2026

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AP® Physics 1: Pulley Problems

Practice Multiple-Choice and Free-Response Questions

Twelve questions on pulleys and connected objects in the formats of the AP Physics 1 exam, with an answer key, explanations for every multiple-choice answer, and scoring guidelines for every free-response part.

Section I	Questions 1 to 8, multiple choice, about 16 minutes
Section II	Questions 9 to 12, one free-response question of each type, 95 minutes
Answer key	Explanations and scoring guidelines begin on page 14

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PHYSICS 1: PULLEY PROBLEMS
PRACTICE QUESTIONS
SECTION I: 8 QUESTIONS · SECTION II: 4 QUESTIONS

Directions:

This booklet has 12 questions on pulleys and connected objects from Unit 2 of AP Physics 1. Questions 1 to 8 are multiple choice, with four answer choices and one correct answer each. Questions 9 to 12 are free response, one of each type used on the exam: mathematical routines, translation between representations, experimental design and analysis, and qualitative/quantitative translation.

Allow about 16 minutes for Questions 1 to 8 and 95 minutes for Questions 9 to 12. These times follow the pace of the exam.

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

Mark your answers to Questions 1 to 8 on the grid below. Write your answers to Questions 9 to 12 on separate paper, labeled with the part (A, B, C, D) and sub-part (i, ii, iii) they answer. Draw arrows, graphs, and best-fit lines directly on the figures in this booklet.

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

The answer key and scoring guidelines begin on page 14.

SECTION I ANSWER GRID

1	A	B	C	D	5	A	B	C	D
2	A	B	C	D	6	A	B	C	D
3	A	B	C	D	7	A	B	C	D
4	A	B	C	D	8	A	B	C	D

Review pages for these topics. Pulley problems guide, with worked examples and an animation: burketutoringinfremont.com/ap-physics-1-pulley-problems/

AP Physics 1 kinematics study guide: burketutoringinfremont.com/ap-physics-1-kinematics-study-guide/

Online version. Each explanation and scoring guide also sits under its question at burketutoringinfremont.com/ap-physics-1-pulley-problems/#practice.

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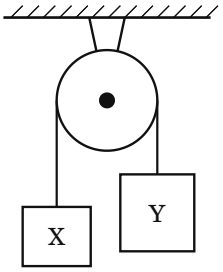
Section I: Multiple Choice — Questions 1 to 8

1. Block X of mass m and block Y of mass $2m$ are connected by a light string that passes over an ideal pulley, as shown. The blocks are released from rest. Which of the following expressions gives the tension in the string while the blocks are moving?



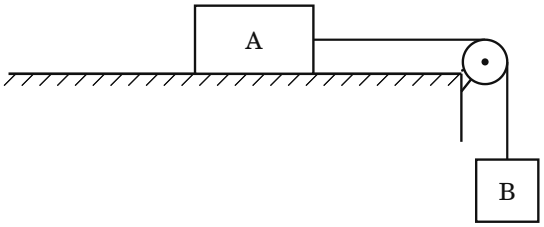
(A) mg

(B) $\frac{3}{2}mg$

(C) $\frac{4}{3}mg$

(D) $2mg$

2. Block A of mass 4.0 kg sits on a horizontal table. A light string attached to block A passes over an ideal pulley at the edge of the table and is attached to block B of mass 2.0 kg, which hangs freely, as shown. The coefficient of kinetic friction between block A and the table is 0.25. The blocks are released from rest, and block B moves downward. What is the magnitude of the acceleration of block B?



(A) 0.82 m/s^2

(B) 1.6 m/s^2

(C) 2.5 m/s^2

(D) 3.3 m/s^2

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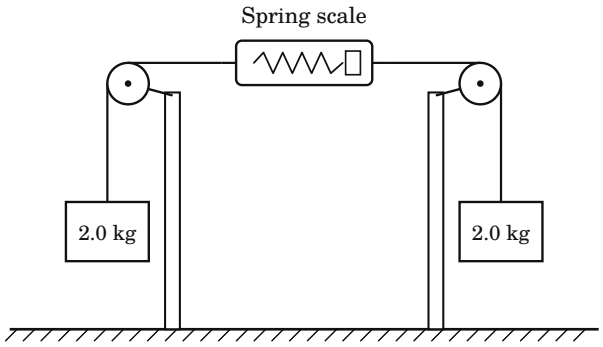
3. Two blocks, each of mass 2.0 kg, hang from light strings that pass over two ideal pulleys and attach to opposite ends of a spring scale of negligible mass, as shown. The blocks and the scale are at rest. What is the reading on the scale?



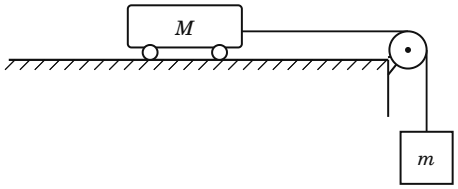
(A) 0 N

(B) 9.8 N

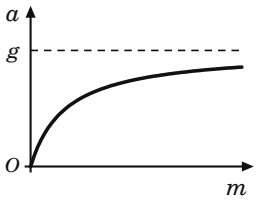
(C) 19.6 N

(D) 39.2 N

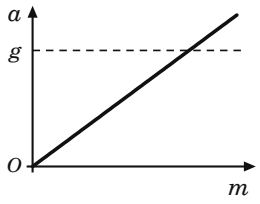
4. A cart of mass M on a horizontal track is connected by a light string over an ideal pulley to a hanging block of mass m, as shown. Friction is negligible. A student repeats the experiment several times, using a different value of m each time while M stays the same. Which of the following graphs best represents the magnitude of the acceleration a of the cart as a function of m?



