2026

BURKE TUTORING

AP® Physics 1: Kinematics

Practice Free-Response Questions

Eight questions in two sets of four, written in the exam's four free-response formats, with scoring guidelines for every part.

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

Directions:

This booklet has eight free-response questions on Unit 1 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. One workable pace is about 25 minutes for each of the first three questions and 20 minutes for the last one.

You may use a calculator, a ruler, and the AP Physics 1 reference information. Use $g = 9.8$ m/s^2 and treat 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 arrows, graphs, and best-fit lines directly on the figures in this booklet, using one color of ink or pencil.

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 20.

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 kinematics study guide: burketutoringinfremont.com/ap-physics-1-kinematics-study-guide/
Free fall problems guide: burketutoringinfremont.com/ap-physics-1-free-fall-problems/

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

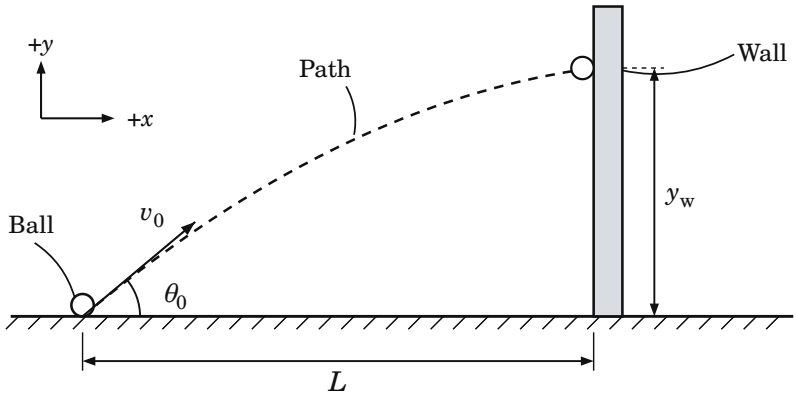
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Question 1: Mathematical Routines

1. A student kicks a ball from level ground toward a tall vertical wall. At time $t = 0$, the ball leaves the ground with speed v_0 at an angle θ_0 above the horizontal. The base of the wall is a horizontal distance L from the point where the ball is kicked, as shown in Figure 1.

At time $t = t_w$, the ball strikes the wall at height y_w above the ground. The ball is still moving upward when it strikes the wall. Air resistance is negligible.

Figure 1

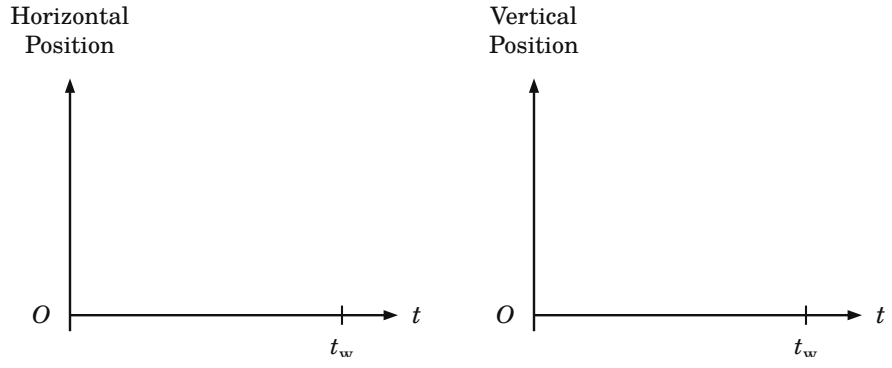


Note: Figure not drawn to scale.

Part A

i. On the axes shown in Figure 2, **sketch** graphs of the horizontal position x and the vertical position y of the ball as functions of time t from $t = 0$ to $t = t_w$. The point where the ball is kicked is $x = 0$, $y = 0$.

Figure 2



ii. **Derive** an expression for y_w. Express your answer in terms of v_0, θ_0, 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.

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iii. **Derive** an expression for the vertical component of the ball's velocity at the instant the ball strikes the wall. Express your answer in terms of v_0, θ_0, L, and physical constants, as appropriate. Begin with a fundamental physics principle or an equation from the reference information.

Part B

The student kicks a second, identical ball from the same spot and at the same angle θ_0, but with a speed greater than v_0. The second ball also strikes the wall while it is still moving upward, at a height y_2 above the ground.

