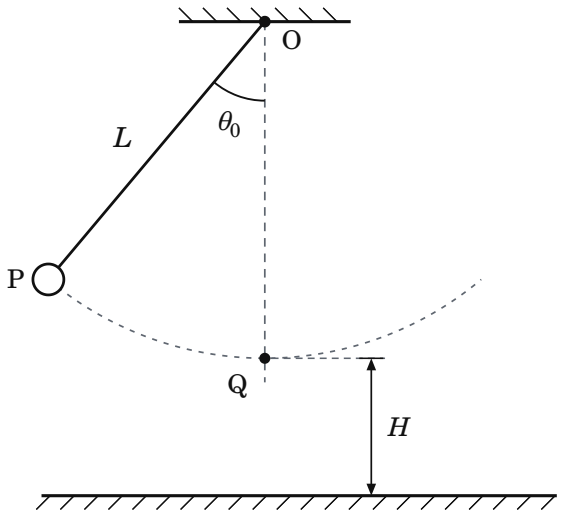
Question 6: Translation Between Representations

6. A small ball of mass m hangs from a light string of length L attached to a fixed point O. The ball is pulled to the left until the string makes an angle θ_0 with the vertical and is then released from rest at point P, as shown in Figure 1. The ball swings through point Q, the lowest point of its path, where its speed is v_Q. Point Q is a height H above the floor. Air resistance is negligible.

Figure 1

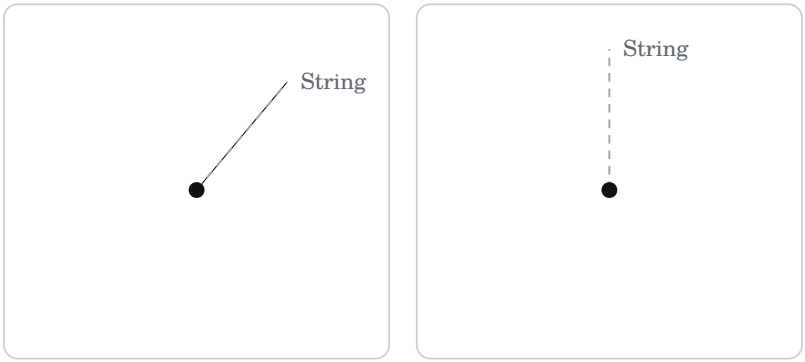


Note: Figure not drawn to scale.

Part A

The dots in Figure 2 represent the ball at point P, just after it is released, and at point Q. On each dot, **draw** and **label** the forces (not components) exerted on the ball. Represent each force with a separate arrow that starts on the dot and points away from it. Use the same scale for both diagrams. The dashed lines show the direction of the string.

Figure 2



Ball at P Ball at Q

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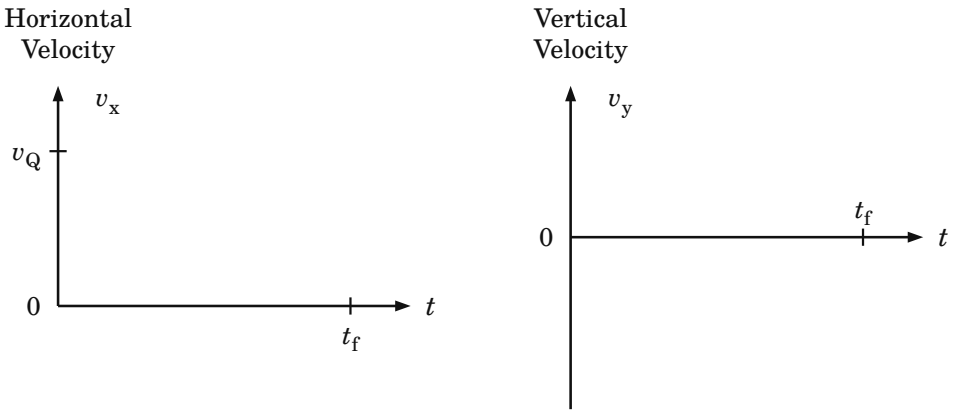
Part B

Derive an expression for the tension F_T in the string at the instant the ball passes through point Q. Express your answer in terms of m, v_Q, L, and physical constants, as appropriate. Begin with a fundamental physics principle or an equation from the reference information, and show the steps that lead to your answer.

Part C

The string is cut at the instant the ball passes through point Q while moving to the right. The ball reaches the floor at time $t = t_f$ after the string is cut. On the axes in Figure 3, **sketch** graphs of the horizontal component v_x and the vertical component v_y of the ball's velocity as functions of time from $t = 0$, the instant the string is cut, to $t = t_f$. Take right and up as the positive directions.

Figure 3



Part D

In another trial, the ball is again released from rest at point P, and this time the string is cut at a later instant when the ball is momentarily at rest at point P. **Describe** the path of the ball after the string is cut. **Explain** why the acceleration of the ball just after the string is cut is different from its acceleration just before the string is cut. Refer to your diagram for point P from Part A.

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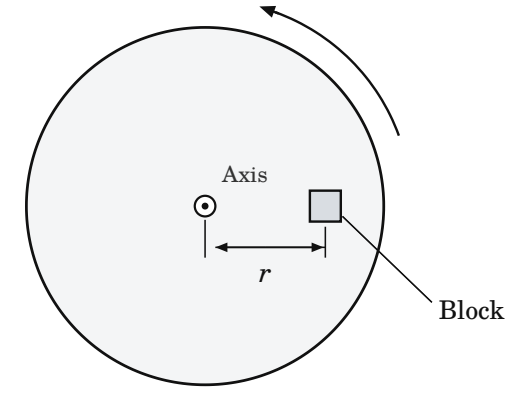
Question 7: Experimental Design and Analysis

The following information applies to Parts A and B.

7. Students want to determine the coefficient of static friction μ_s between a small rubber block and the surface of a level turntable. The turntable rotates about its center at a constant rate that the students can set with a dial. The block is placed on the turntable a distance r from the axis of rotation, as shown in Figure 1. The students have a meterstick and a stopwatch.

Figure 1



Top view

Note: Figure not drawn to scale.

Part A

i. **Describe** a procedure the students could follow to collect data that would let them determine μ_s from a linear graph. Identify each quantity they would measure and how they would measure it.

ii. Briefly **describe** one way the students could reduce the experimental uncertainty in their measurements.