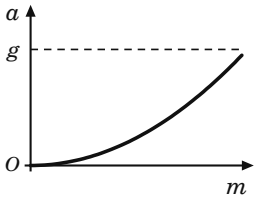
(A)



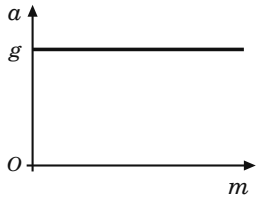
(B)



(C)



(D)



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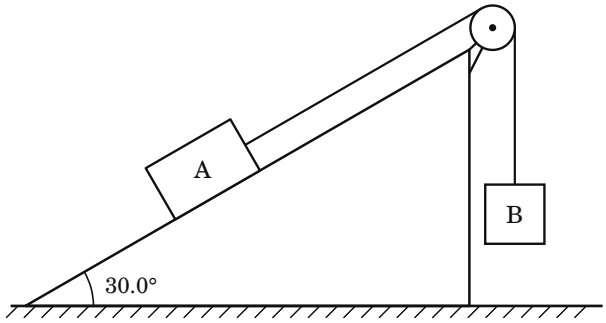
5. Block A of mass 5.00 kg rests on a ramp inclined at 30.0° above the horizontal. A light string attached to block A runs parallel to the ramp, over an ideal pulley at the top of the ramp, to block B of mass 1.00 kg, which hangs freely, as shown. The coefficient of static friction between block A and the ramp is 0.400. The blocks remain at rest. What are the magnitude and direction of the static friction force exerted on block A by the ramp?



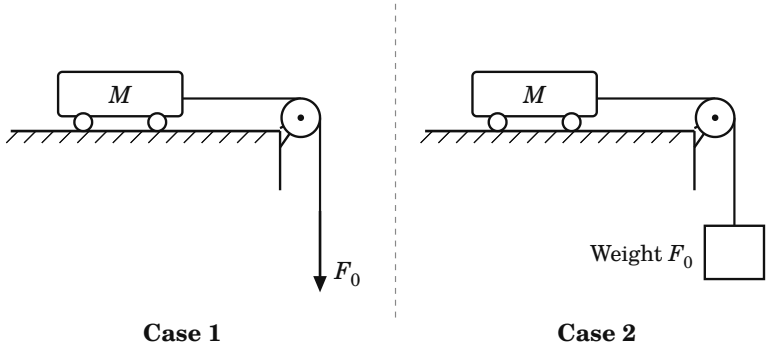
(A) 14.7 N, up the ramp

(B) 14.7 N, down the ramp

(C) 17.0 N, up the ramp

(D) 9.80 N, up the ramp

6. A cart of mass M rests on a horizontal track with negligible friction. A light string attached to the cart passes over an ideal pulley at the end of the track. In Case 1, a student pulls down on the end of the string with a constant force of magnitude F_0. In Case 2, the student instead hangs a block of weight F_0 from the end of the string. Which of the following correctly compares the magnitude a_1 of the cart's acceleration in Case 1 with the magnitude a_2 in Case 2?



Case 1 **Case 2**

(A) $a_1 = a_2$, because the downward force on the end of the string has magnitude F_0 in both cases.

(B) $a_1 < a_2$, because the hanging block falls with acceleration g and pulls the cart along with it.

(C) $a_1 > a_2$, because the pulley exerts a force on the string that opposes its motion in Case 2.

(D) $a_1 > a_2$, because in Case 2 the force F_0 must accelerate the hanging block as well as the cart.

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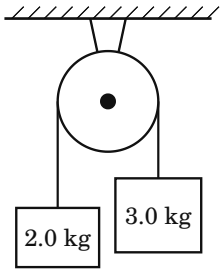
7. A 3.0 kg block and a 2.0 kg block hang from opposite ends of a light string that passes over an ideal pulley, as shown. The blocks are released from rest. What is the speed of the 3.0 kg block after it has moved 0.50 m downward?



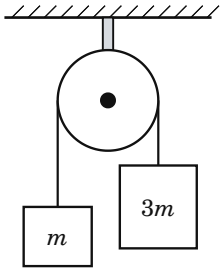
(A) 0.99 m/s

(B) 1.4 m/s

(C) 2.2 m/s

(D) 3.1 m/s

8. Blocks of mass m and $3m$ hang from opposite ends of a light string that passes over an ideal pulley. The pulley hangs from the ceiling by a light rod, as shown. The blocks are released from rest. While the blocks are moving, what is the magnitude of the force exerted on the pulley by the rod?



(A) $2mg$, because the string pulls down on each side of the pulley with a force equal to the weight of the lighter block

(B) $4mg$, because the rod supports the total weight of the two blocks

(C) $6mg$, because the string pulls down on each side of the pulley with a force equal to the weight of the heavier block

(D) $3mg$, because the center of mass of the two blocks accelerates downward

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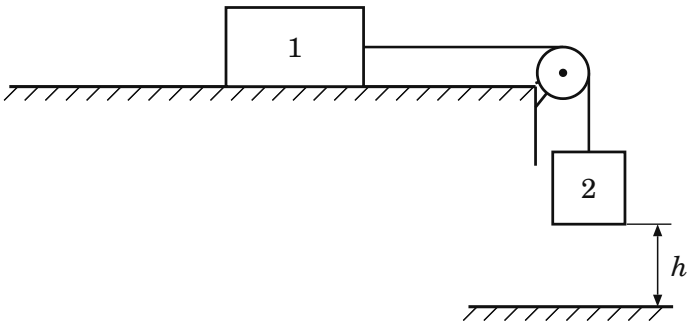
Question 9: Mathematical Routines — 10 points

9. Block 1 of mass M sits on a horizontal table. A light string attached to block 1 passes over an ideal pulley at the edge of the table and is attached to block 2 of mass m, which hangs a height h above the floor, as shown in Figure 1. The coefficient of kinetic friction between block 1 and the table is μ_k. At time $t = 0$, the blocks are released from rest and begin to move. Block 2 reaches the floor at time $t = t_1$ and does not bounce. Block 1 continues to slide and comes to rest before it reaches the pulley. Air resistance is negligible.