Indicate whether y_2 is greater than, less than, or equal to y_w by writing one of the following.

- $y_2 > y_w$
- $y_2 < y_w$
- $y_2 = y_w$

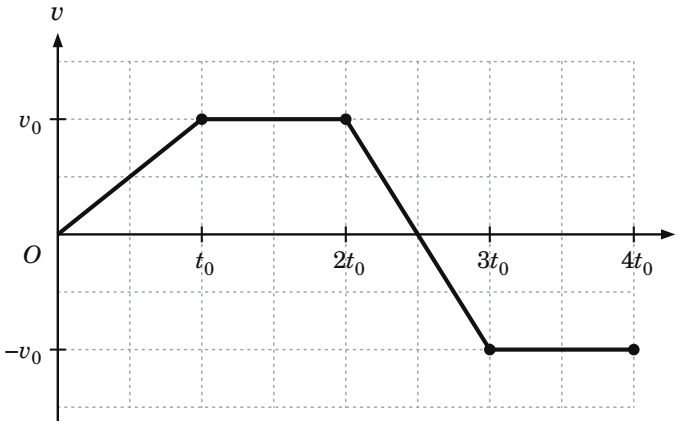
Justify your answer. Your justification must include reasoning in words, not only equations or derivations.

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Question 2: Translation Between Representations

2. A cart moves along a straight, horizontal track. Figure 1 shows the velocity v of the cart as a function of time t from $t = 0$ to $t = 4t_0$. The positive direction is to the right. At $t = 0$, the cart is at position $x = 0$.

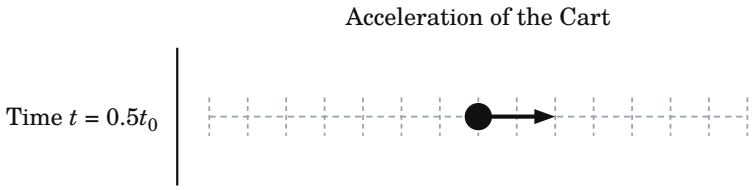
Figure 1



Part A

The acceleration diagram in Figure 2 represents the acceleration of the cart at $t = 0.5t_0$.

Figure 2

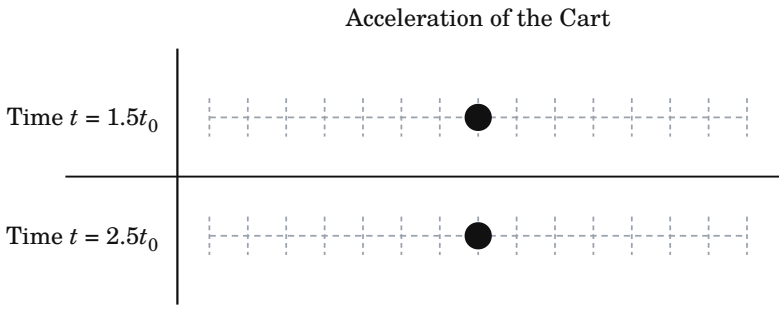


Draw arrows on Figure 3 to represent the acceleration of the cart at $t = 1.5t_0$ and at $t = 2.5t_0$.

- Start each arrow on the dot and point it away from the dot.
- If the acceleration at that instant is zero, write "$a = 0$" next to the dot.
- Make the length of each arrow represent the magnitude of the acceleration, using the same scale as Figure 2.

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Figure 3



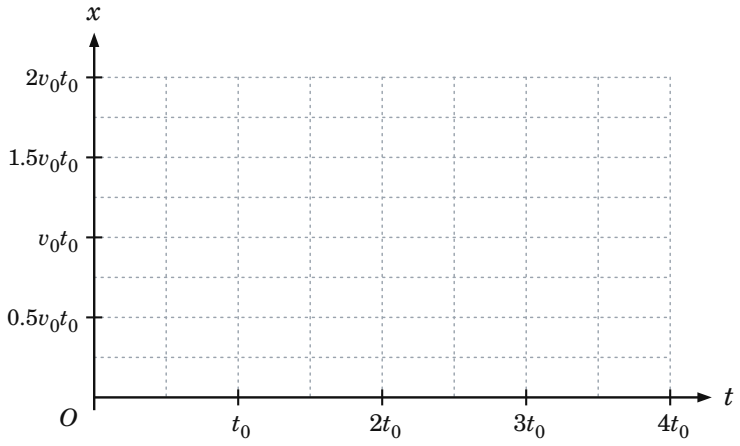
Part B

Derive an expression for the maximum position x_{max} that the cart reaches between $t = 0$ and $t = 4t_0$. Express your answer in terms of v_0, t_0, and physical constants, as appropriate. Begin with a fundamental physics principle or an equation from the reference information.