Part B

i. **Indicate** the quantities that could be plotted on the horizontal and vertical axes to produce a linear graph from which μ_s could be determined. State clearly which quantity goes on each axis.

ii. Briefly **describe** how μ_s is related to a feature of the graph from Part B(i). You may include an equation that relates μ_s to that feature.

The following information applies to Parts C and D.

In a different experiment, the students test a small remote-controlled car on a level floor. The car drives in circles of radius r. For each radius, the students find the greatest constant speed v at which

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the car can complete the circle without its tires sliding sideways. The data are shown in Table 1. The students make a graph with r plotted on the horizontal axis.

Table 1

r (m)	v (m/s)		
0.40	1.62		
0.60	2.06		
0.80	2.31		
1.00	2.66		
1.20	2.85		

Part C

i. **Label** the vertical axis of Figure 2 with a measured or calculated quantity, with units if it has any. Choose a quantity that makes the graph linear and that can be used to determine the coefficient of static friction between the tires and the floor.

ii. On the grid in Figure 2, make a graph that can be used to determine that coefficient.

- Add a numerical scale to the vertical axis.
- **Plot** the data points.
- Table 1 gives space for calculations and is not scored.

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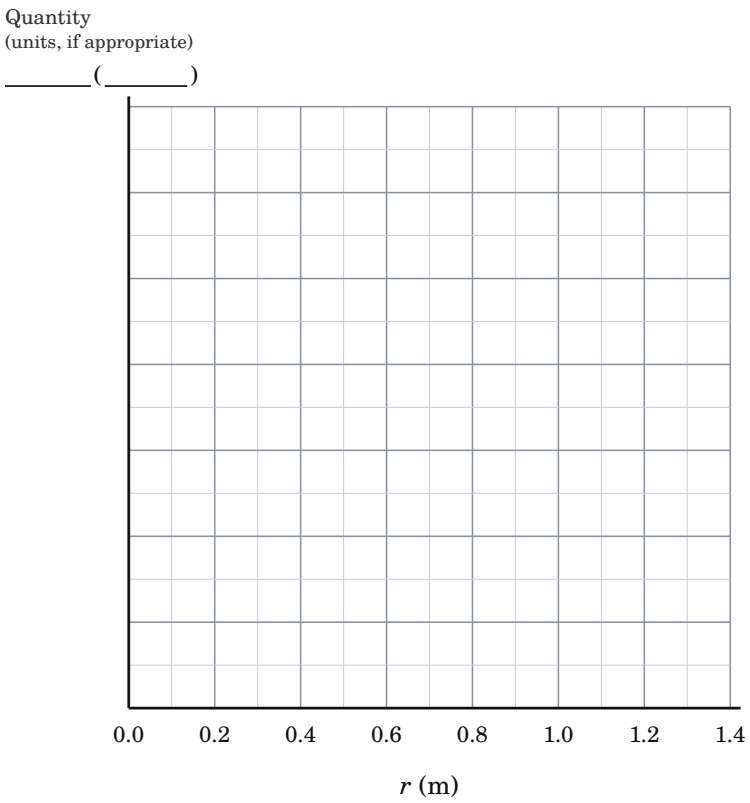
Figure 2



iii. **Draw** a best-fit line through the data you plotted in Part C(ii).

Part D

Use your best-fit line from Part C(iii) to **calculate** an experimental value for the coefficient of static friction between the tires and the floor.

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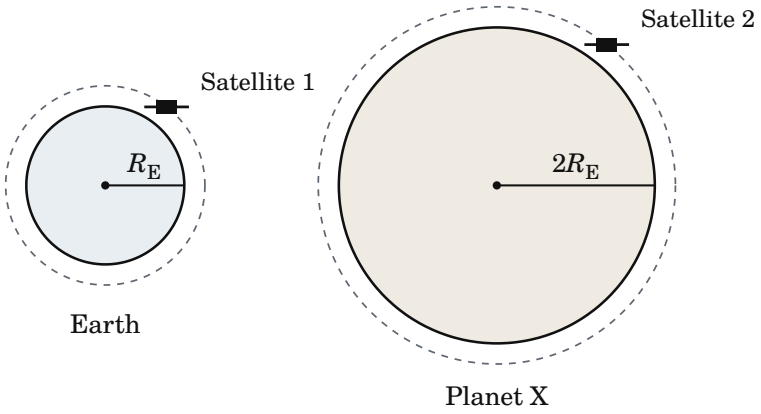
Question 8: Qualitative/Quantitative Translation

8. Planet X has twice the mass of Earth and twice the radius of Earth. Satellite 1 moves in a circular orbit just above the surface of Earth, so the radius of its orbit equals the radius of Earth, R_E. Satellite 2 moves in a circular orbit just above the surface of Planet X, as shown in Figure 1. The satellites have the same mass. Earth has mass M_E. Ignore any atmosphere, and assume the only force on each satellite is the gravitational force exerted by the planet it orbits.

Figure 1



Note: Figure not drawn to scale.

Part A

Indicate whether the orbital period T_2 of Satellite 2 is greater than, less than, or equal to the orbital period T_1 of Satellite 1 by writing one of the following.

- $T_2 > T_1$
- $T_2 < T_1$
- $T_2 = T_1$

Without deriving or using equations, **justify** your answer. Your justification should address both the strength of each planet's gravitational pull on its satellite and the size of each satellite's orbit.

Part B

Derive an expression for T_2. Express your answer in terms of M_E, R_E, and physical constants, as appropriate. Begin with a fundamental physics principle or an equation from the reference information, and show the steps that lead to your answer.

Part C

Explain how your expression from Part B is consistent with your reasoning in Part A.

STOP
END OF SET B

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Scoring Guidelines

Point totals follow the 2026 AP Physics 1 scoring guidelines: 10 points for mathematical routines, 12 for translation between representations, 10 for experimental design and analysis, and 8 for qualitative/quantitative translation, so each set is worth 40 points. Each point is listed with what earns it, and the example responses show one correct way to earn them.