Figure 1



Part A

i. **Derive** an expression for the magnitude of the acceleration of block 1 for $0 < t < t_1$. Express your answer in terms of M, m, μ_k, and physical constants, as appropriate. Begin your derivation by writing a fundamental physics principle or an equation from the reference information.

ii. **Derive** an expression for the tension in the string for $0 < t < t_1$. Express your answer in terms of M, m, μ_k, and physical constants, as appropriate.

Part B

On the axes in Figure 2, **sketch** a graph of the velocity v of block 1 as a function of time t, from $t = 0$ until block 1 comes to rest. Take the direction in which block 1 moves as positive.

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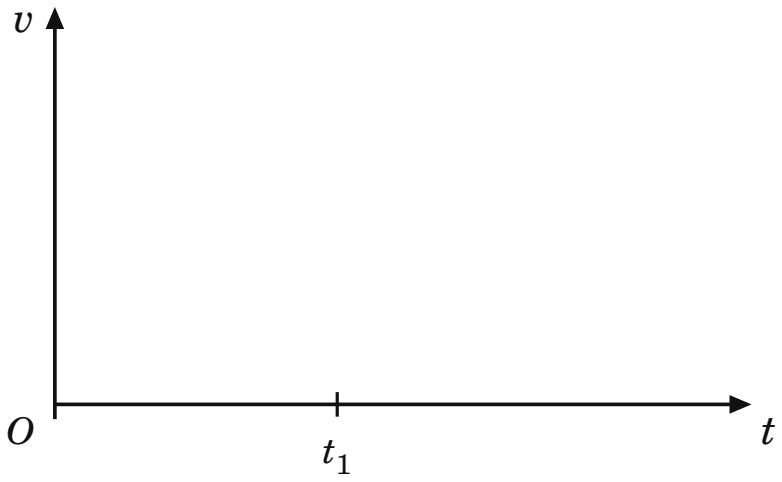
Figure 2



Part C

The experiment is repeated with block 2 replaced by a block of greater mass. Block 1, the table, and the height h are the same as before. **Indicate** whether the speed of block 1 at the instant the hanging block reaches the floor is greater than, less than, or equal to the speed of block 1 at that instant in the original experiment.

- Greater than
- Less than
- Equal to

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

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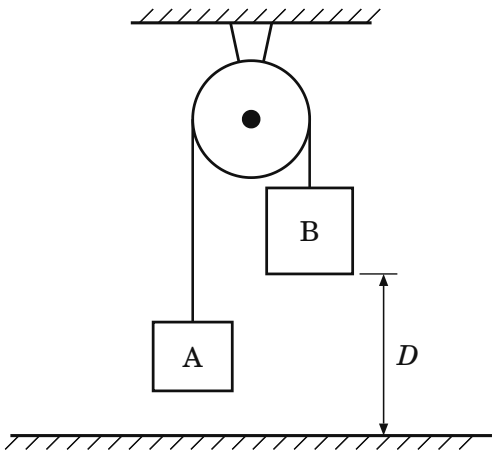
Question 10: Translation Between Representations — 12 points

10. Block A of mass m_A and block B of mass m_B, where $m_B > m_A$, are connected by a light string that passes over an ideal pulley, as shown in Figure 1. Block B is held at rest a height D above the floor. At time $t = 0$, block B is released. Block B reaches the floor at time $t = t_1$ and stops without bouncing. Block A continues to move upward and reaches its maximum height at time $t = t_2$. Air resistance is negligible.

Figure 1



Part A

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 for $0 < t < t_1$. Draw each force as a separate arrow that starts on the dot and points away from it. Draw the relative lengths of the arrows to reflect the relative magnitudes of all the forces.

Figure 2

Block A Block B

Part B

Derive an expression for the magnitude of the acceleration of block A for $0 < t < t_1$. Express your answer in terms of m_A, m_B, and physical constants, as appropriate. Begin your derivation with

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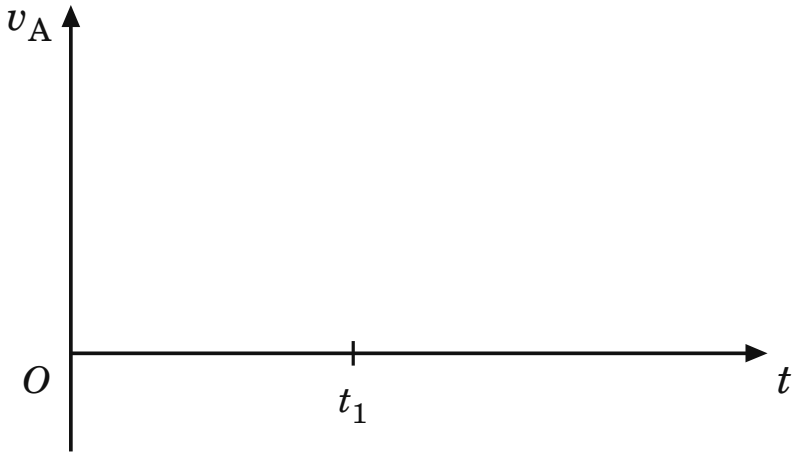
equations that are consistent with your free-body diagrams in Part A.