Part C

On the axes in Figure 4, **sketch** a graph of the position x of the cart as a function of time t from $t = 0$ to $t = 4t_0$.

Figure 4



Part D

Indicate whether the average speed of the cart from $t = 0$ to $t = 4t_0$ is greater than, less than, or equal to the magnitude of the cart's average velocity over the same interval by writing one of the following.

- Average speed > magnitude of average velocity
- Average speed < magnitude of average velocity
- Average speed = magnitude of average velocity

Briefly **justify** your answer.

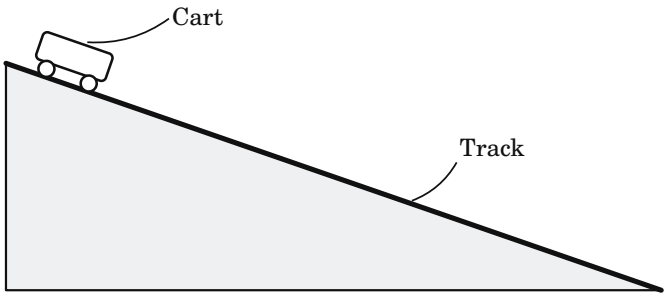
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Question 3: Experimental Design and Analysis

The following information applies to Parts A and B.

3. A group of students wants to determine the magnitude a of the acceleration of a cart that rolls down a long, straight inclined track. The cart is released from rest at the top of the track, as shown in Figure 1. The angle of the track stays the same for the whole experiment, and the acceleration of the cart is constant.

Figure 1



Note: Figure not drawn to scale.

The students must design an experiment in which they vary one quantity and collect data that can be graphed to determine a. The only equipment available is a meterstick and a stopwatch.

Part A

i. **Indicate** the quantities the students should measure so that they can determine a from a linear graph.

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

Part B

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

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

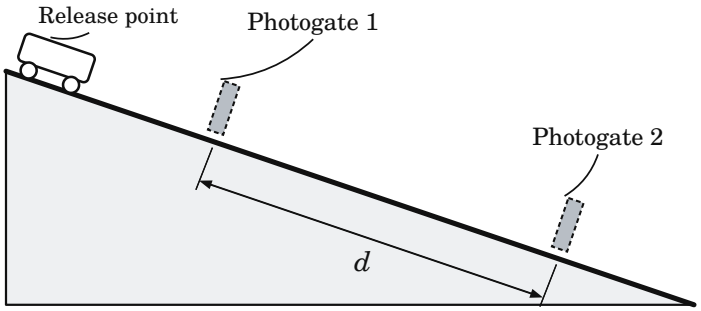
The following information applies to Parts C and D.

In a different experiment, the students use two photogates connected to a timer, as shown in Figure 2. The cart is released from rest at the same point each time, so it passes Photogate 1 with the same speed u on every trial. The timer starts when the cart passes Photogate 1 and stops when the cart passes Photogate 2. The students move Photogate 2 to change the distance d

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between the photogates and record the time t the cart takes to travel from one photogate to the other. Table 1 shows the data.

Figure 2



Note: Figure not drawn to scale.

Table 1

d (m)	t (s)
0.40	0.84
0.80	1.40
1.20	1.80
1.60	2.19
2.00	2.49

The students correctly determine that d and t are related by $d = ut + \frac{1}{2}at^2$, where u is the speed of the cart at Photogate 1. The students make a graph with t plotted on the horizontal axis.

Part C

i. **Label** the vertical axis of Figure 3 with a measured or calculated quantity, with units if it has any. Choose a quantity that makes the graph linear and lets you determine a.

ii. On the grid in Figure 3, make a graph that can be used to determine a.

- Add a numerical scale to the vertical axis.
- **Plot** the data points.
- Table 2 gives space for calculations and is not scored.