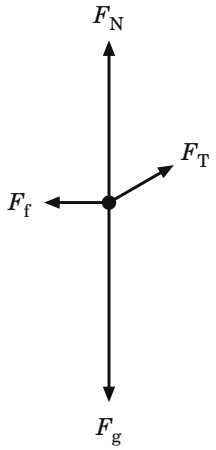
General scoring note. Equivalent physics reasoning and derivations earn the same points as the example responses. When a criterion names one method, the matching step in another correct method earns that point. For example, a single system equation can replace the two single-block equations in Question 5. In Questions 3 and 7, any pair of quantities that makes the graph linear earns credit, as long as the slope or intercept is then related to the friction coefficient correctly for that pair. On a free-body diagram, extra arrows for velocity, acceleration, or net force, or a force replaced by its components, do not earn the point for the forces.

Question 1: Mathematical Routines (MR) — 10 points

Part A(i) — 2 points

A1	For four forces with correct directions, each labeled, and no extra arrows: a downward gravitational force, an upward normal force, a force from the rope directed up and to the right along the rope, and a kinetic friction force directed to the left.	1 point
A2	For a normal force arrow shorter than the gravitational force arrow, and a friction arrow shorter than the arrow for the rope's force.	1 point

EXAMPLE RESPONSE



Scoring note: The rope pulls partly upward, so the floor supports less than the full weight and the normal force is less than Mg. The crate does not accelerate, so the friction force equals the horizontal part of the rope's force, which is less than the whole rope force.

Scoring note: Arrows for velocity or acceleration, or the rope's force drawn as two components, are extra arrows and do not earn point A1.

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Part A(ii)		3 points
A3	For applying Newton's second law with zero acceleration, or Newton's first law, in both the horizontal and the vertical directions.	1 point
A4	For a normal force of $Mg - F_T \sin\theta$, so that the friction force is $\mu_k(Mg - F_T \sin\theta)$.	1 point
A5	For a correct expression for F_T.	1 point

EXAMPLE RESPONSE

Vertical, with $a_y = 0$: $F_N + F_T \sin\theta - Mg = 0$, so $F_N = Mg - F_T \sin\theta$

Horizontal, with $a_x = 0$: $F_T \cos\theta - \mu_k F_N = 0$

$F_T \cos\theta = \mu_k(Mg - F_T \sin\theta) \rightarrow F_T(\cos\theta + \mu_k \sin\theta) = \mu_k Mg$

$$F_T = \frac{\mu_k Mg}{\cos\theta + \mu_k \sin\theta}$$

Scoring note: A response that uses Mg for the normal force can earn point A3 but not points A4 and A5.

Part A(iii)		1 point
A6	For a correct value of F_T, about 165 N, with units.	1 point

EXAMPLE RESPONSE

$$F_T = \frac{(0.40)(45\text{ kg})(9.8\text{ m/s}^2)}{\cos 30° + (0.40)(\sin 30°)} = \frac{176.4\text{ N}}{1.066} = 165\text{ N}$$

Part B		4 points
B1	For indicating $F_P > F_T$.	1 point
B2	For explaining that the push has a downward vertical component, so the floor pushes up with a normal force greater than Mg, while in Trip 1 the rope's upward component makes the normal force less than Mg.	1 point
B3	For explaining that the kinetic friction force is proportional to the normal force, so the friction force is greater in Trip 2.	1 point
B4	For explaining that at constant velocity the horizontal component of the worker's force equals the friction force in each trip, and both forces make the same angle θ with the horizontal, so the larger friction force in Trip 2 requires a larger force from the worker.	1 point

EXAMPLE RESPONSE

$F_P > F_T$. In Trip 1, the rope pulls partly upward, so the floor does not have to support the whole weight of the crate, and the normal force is less than Mg. In Trip 2, the push presses the crate into the floor, so the normal force is greater than Mg. Kinetic friction equals μ_k times the normal force, so the friction force is greater in Trip 2. In both trips the crate moves at constant velocity, so the net force is zero and the horizontal part of the worker's force equals the friction force. Both forces are at the angle θ, so the same fraction of each force, $\cos\theta$, is horizontal. The push has to balance a larger friction force, so F_P is greater than F_T.

Scoring note: Comparing $F_T = \mu_k Mg \div (\cos\theta + \mu_k \sin\theta)$ with $F_P = \mu_k Mg \div (\cos\theta - \mu_k \sin\theta)$ also earns points B2 to B4 if the response explains in words why the denominators differ: the vertical component of the worker's force lowers

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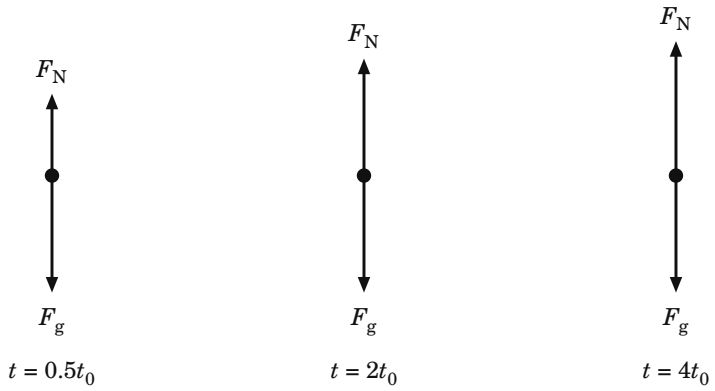
the normal force in Trip 1 and raises it in Trip 2. With the values in Part A(iii), F_P is about 265 N.

Review: The table of normal force cases and worked example 2 in the dynamics study guide show how a rope pulled at an angle changes the normal force, and static and kinetic friction explains why friction follows the normal force. If splitting a force into components is the hard step, the vectors section of the relative velocity guide practices it with drawings.

Question 2: Translation Between Representations (TBR) — 12 points

Part A		3 points
A1	For each diagram showing exactly two forces, both labeled: a downward gravitational force and an upward normal force exerted by the scale.	1 point
A2	For gravitational force arrows of equal length in all three diagrams, with the normal force arrow shorter than the gravitational force arrow at $t = 0.5t_0$ and equal to it at $t = 2t_0$.	1 point
A3	For a normal force arrow longer than the gravitational force arrow at $t = 4t_0$.	1 point

EXAMPLE RESPONSE



Scoring note: The direction of the velocity does not set the lengths. The acceleration does: downward from 0 to t_0, zero from t_0 to $3t_0$, and upward from $3t_0$ to $5t_0$.