Part C

On the axes in Figure 3, **sketch** a graph of the vertical velocity v_A of block A as a function of time t, from $t = 0$ to $t = t_2$. Take upward as positive, and label time t_2 on the time axis.

Figure 3



Part D

Indicate whether the magnitude of the slope of your graph for $t_1 < t < t_2$ is greater than, less than, or equal to the magnitude of its slope for $0 < t < t_1$.

- Greater than
- Less than
- Equal to

Justify your answer by referring to your free-body diagram of block A in Part A and your expression in Part B.

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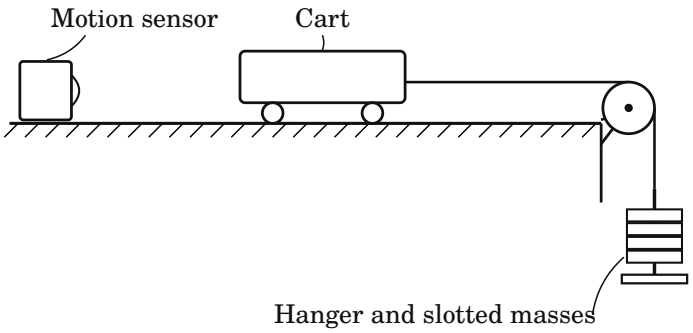
Question 11: Experimental Design and Analysis — 10 points

11. A student wants to determine the mass M of a cart. The cart rides on a horizontal track. A light string attached to the cart passes over an ideal pulley at the end of the track to a hanger that holds slotted masses, as shown in Figure 1. The cart's mass is greater than the 0.500 kg limit of the only available balance. The student also has a motion sensor, a stopwatch, a meterstick, and a set of slotted masses. Friction between the cart and the track is negligible.

Figure 1



Part A

Describe an experimental procedure that the student could use to collect data that would allow M to be determined. Include enough detail that another student could follow the procedure, including how each quantity is measured.

Part B

The student collects the data shown in Table 1, where m is the total mass of the hanger and slotted masses and a is the magnitude of the cart's acceleration.

Table 1

m (kg)	a (m/s²)		
0.050	0.61		
0.100	1.16		
0.150	1.60		
0.200	2.08		
0.250	2.44		

i. **Indicate** two quantities that could be graphed to yield a straight line whose slope or vertical intercept could be used to determine M. Use the remaining columns in Table 1 to record any quantities that you calculate.

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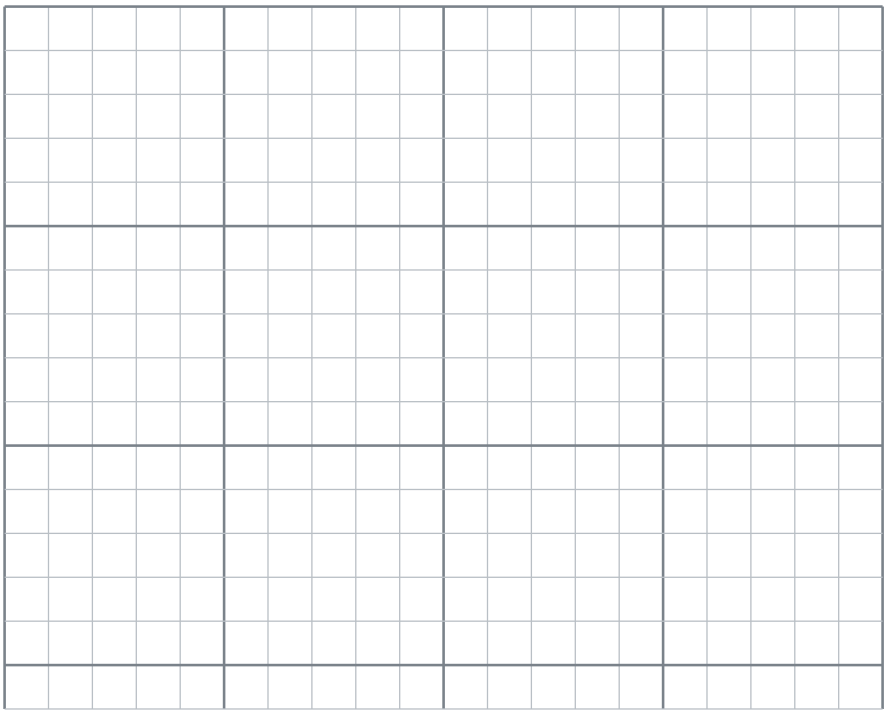
ii. On the grid in Figure 2, **plot** the data points for the quantities indicated in part i. Clearly scale and label all axes, including units.

iii. **Draw** a straight line that best represents the data.

Figure 2



Part C

Using the best-fit line that you drew in Part B, **calculate** an experimental value for M.

Part D

The student later learns that a small, constant friction force acts on the cart as it moves. **Indicate** whether the value of M calculated in Part C is greater than, less than, or equal to the actual mass of the cart.

- Greater than
- Less than
- Equal to

Justify your answer by referring to the quantities you graphed in Part B.