Part B		3 points
B1	For finding the acceleration from the slope of Figure 1: $a = -v_0/t_0$, a magnitude of v_0/t_0 directed downward.	1 point
B2	For applying Newton's second law to the student, with F_{scale} equal to the magnitude of the normal force, such as $F_N - mg = m(-v_0/t_0)$.	1 point
B3	For a correct expression for F_{scale}.	1 point

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EXAMPLE RESPONSE

Slope of Figure 1 from 0 to t_0: $a = \frac{-v_0 - 0}{t_0 - 0} = -\frac{v_0}{t_0}$

Newton's second law, up positive: $F_N - mg = ma = -\frac{mv_0}{t_0}$

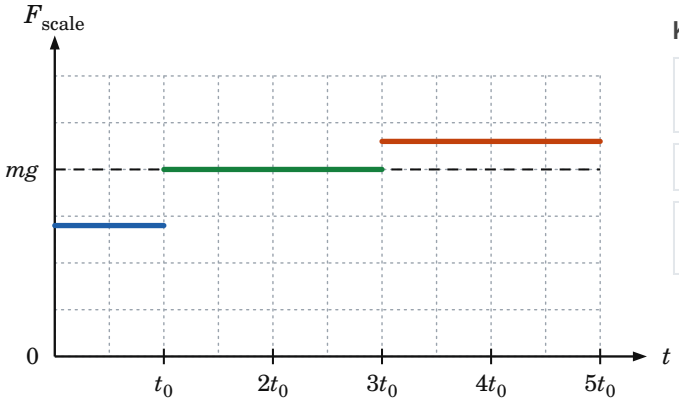
The scale pushes up on the student with F_N, and the student pushes down on the scale with a force of the same magnitude (Newton's third law), so

$F_{scale} = m(g - \frac{v_0}{t_0})$

Scoring note: A response that gives $m(g + v_0/t_0)$ can earn point B2 but not points B1 and B3.

Part C		3 points
C1	For a graph made of horizontal segments: one value from 0 to t_0, one from t_0 to $3t_0$, and one from $3t_0$ to $5t_0$.	1 point
C2	For a graph below the dashed line from 0 to t_0, on it from t_0 to $3t_0$, and above it from $3t_0$ to $5t_0$.	1 point
C3	For a drop below mg from 0 to t_0 that is twice as large as the rise above mg from $3t_0$ to $5t_0$.	1 point

EXAMPLE RESPONSE



Scoring note: From $3t_0$ to $5t_0$, the velocity changes by the same amount, v_0, over twice the time, so the acceleration has half the magnitude it had from 0 to t_0. The jumps at t_0 and $3t_0$ can be drawn as vertical lines or left as gaps.

Part D		3 points
D1	For indicating greater than.	1 point
D2	For explaining that from $3t_0$ to $5t_0$ the velocity is negative but approaching zero, so the slope of Figure 1, and the acceleration, point upward. The net force on the student is then upward, so the normal force is greater than mg.	1 point
D3	For explaining that the force exerted on the scale by the student and the force exerted on the student by the scale form a Newton's third law pair, so they have equal magnitudes.	1 point

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EXAMPLE RESPONSE

Greater than. At $t = 4t_0$ the elevator is still moving down, but Figure 1 shows its velocity getting closer to zero, so the graph has a positive slope and the acceleration points up. For the student to accelerate upward, the upward normal force from the scale must be larger than the downward gravitational force, mg. The student pushes down on the scale and the scale pushes up on the student, and these two forces are a third-law pair with equal magnitudes. So the force the student exerts on the scale is also greater than mg.

Review: Worked example 1 in the dynamics study guide finds the reading of a scale in an elevator that slows down on its way up, and its section on Newton's three laws covers third-law pairs. Reading an acceleration from the slope of a velocity graph is covered in motion graphs in the kinematics study guide.

Question 3: Experimental Design and Analysis (LAB) — 10 points

Part A		2 points
A(i)	For a procedure that measures the angle θ with the protractor, and the distance the block slides from rest and the time it takes with the meterstick and stopwatch, at several angles at which the block slides.	1 point
A(ii)	For a valid way to reduce uncertainty, such as timing several trials at each angle and averaging, using a long sliding distance so the time is large compared with reaction time, or releasing the block from the same marked point each time.	1 point

EXAMPLE RESPONSE

Mark a start line near the top of the board and a finish line a measured distance d farther down. Set the board to an angle θ, measured with the protractor, release the block from rest at the start line, and time how long it takes to reach the finish line. Find the acceleration from $d = \frac{1}{2}at^2$, so $a = 2d/t^2$. Repeat for at least five angles that are large enough for the block to slide.

Scoring note: Any correct kinematic method for finding the acceleration from measured quantities earns point A(i).

Part B		2 points
B(i)	For describing raising the board slowly, starting with the block at rest, and measuring the angle at which the block just begins to slide.	1 point
B(ii)	For indicating that μ_s is the tangent of that angle.	1 point

EXAMPLE RESPONSE

Place the block on the board while it is level and raise one end slowly until the block just starts to slide. Measure that angle, θ_c, with the protractor, and repeat several times. Just before the block slips, static friction is at its maximum, $\mu_s mg \cos \theta_c$, and it balances the downhill component of gravity, $mg \sin \theta_c$. So $\mu_s = \tan \theta_c$.

Part C		4 points
C(i)	For labeling the vertical axis with a quantity that makes the graph linear with $a/\cos \theta$ on the horizontal axis, such as $\tan \theta$, which has no units.	1 point
C(ii)	For a linear numerical scale on the vertical axis that uses at least half of the grid.	1 point

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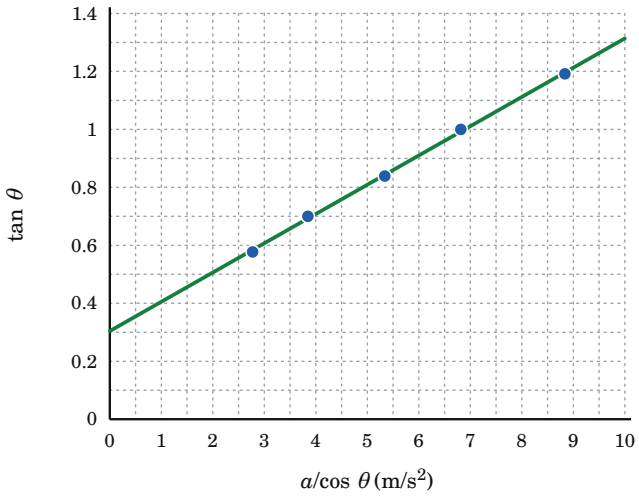
C(iii)	For plotting the five data points correctly for the chosen quantity.	1 point
C(iv)	For a straight best-fit line that follows the trend of the data, with points on both sides of the line.	1 point