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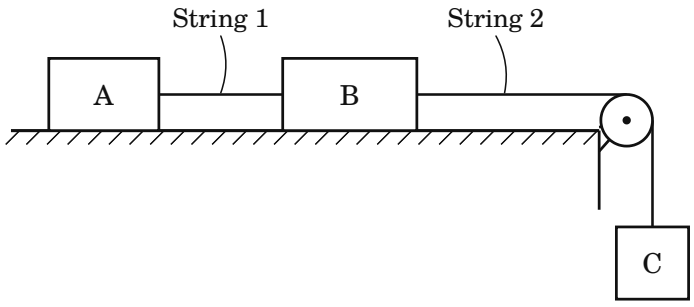
Question 12: Qualitative/Quantitative Translation — 8 points

12. Blocks A and B, of masses m_A and m_B, sit on a horizontal table. String 1 connects block A to block B, and string 2 connects block B to block C, of mass m_C, passing over an ideal pulley at the edge of the table, as shown in Figure 1. Both strings are light, and friction between the blocks and the table is negligible. Block C hangs freely. The blocks are released from rest. Let T_1 be the magnitude of the tension in string 1 and T_2 be the magnitude of the tension in string 2.

Figure 1



Part A

Rank T_1, T_2, and the weight W_C of block C from greatest to least. If any are equal, state so. Without deriving or using equations, **justify** each comparison in your ranking.

Part B

Derive expressions for T_1 and T_2 in terms of m_A, m_B, m_C, and physical constants, as appropriate. Begin your derivation by writing a fundamental physics principle or an equation from the reference information.

Part C

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

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Answer Key and Scoring Guidelines

Section I answers and explanations are first, followed by the scoring guidelines for Questions 9 to 12. The free-response questions use the 2026 point values: 10 points for mathematical routines, 12 for translation between representations, 10 for experimental design and analysis, and 8 for qualitative/quantitative translation.

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. In Question 11, any pair of quantities that makes the data linear earns credit when the slope or intercept is then related to *M* correctly, and Part D is scored against the graph the student chose.

Question	Answer	Topic
1	**(C)**	Tension in an Atwood machine
2	**(B)**	Block on a table with friction
3	**(C)**	Reading a spring scale
4	**(A)**	Graph of acceleration against hanging mass
5	**(A)**	Static friction on an incline
6	**(D)**	Pulling the string or hanging a weight
7	**(B)**	Speed after a set distance
8	**(D)**	Force on the pulley support

Question 1 Answer (C)

Take the direction each block accelerates as positive. Block X accelerates upward, so $F_T - mg = ma$. Block Y accelerates downward, so $2mg - F_T = 2ma$. Adding the two equations eliminates the tension and gives $mg = 3ma$, so $a = g/3$. Then $F_T = m(g + a) = \frac{4}{3}mg$. The tension is greater than the weight of X because X accelerates upward, and less than the weight of Y because Y accelerates downward.

Choices (A) and (D) are the two weights, which would equal the tension only if the blocks had no acceleration. Choice (B) is the average of the two weights, which does not follow from Newton's second law.

Review: The Atwood machine, burketutoringinfremont.com/ap-physics-1-pulley-problems/#atwood-machine

Question 2 Answer (B)

Write Newton's second law along the string for both blocks together, with the direction of motion positive. The weight of block B pulls the positive way: (2.0 kg)(9.8 m/s²) = 19.6 N. Kinetic friction on block A pulls the other way: (0.25)(4.0 kg)(9.8 m/s²) = 9.8 N. The tension pulls block A forward and block B back by the same amount, so it cancels. Then a = (19.6 N − 9.8 N)/(6.0 kg) = 1.6 m/s².

Choice (D) leaves out friction. Choice (C) divides the 9.8 N difference by the mass of block A only. Choice (A) finds friction from the weight of both blocks, but only block A presses on the table.

Review: Block on a table with a hanging block, burketutoringinfremont.com/ap-physics-1-pulley-problems/#table-pulley

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Question 3 Answer (C)

A spring scale reads the tension in the string attached to its hook. Each block is at rest, so the string holding it up pulls with a force equal to its weight, (2.0 kg)(9.8 m/s²) = 19.6 N, and an ideal string over an ideal pulley has the same tension on both sides. Each end of the scale is pulled with 19.6 N, so the scale reads 19.6 N. Tying one end of the scale to a wall instead of the second block would give the same reading.

The net force on the scale is zero, which makes (A) tempting, but the reading is the size of the pull on each end. Choice (D) adds the two pulls, and choice (B) halves the weight of one block.

Review: Where students lose points, error 6, burketutoringinfremont.com/ap-physics-1-pulley-problems/#mistakes

Question 4 Answer (A)

Along the string, the weight of the hanging block, mg, is the only unbalanced force, and it accelerates the total mass $M + m$, so $a = mg/(M + m)$. When m is much smaller than M, a is close to $(g/M)m$, so the graph starts out nearly straight. As m increases, the added weight also adds mass to accelerate, so a rises by smaller amounts and approaches g without reaching it.

Choice (B) uses $a = mg/M$, which leaves out the mass of the hanging block. Choice (D) treats the hanging block as if it were falling freely. Choice (C) curves the wrong way.

Review: Block on a table with a hanging block, burketutoringinfremont.com/ap-physics-1-pulley-problems/#table-pulley

Question 5 Answer (A)

Block B is at rest, so the tension equals its weight, (1.00 kg)(9.8 m/s²) = 9.80 N. Along the ramp, gravity pulls block A down the slope with (5.00 kg)(9.8 m/s²)(sin 30.0°) = 24.5 N, and the string pulls it up the slope with 9.80 N. With no friction, block A would slide down the ramp, so static friction points up the ramp. For zero net force along the ramp, 9.80 N + F_f = 24.5 N, so F_f = 14.7 N.

Choice (C) is $\mu_s F_N$ = (0.400)(5.00 kg)(9.8 m/s²)(cos 30.0°) = 17.0 N, the largest static friction force the ramp can exert. The actual static friction is the value that keeps block A at rest, and because 14.7 N is less than 17.0 N, the blocks stay at rest as the question states. Choice (B) has the wrong direction, and choice (D) sets friction equal to the tension.

Review: Block on an incline with a hanging block, burketutoringinfremont.com/ap-physics-1-pulley-problems/#incline-pulley

Question 6 Answer (D)

In Case 1 the string pulls the cart with the student's force, so $a_1 = F_0/M$. In Case 2 the weight F_0 accelerates the cart and the hanging block together. Their total mass is $M + F_0/g$, so $a_2 = F_0/(M + F_0/g)$, which is less than a_1. The tension in Case 2 is less than F_0, because the hanging block accelerates downward.

Choice (A) assumes the tension equals the weight of the block in Case 2. Choice (C) has the correct comparison with an incorrect reason, since an ideal pulley exerts no force along the string. Choice (B) treats the hanging block as if it were in free fall.

Review: System method and object method, burketutoringinfremont.com/ap-physics-1-pulley-problems/#two-methods

Question 7 Answer (B)

Along the string, for both blocks together, a = (3.0 kg − 2.0 kg)(9.8 m/s²)/(5.0 kg) = 1.96 m/s². The acceleration is constant and the blocks start from rest, so $v^2 = 2a\Delta y$ gives $v = \sqrt{(2(1.96\ \text{m/s}^2)(0.50\ \text{m}))}$ = 1.4 m/s.

Choice (D) treats the block as if it were falling freely with acceleration g. Choice (C) divides the 9.8 N difference between the weights by the mass of the 2.0 kg block only. Choice (A) leaves the 2 out of $v^2 = 2a\Delta y$.

Review: The constant-acceleration equations in the kinematics study guide, burketutoringinfremont.com/ap-physics-1-kinematics-study-guide/#equations

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Question 8 Answer (D)

Along the string, $a = (3m - m)g/(4m) = g/2$. For the lighter block, $F_T - mg = m(g/2)$, so $F_T = \frac{3}{2}mg$. The string pulls down on both sides of the massless pulley, so the rod pulls up on it with $2F_T = 3mg$. As a check, treat both blocks, the string, and the pulley as one system. The heavier block moves down as fast as the lighter block moves up, so the center of mass accelerates downward, and the upward force from the rod must be less than the total weight, $4mg$.

Choice (B) would be correct only if the blocks were held at rest. Choices (A) and (C) set the tension equal to one of the weights, which is true only when nothing accelerates.

Review: The Atwood machine, burketutoringinfremont.com/ap-physics-1-pulley-problems/#atwood-machine

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Section II Scoring Guidelines

Question 9: Mathematical Routines — 10 points

Part A(i) — 3 points

A1	For a multistep derivation that applies Newton's second law along the string to both blocks together, or to each block with the same tension in both equations	1 point
A2	For a kinetic friction force of magnitude $\mu_k Mg$ on block 1, using a normal force equal to Mg	1 point
A3	For a correct expression for the acceleration	1 point

EXAMPLE RESPONSE

Both blocks, along the string, positive in the direction of motion: $\Sigma F = (M + m)a$

$mg - \mu_k Mg = (M + m)a$

$$a = \frac{(m - \mu_k M)g}{M + m}$$

Scoring note: A correct expression with no supporting work earns point A3 but not points A1 and A2.

Part A(ii) — 2 points

A4	For applying Newton's second law to one block, with the tension included	1 point
A5	For a correct expression for the tension that is consistent with Part A(i)	1 point

EXAMPLE RESPONSE

Block 2, positive downward: $mg - F_T = ma$, so $F_T = m(g - a)$

$$F_T = mg - \frac{m(m - \mu_k M)g}{M + m} = \frac{(1 + \mu_k)Mmg}{M + m}$$

Scoring note: Writing the second law for block 1 instead, $F_T - \mu_k Mg = Ma$, gives the same result.

Scoring note: As a check, with M = 2.0 kg, m = 1.5 kg, and μ_k = 0.25, the expressions give a = 2.8 m/s² and F_T = 10.5 N, and both block equations hold.

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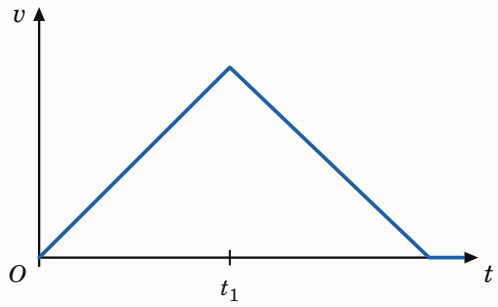
Part B		2 points
B1	For a straight line with positive slope from $v = 0$ at $t = 0$ to time t_1	1 point
B2	For a straight line with negative slope that starts at time t_1 at the velocity reached at t_1 and ends at $v = 0$	1 point

EXAMPLE RESPONSE



Scoring note: After t_1 the string is slack, so kinetic friction is the only horizontal force on block 1 and its acceleration is $-\mu_k g$. This slope can be steeper or less steep than the slope before t_1, depending on M, m, and μ_k, so either is accepted. A graph that drops to zero at t_1 does not earn point B2, because block 1 keeps sliding.

Part C		3 points
C1	For indicating that the speed is greater	1 point
C2	For explaining that the acceleration before the hanging block lands is greater with the heavier hanging block	1 point
C3	For connecting a greater acceleration over the same distance h to a greater speed	1 point

EXAMPLE RESPONSE

Greater than. Adding mass Δm to the hanging block adds $\Delta m \cdot g$ to the net driving force along the string but only Δm to the total mass, and friction on block 1 does not change. The original acceleration is less than g, so the added force for each added kilogram is more than the original driving force for each kilogram, and the acceleration increases. The expression from Part A(i) shows the same result when written as $a = g[1 - (1 + \mu_k)M/(M + m)]$, which increases as m increases.