EXAMPLE RESPONSE



Key

Data points ($a/\cos\theta$, $\tan\theta$)

Best-fit line: slope about 0.101 s²/m, crosses the vertical axis at about 0.30

Values plotted

θ (°)	$\tan\theta$	$a/\cos\theta$ (m/s²)
30	0.577	2.77
35	0.700	3.85
40	0.839	5.34
45	1.000	6.82
50	1.192	8.84

Scoring note: Dividing $a = g\sin\theta - \mu_k g\cos\theta$ by $g\cos\theta$ gives $\tan\theta = \frac{1}{g}(a/\cos\theta) + \mu_k$. Plotting $g\tan\theta$ on the vertical axis also makes the graph linear and earns point C(i).

Part D		**2 points**
D(i)	For relating a feature of the graph to μ_k correctly for the quantity plotted in Part C. For $\tan\theta$ versus $a/\cos\theta$, μ_k is the vertical intercept. For $g\tan\theta$, the intercept is $\mu_k g$.	1 point
D(ii)	For a value of μ_k between 0.26 and 0.34.	1 point

EXAMPLE RESPONSE

$\tan\theta = \frac{1}{g}(a/\cos\theta) + \mu_k$, so the vertical intercept of the graph is μ_k.

The best-fit line crosses the vertical axis at about 0.30, so $\mu_k \approx 0.30$.

Check with two points on the line, (2.0 m/s², 0.51) and (9.0 m/s², 1.21): slope = (1.21 – 0.51) ÷ (9.0 – 2.0) m/s² = 0.100 s²/m, close to $1/g$ = 0.102 s²/m.

Scoring note: The angle at which the block would slide at constant velocity has $\tan\theta = \mu_k$, which is where the best-fit line meets the vertical axis (a = 0).

Review: Friction on an incline in the dynamics study guide sets up the forces on a block on a tilted board, and its incline animation shows the friction force at every angle. Feynman's lecture on the characteristics of force describes measuring a friction coefficient with a tilted plane and explains why the coefficient is only approximately constant.

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Question 4: Qualitative/Quantitative Translation (QQT) — 8 points

Part A		3 points
A1	For explaining that when $m_2 = m_{\text{min}}$, block 1 is about to slide down the ramp, so static friction points up the ramp and helps the string hold block 1.	1 point
A2	For explaining that when $m_2 = m_{\text{max}}$, block 1 is about to be pulled up the ramp, so static friction points down the ramp, against the pull of the string.	1 point
A3	For explaining that static friction can take any magnitude up to its maximum, in whichever direction keeps block 1 at rest, so it can make up the difference between the pull of the string and the downhill pull of gravity for every hanging mass between the two limits.	1 point

EXAMPLE RESPONSE

Static friction adjusts to whatever keeps block 1 at rest, up to a maximum value, and it can point either way along the ramp. With a light block 2, the string pulls up the ramp less than gravity pulls block 1 down the ramp, so block 1 tends to slide down and friction points up the ramp. At $m_2 = m_{\text{min}}$, that friction is at its maximum. As m_2 increases, the string pulls harder, so less friction is needed. The friction reaches zero when the string alone balances the downhill pull, and then it points down the ramp. At $m_2 = m_{\text{max}}$, block 1 is about to be pulled up the ramp and friction is at its maximum down the ramp. Every mass in between can be balanced, so there is a range. On a frictionless ramp, only the one mass whose weight equals the downhill pull of gravity on block 1 would hold it.

Part B		3 points
B1	For applying Newton's second law with zero acceleration to both blocks: $F_{\text{T}} = m_2 g$ for block 2, $F_{\text{N}} = m_1 g \cos\theta$ for block 1, and a force balance along the ramp that includes the friction force.	1 point
B2	For a correct expression for m_{min}.	1 point
B3	For a correct expression for m_{max}.	1 point

EXAMPLE RESPONSE

Block 2: $F_{\text{T}} - m_2 g = 0$, so $F_{\text{T}} = m_2 g$. Block 1, perpendicular to the ramp: $F_{\text{N}} = m_1 g \cos\theta$

At m_{min}, friction acts up the ramp at its maximum: $m_{\text{min}} g + \mu_s m_1 g \cos\theta - m_1 g \sin\theta = 0$

$m_{\text{min}} = m_1(\sin\theta - \mu_s \cos\theta)$

At m_{max}, friction acts down the ramp at its maximum: $m_{\text{max}} g - \mu_s m_1 g \cos\theta - m_1 g \sin\theta = 0$

$m_{\text{max}} = m_1(\sin\theta + \mu_s \cos\theta)$

Part C		2 points
C1	For explaining that the two expressions differ only in the sign of the friction term, $\mu_s \cos\theta$: it is subtracted in m_{min}, where friction acts up the ramp and helps the string, and added in m_{max}, where friction acts down the ramp and the string must also overcome it, matching the directions in Part A.	1 point

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C2	For explaining that the width of the range, $m_{max} - m_{min} = 2\mu_s m_1 \cos\theta$, comes from friction and shrinks to zero as μ_s approaches zero, leaving the single value $m_1 \sin\theta$ for a frictionless ramp.	1 point

EXAMPLE RESPONSE

Consistent. In m_{min}, the friction term $\mu_s \cos\theta$ is subtracted, because friction acts up the ramp along with the string, so less hanging weight is needed. In m_{max}, the term is added, because friction acts down the ramp and the string must overcome it too. The difference, $2\mu_s m_1 \cos\theta$, comes entirely from friction. With $\mu_s = 0$, both expressions become $m_1 \sin\theta$, the single mass that a frictionless ramp would allow, which matches the reasoning in Part A.

Scoring note: Another limiting case connected to Part A also earns point C2. For example, at $\theta = 0$, m_{max} becomes $\mu_s m_1$, the largest hanging mass a level table can hold at rest.

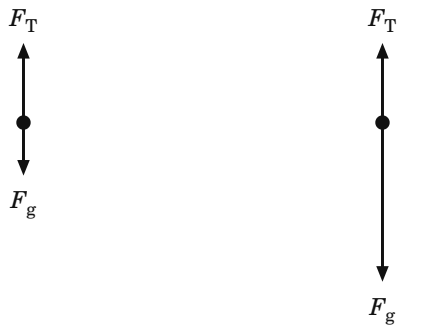
Review: Block on an incline in the pulley problems guide uses the same setup with the blocks moving, and its pulley animation shows a range of hanging masses that leaves the blocks at rest. Block on a table covers the level case, and static and kinetic friction in the dynamics study guide explains why static friction can point either way.

Question 5: Mathematical Routines (MR) — 10 points

Part A(i) — 2 points

A1	For each diagram showing exactly two forces, both labeled: an upward tension force exerted by the string and a downward gravitational force.	1 point
A2	For tension arrows of equal length in the two diagrams, longer than the gravitational force arrow on block A and shorter than the gravitational force arrow on block B.	1 point

EXAMPLE RESPONSE



Block A Block B

Scoring note: The gravitational force on block B is three times the one on block A. That ratio is shown in the example but is not required for point A2.

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Part A(ii)		3 points
A3	For applying Newton's second law to each block, or to the two blocks as one system, with the tension included in each single-block equation.	1 point
A4	For using the same magnitude of acceleration for both blocks, with block A accelerating upward and block B downward.	1 point
A5	For $a = g/2$.	1 point

EXAMPLE RESPONSE

Block A, up positive: $F_T - mg = ma$

Block B, down positive: $3mg - F_T = 3ma$

Adding the two equations: $2mg = 4ma$, so $a = \frac{g}{2}$

Scoring note: Treating both blocks as one system moving along the string gives $(3m - m)g = (4m)a$ in one step and earns points A3 and A4.

Part A(iii)		2 points
A6	For using the acceleration from Part A(ii) in Newton's second law for one of the blocks.	1 point
A7	For $F_T = 3mg/2$.	1 point

EXAMPLE RESPONSE

$F_T = m(g + a) = m(g + \frac{g}{2}) = \frac{3mg}{2}$

Check with block B: $F_T = 3m(g - a) = 3m(\frac{g}{2}) = \frac{3mg}{2}$

Part B		3 points
B1	For indicating less than $4mg$.	1 point
B2	For relating the scale reading to the forces, such as: the scale holds up the pulley, which does not accelerate and has negligible mass, against the two sections of string pulling down on it, so the reading is $2F_T$; or the force from the scale and the total weight, $4mg$, are the only external forces on the system of the pulley, the string, and both blocks.	1 point
B3	For completing the comparison with $4mg$, such as: $2F_T = 2(3mg/2) = 3mg$, which is less than $4mg$; or the heavier block speeds up downward while the lighter block speeds up upward, so the center of mass of the system accelerates downward, the net external force is downward, and the force from the scale is less than the total weight.	1 point

EXAMPLE RESPONSE

Less than $4mg$. The pulley does not accelerate and its mass is negligible, so the upward force from the scale balances the two sections of string that pull down on it. The scale reading is $2F_T = 2(3mg/2) = 3mg$, which is less than $4mg$.

Scoring note: A complete pulley-force argument showing that the scale reading equals twice the string tension, giving $3mg < 4mg$, earns all three Part B points. A separate center-of-mass explanation is not required.

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Scoring note: Alternate solution (center of mass): treat the pulley, the string, and both blocks as one system. Its external forces are the upward force from the scale and the total weight, $4mg$. Block B speeds up downward while block A speeds up upward, both at $g/2$, so the center of mass accelerates downward at $(3m \cdot g/2 - m \cdot g/2) \div 4m = g/4$. Newton's second law for the system gives $4mg$ – (scale reading) = $4m(g/4)$, so the scale reads $3mg$. This argument earns points B2 and B3.

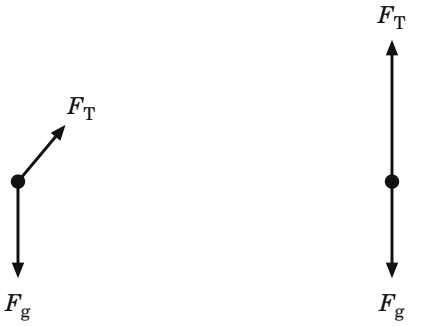
Review: The Atwood machine section of the pulley problems guide derives the same acceleration and tension and shows that the support holding a massless pulley pulls up with twice the tension, the relation Part B uses. System method and object method explains when the tension drops out of the equations.

Question 6: Translation Between Representations (TBR) — 12 points

Part A — 3 points

A1	For each diagram showing exactly two forces, both labeled: a downward gravitational force and a tension force directed along the string toward point O.	1 point
A2	For a tension arrow at P that points up along the string, at the angle θ_0 from the vertical, and is shorter than the gravitational force arrow.	1 point
A3	For a vertical tension arrow at Q that is longer than the gravitational force arrow.	1 point

EXAMPLE RESPONSE



Ball at P Ball at Q

Scoring note: At P the ball is momentarily at rest, so it has no acceleration toward O, and the tension balances only the component of the gravitational force along the string: $F_T = mg \cos \theta_0$, which is less than mg. At Q the ball moves on a circle around O, so the net force points up, toward O.

Part B — 3 points

B1	For identifying that at Q the ball's acceleration is v_Q^2/L, directed up toward O.	1 point
B2	For applying Newton's second law along the vertical: $F_T - mg = mv_Q^2/L$.	1 point
B3	For a correct expression for F_T.	1 point

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EXAMPLE RESPONSE

At Q the ball moves on a circle of radius L, so its acceleration is $\frac{v_Q^2}{L}$, directed up toward O.