Block 1 starts from rest and speeds up over the same distance h, so $v^2 = 2ah$ gives a greater speed when the acceleration is greater.

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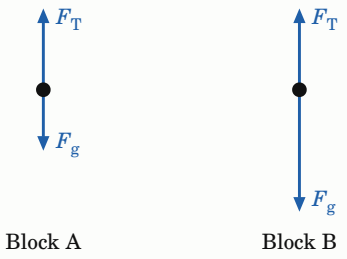
Question 10: Translation Between Representations — 12 points

Part A		3 points
A1	For a free-body diagram of block A with an upward tension force and a downward gravitational force, and no other forces	1 point
A2	For a free-body diagram of block B with an upward tension force and a downward gravitational force, and no other forces	1 point
A3	For relative lengths: on block A the tension arrow is longer than the gravitational force arrow, on block B it is shorter, and the two tension arrows are the same length	1 point

EXAMPLE RESPONSE



Scoring note: The example is drawn for $m_B = 2m_A$. The gravitational force arrow on block B is longer than the one on block A because $m_B > m_A$. Labels such as F_T and m_Ag, or the words tension and weight, are acceptable.

Part B		3 points
B1	For a Newton's second law equation for block A that is consistent with its free-body diagram, such as $F_T - m_Ag = m_Aa$	1 point
B2	For a Newton's second law equation for block B with the same tension and the same magnitude of acceleration, such as $m_Bg - F_T = m_Ba$	1 point
B3	For a correct expression for the acceleration	1 point

EXAMPLE RESPONSE

Block A, up positive: $F_T - m_Ag = m_Aa$

Block B, down positive: $m_Bg - F_T = m_Ba$

Adding: $(m_B - m_A)g = (m_A + m_B)a$, so $a = \dfrac{(m_B - m_A)g}{m_A + m_B}$

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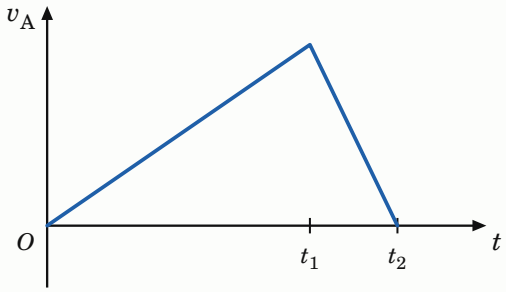
Part C		3 points
C1	For a straight line with positive slope from the origin to time t_1	1 point
C2	For a straight line with negative slope from time t_1 that reaches $v_A = 0$ at time t_2	1 point
C3	For a graph with no jump in velocity at t_1 and a steeper slope after t_1 than before it	1 point

EXAMPLE RESPONSE



Scoring note: Because the slope after t_1 is steeper, the time from t_1 to t_2 is shorter than the time from 0 to t_1.

Part D		3 points
D1	For indicating greater than	1 point
D2	For explaining, with the free-body diagram, that the string is slack after t_1, so gravity is the only force on block A and its acceleration has magnitude g	1 point
D3	For using the expression from Part B to show that the acceleration before t_1 is less than g, because $m_B - m_A$ is less than $m_A + m_B$	1 point

EXAMPLE RESPONSE

Greater than. Before t_1, the net force on block A is the tension minus its weight. The expression from Part B, $a = (m_B - m_A)g/(m_A + m_B)$, is less than g because $m_B - m_A$ is less than $m_A + m_B$. After block B lands, the string goes slack and the tension arrow is no longer on block A's free-body diagram. Only the gravitational force is left, so block A slows down with an acceleration of magnitude g. The slope of a velocity graph is the acceleration, so the slope is steeper after t_1.

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Question 11: Experimental Design and Analysis — 10 points

Part A		3 points
A1	For using the balance to measure the total hanging mass m, the hanger plus the slotted masses	1 point
A2	For a method that finds the acceleration of the cart released from rest, such as the slope of a velocity-time graph from the motion sensor, or $a = 2d/t^2$ from a distance d measured with the meterstick and a time t measured with the stopwatch	1 point
A3	For repeating the measurement for several different values of m, with repeated trials averaged for each value	1 point

EXAMPLE RESPONSE

Measure the mass of the hanger and the slotted masses on the balance and record the total hanging mass. Hold the cart at rest near the motion sensor, release it, and record a velocity-time graph as it moves toward the pulley. The slope of the straight part of the graph is the acceleration. Do three trials and average the accelerations. Repeat for five different hanging masses.

Scoring note: A procedure that measures the mass of the cart directly on the balance does not earn points, because the cart is beyond the balance's limit.

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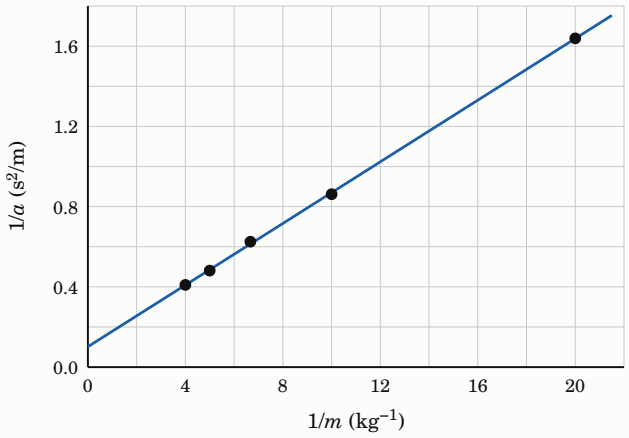
Part B		3 points
B1	For indicating quantities that give a straight line, with a correct relationship to M, such as $1/a$ and $1/m$ (slope = M/g), mg/a and m (vertical intercept = M), or $m(g - a)$ and a (slope = M)	1 point
B2	For plotting the data correctly on axes that are labeled and scaled, including units	1 point
B3	For a straight best-fit line with data points on both sides of it	1 point