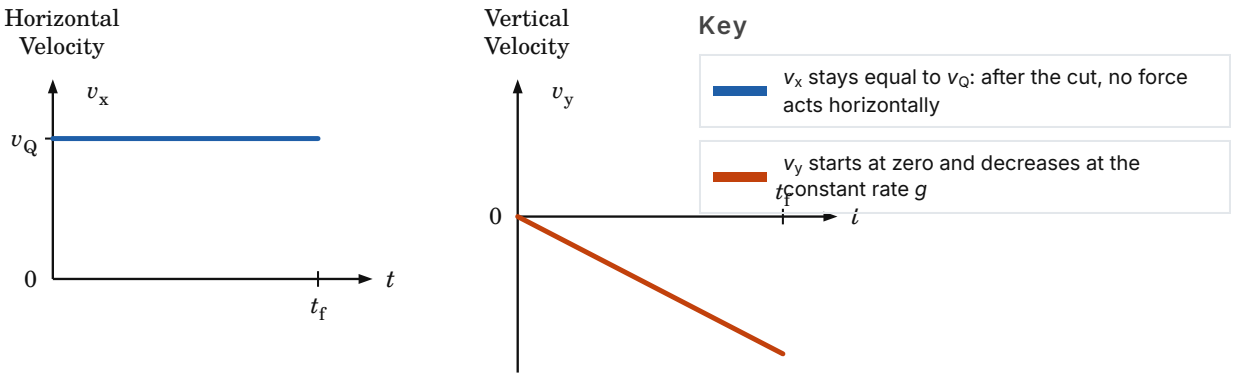
Newton's second law, up positive: $F_T - mg = \frac{mv_Q^2}{L}$

$F_T = mg + \frac{mv_Q^2}{L}$

Scoring note: A response that sets the net force equal to zero at Q, giving $F_T = mg$, earns none of the Part B points: the ball is changing direction at Q, so it is accelerating.

Part C		3 points
C1	For a v_x graph that is a horizontal line at the positive value v_Q from $t = 0$ to t_f.	1 point
C2	For a v_y graph that starts at zero at $t = 0$.	1 point
C3	For a v_y graph that is a straight line with negative slope from $t = 0$ to t_f.	1 point

EXAMPLE RESPONSE



Scoring note: The slope of the v_y graph is $-g$, and its value at t_f is $-gt_f$. Values are not required.

Part D		3 points
D1	For describing a path straight down from point P.	1 point
D2	For explaining that just before the cut, the tension cancels only the part of the gravitational force along the string, so the net force, $mg \sin \theta_0$, is perpendicular to the string, along the arc, and the acceleration is $g \sin \theta_0$ in that direction.	1 point
D3	For explaining that just after the cut the tension is gone, so gravity is the only force and the acceleration is g straight down. Because the velocity is zero at that instant, the ball falls straight down.	1 point

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EXAMPLE RESPONSE

The ball falls straight down from P. At the instant the string is cut, the ball is momentarily at rest, and after the cut gravity is the only force on it, so it starts from rest with an acceleration of g straight down, like a dropped object. Just before the cut, the diagram for point P has two forces. The tension points along the string and cancels only the part of the gravitational force along the string, $mg \cos \theta_0$. The rest of the gravitational force, $mg \sin \theta_0$, is perpendicular to the string, so the acceleration just before the cut is $g \sin \theta_0$, along the arc. Cutting the string removes the tension, so the acceleration becomes larger and changes direction, to g straight down.

Review: The pendulum section of the circular motion guide covers the forces at the bottom and at the ends of a swing, and when the string is cut works through what happens next. After a cut at Q, the ball moves like a projectile launched horizontally from a height, as in projectiles launched from a platform in the projectile motion guide, and a ball that starts from rest falls like an object dropped from a height.

Question 7: Experimental Design and Analysis (LAB) — 10 points

Part A		2 points
A(i)	For a procedure that finds, for several radii (or several rotation rates), the condition at which the block just begins to slide, measuring the radius r with the meterstick and the period T of the turntable with the stopwatch.	1 point
A(ii)	For a valid way to reduce uncertainty, such as timing 10 rotations and dividing by 10, repeating each trial and averaging, or raising the rotation rate in small steps near the slipping point.	1 point

EXAMPLE RESPONSE

Place the block at a measured distance r from the center. Start the turntable slowly and raise the rate in small steps, waiting a few seconds at each setting. At the first setting where the block slides, time 10 rotations with the stopwatch and divide by 10 to find the period T. Repeat for five different radii.

Scoring note: A procedure that fixes the rotation rate and moves the block outward until it slides, measuring the largest radius at which it stays in place, also earns point A(i).

Part B		2 points
B(i)	For a pair of quantities that gives a linear graph, such as T^2 on the vertical axis and r on the horizontal axis.	1 point
B(ii)	For relating a feature of the graph to μ_s correctly for the quantities chosen. For T^2 versus r, the slope is $4\pi^2/(\mu_s g)$, so $\mu_s = 4\pi^2/(g \times \text{slope})$.	1 point

EXAMPLE RESPONSE

When the block is about to slide, maximum static friction supplies the net force toward the center: $\mu_s mg = \frac{mv^2}{r}$, with $v = \frac{2\pi r}{T}$

$\mu_s g = \frac{4\pi^2 r}{T^2}$, so $T^2 = \frac{4\pi^2}{\mu_s g}\, r$

A graph of T^2 versus r is a straight line through the origin with slope $\frac{4\pi^2}{\mu_s g}$.

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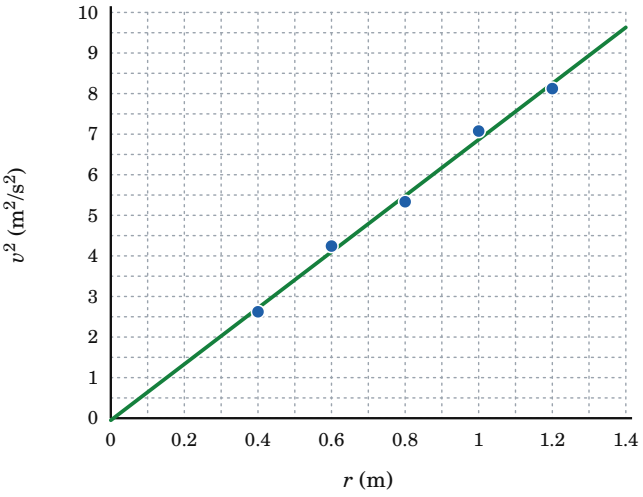
Scoring note: Other linear pairs earn credit, such as r versus T^2, with slope $\mu_s g/(4\pi^2)$, when the slope is related to μ_s correctly.