EXAMPLE RESPONSE

Newton's second law along the string, for the cart and hanging mass together, gives $mg = (M + m)a$, so $1/a = (M/g)(1/m) + 1/g$. A graph of $1/a$ against $1/m$ is a straight line with slope M/g.

m (kg)	a (m/s²)	$1/m$ (kg⁻¹)	$1/a$ (s²/m)
0.050	0.61	20.0	1.64
0.100	1.16	10.0	0.862
0.150	1.60	6.67	0.625
0.200	2.08	5.00	0.481
0.250	2.44	4.00	0.410



Scoring note: Any choice of quantities that makes the data linear earns point B1 when the slope or intercept is related to M correctly. For example, a graph of mg/a against m is a line with slope 1 and vertical intercept M, and a graph of $m(g - a)$ against a is a line with slope M that passes through the origin when friction is negligible.

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Part C		2 points
C1	For using the slope or intercept of the best-fit line, not individual data points, with the relationship from Part B	1 point
C2	For a value of M between 0.70 kg and 0.80 kg that is consistent with the line drawn	1 point

EXAMPLE RESPONSE

Slope of the best-fit line $\approx 0.0768\ \text{s}^2\cdot\text{kg/m}$

$M = (\text{slope})g = (0.0768\ \text{s}^2\cdot\text{kg/m})(9.8\ \text{m/s}^2) \approx 0.75\ \text{kg}$

Scoring note: Dividing the slope by the vertical intercept, (0.0768)/(0.102) ≈ 0.75 kg, gives the same value without using g. The intercept itself, $1/g$, is a useful check: 1/0.102 ≈ 9.8 m/s².

Scoring note: Every graph listed in Part B gives a value of M close to 0.75 kg with the data in Table 1. For example, the slope of $m(g - a)$ against a is about 0.75 kg.

Part D		2 points
D1	For an indication that matches the quantities graphed in Part B: greater than for a graph in which a constant friction force changes the slope or intercept used to find M, such as $1/a$ against $1/m$, mg/a against m, or m/a against m; equal to for a graph of $m(g - a)$ against a, in either order, where friction changes only the intercept	1 point
D2	For a justification that matches that graph: friction makes each acceleration smaller than $a = mg/(M + m)$ predicts, and that relationship assigns the smaller acceleration to a larger cart mass; or, for $m(g - a)$ against a, friction adds a constant term, $m(g - a) = Ma + F_f$, so the slope still equals M	1 point

EXAMPLE RESPONSE

For the graph of $1/a$ against $1/m$ in the Part B example: greater than. With friction, each hanging mass produces a smaller acceleration than it would without friction. The analysis assumes $a = mg/(M + m)$, and a smaller a for the same m fits that equation only with a larger M, so the calculated mass is too large.

For a graph of $m(g - a)$ against a: equal to. The hanging block gives $F_T = m(g - a)$, and the cart gives $F_T - F_f = Ma$, so $m(g - a) = Ma + F_f$. A constant friction force raises the line by F_f without changing its slope, so the slope still gives the actual mass.

Scoring note: An indication that does not match the student's own graph, such as equal to with a graph of $1/a$ against $1/m$, does not earn point D1.

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Question 12: Qualitative/Quantitative Translation — 8 points

Part A		3 points
A1	For the ranking $W_C > T_2 > T_1$	1 point
A2	For justifying $T_2 > T_1$, such as that string 2 accelerates blocks A and B together while string 1 accelerates only block A, or that the net force on block B points toward the pulley	1 point
A3	For justifying $W_C > T_2$: block C accelerates downward, so the downward gravitational force on it is greater than the upward tension	1 point

EXAMPLE RESPONSE

$W_C > T_2 > T_1$. Block B speeds up toward the pulley, so the forward pull of string 2 on it is greater than the backward pull of string 1. Said another way, string 2 accelerates both A and B, while string 1 accelerates only A. Block C speeds up as it falls, so the downward gravitational force on it is greater than the upward pull of string 2.

Part B		3 points
B1	For applying Newton's second law to all three blocks together along the strings, or to each block, with one acceleration for all three blocks and one tension for each string	1 point
B2	For a correct expression for T_1	1 point
B3	For a correct expression for T_2	1 point

EXAMPLE RESPONSE

All three blocks, along the strings: $m_C g = (m_A + m_B + m_C)a$, so $a = \dfrac{m_C g}{m_A + m_B + m_C}$

Block A: $T_1 = m_A a = \dfrac{m_A m_C g}{m_A + m_B + m_C}$

Blocks A and B: $T_2 = (m_A + m_B)a = \dfrac{(m_A + m_B)m_C g}{m_A + m_B + m_C}$

Part C		2 points
C1	For showing that $T_2 > T_1$, for example because $T_2/T_1 = (m_A + m_B)/m_A$, which is greater than 1	1 point
C2	For showing that $T_2 < W_C$, for example because T_2 equals $m_C g$ multiplied by $(m_A + m_B)/(m_A + m_B + m_C)$, a fraction less than 1	1 point

EXAMPLE RESPONSE

The ratio $T_2/T_1 = (m_A + m_B)/m_A$ is greater than 1, so $T_2 > T_1$. And $T_2 = m_C g \times (m_A + m_B)/(m_A + m_B + m_C)$, where the fraction is less than 1, so $T_2 < m_C g = W_C$. Both match the ranking in Part A.

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