Part C		4 points
C(i)	For labeling the vertical axis with a quantity that makes the graph linear with r on the horizontal axis, such as v^2 in m^2/s^2.	1 point
C(ii)	For a linear numerical scale on the vertical axis that uses at least half of the grid.	1 point
C(iii)	For plotting the five data points correctly for the chosen quantity.	1 point
C(iv)	For a straight best-fit line that follows the trend of the data, with points on both sides of the line.	1 point

EXAMPLE RESPONSE



Key

- Data points (r, v^2)
- Best-fit line: slope about 6.9 m/s^2, passing close to the origin

Values plotted

r (m)	v^2 (m^2/s^2)
0.40	2.62
0.60	4.24
0.80	5.34
1.00	7.08
1.20	8.12

Scoring note: At the top speed, maximum static friction supplies the net force toward the center: $\mu_s mg = mv^2/r$, so $v^2 = \mu_s g r$. The graph of v^2 versus r is linear and passes through the origin.

Part D		2 points
D(i)	For relating the slope to the coefficient correctly for the quantity plotted. For v^2 versus r, the slope is $\mu_s g$, so μ_s = slope ÷ g.	1 point
D(ii)	For a value of the coefficient between 0.63 and 0.77.	1 point

EXAMPLE RESPONSE

Two points on the best-fit line: (0.30 m, 2.02 m^2/s^2) and (1.20 m, 8.25 m^2/s^2)

slope = (8.25 – 2.02) m^2/s^2 ÷ (1.20 – 0.30) m = 6.92 m/s^2

$$\mu_s = \frac{\text{slope}}{g} = \frac{6.92\ \text{m/s}^2}{9.8\ \text{m/s}^2} = 0.71$$

Review: The rule for circular motion explains what supplies the net force toward the center, and banked road problems in the circular motion guide show how banking a curve reduces the friction a car needs. Static and kinetic friction in the dynamics study guide explains why a surface that is not sliding uses static friction.

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Question 8: Qualitative/Quantitative Translation (QQT) — 8 points

Part A — 3 points

A1	For indicating $T_2 > T_1$.	1 point
A2	For explaining that the gravitational pull on each kilogram of a satellite at the surface of Planet X is half as strong as at the surface of Earth: twice the mass doubles the pull, and twice the distance from the center reduces it to one fourth.	1 point
A3	For connecting the pull to the orbit: Satellite 2 travels a path twice as long while held by a weaker pull, so it takes longer to complete an orbit. For example, at the same speed, a circle twice as large needs only half the centripetal acceleration, which matches the half-strength pull, so Satellite 2 moves at the same speed as Satellite 1 over a path twice as long.	1 point

EXAMPLE RESPONSE

$T_2 > T_1$. Satellite 2 is twice as far from the center of its planet as Satellite 1, which by itself would make the gravitational pull one fourth as strong, and Planet X has twice the mass, which doubles it. So the pull on each kilogram of Satellite 2 is half as strong. A satellite stays in a circular orbit when gravity supplies exactly the centripetal acceleration it needs. At the same speed, a circle twice as large needs only half the centripetal acceleration, which is what the half-strength pull provides. So Satellite 2 moves at the same speed as Satellite 1, but each orbit is twice as long, and it takes twice as long to complete.

Scoring note: Reasoning that both effects lengthen the period, a larger orbit to travel and a weaker pull keeping the satellite on it, also earns point A3. A response that says Satellite 2 moves faster does not earn point A3.

Part B — 3 points

B1	For setting the gravitational force equal to the satellite's mass times its centripetal acceleration, with a mass of $2M_E$ and a radius of $2R_E$.	1 point
B2	For relating the speed to the period: $v = 2\pi(2R_E)/T_2$.	1 point
B3	For a correct expression for T_2.	1 point

EXAMPLE RESPONSE

$$\frac{G(2M_E)m}{(2R_E)^2} = \frac{mv^2}{2R_E} \rightarrow v^2 = \frac{G(2M_E)}{2R_E} = \frac{GM_E}{R_E}$$

$$T_2 = \frac{2\pi(2R_E)}{v} = \frac{4\pi R_E}{\sqrt{\frac{GM_E}{R_E}}} = 4\pi\sqrt{\frac{R_E^3}{GM_E}}$$

Part C — 2 points

C1	For comparing with the same derivation for Satellite 1, $T_1 = 2\pi\sqrt{(R_E^3/GM_E)}$, to show that $T_2 = 2T_1$, greater than T_1, as in Part A.	1 point
C2	For connecting the derivation to the reasoning, such as: the speed $\sqrt{(GM_E/R_E)}$ is the same for both satellites because the planet's mass and the orbit's radius are both doubled, and the circumference is twice as large for Satellite 2.	1 point

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EXAMPLE RESPONSE

Consistent. The same steps for Satellite 1 give $T_1 = 2\pi\sqrt{\frac{{R_E}^3}{GM_E}}$, so $T_2 = 2T_1$. In the derivation, doubling the mass of the planet and doubling the radius leave the speed unchanged, because the speed depends on the planet's mass divided by the orbit's radius. The period is the circumference divided by the speed, and the circumference of Satellite 2's orbit is twice as large. That matches Part A: the same speed over a path twice as long.

Review: Gravity and satellite orbits in the circular motion guide derives the orbital speed and period from Newton's second law, and Question 12 in its practice set compares two satellites around the same planet.

Score Tracker

Record the points you earned on each question, using the scoring guidelines above. Each set is worth 40 points.

Question	Type	Topic	Possible	Earned
Question 1	Mathematical Routines	Pulling and pushing a crate	10	
Question 2	Translation Between Representations	An elevator ride on a scale	12	
Question 3	Experimental Design and Analysis	Friction on a tilted board	10	
Question 4	Qualitative/Quantitative Translation	A block held on a rough ramp	8	
Set A total			**40**	
Question 5	Mathematical Routines	An Atwood machine on a spring scale	10	
Question 6	Translation Between Representations	A pendulum with a cut string	12	
Question 7	Experimental Design and Analysis	Static friction in a circle	10	
Question 8	Qualitative/Quantitative Translation	Orbits around two planets	8	
Set B total			**40**	

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