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Figure 3

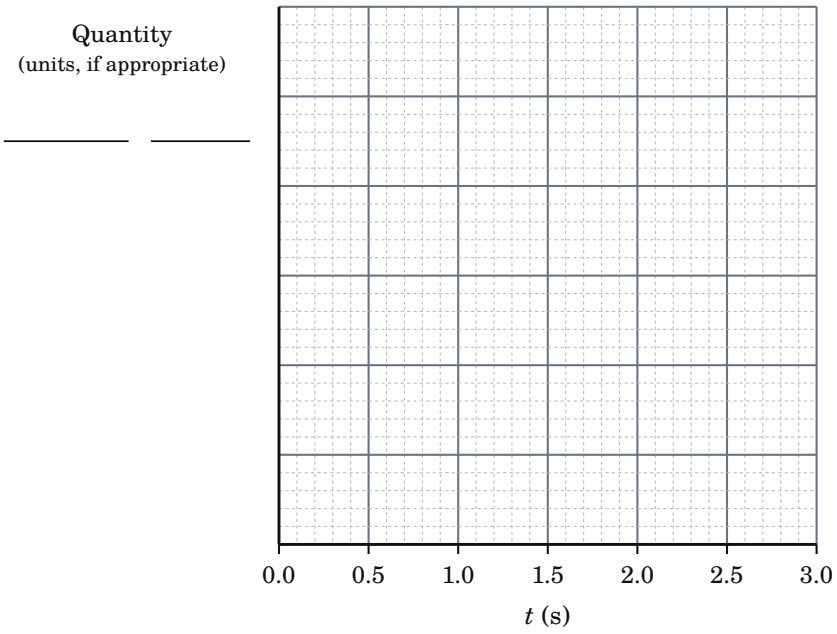


Table 2

t (s)	d (m)	
0.84	0.40	
1.40	0.80	
1.80	1.20	
2.19	1.60	
2.49	2.00	

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

Part D

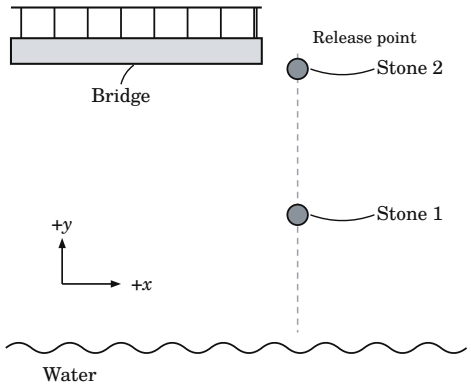
Use your best-fit line from Part C(iii) to **calculate** an experimental value for a.

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Question 4: Qualitative/Quantitative Translation

4. Two small stones are released from rest from the same point beside a high bridge. Stone 1 is released at time $t = 0$. Stone 2 is released at time $t = t_0$, as shown in Figure 1. Both stones are still falling at time $t = 2t_0$. Air resistance is negligible.

Figure 1



Note: Figure not drawn to scale.

The distance between the stones is D_1 at $t = t_0$ and D_2 at $t = 2t_0$.

Part A

Indicate whether D_2 is greater than, less than, or equal to D_1 by writing one of the following.

- $D_2 > D_1$
- $D_2 < D_1$
- $D_2 = D_1$

Justify your answer in words, without relying on equations.

Part B

Starting with a kinematic equation, **derive** an expression for the distance D between the stones at any time t after Stone 2 is released, while both stones are still falling. Express your answer in terms of t, t_0, and physical constants, as appropriate. Begin with a fundamental physics principle or an equation from the reference information.

Part C

Justify whether your expression from Part B is consistent with your reasoning in Part A.

END OF SET A

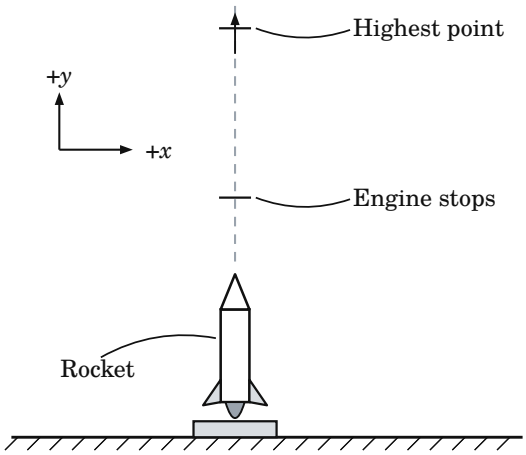
Set B begins with Question 5.

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Question 5: Mathematical Routines

5. A model rocket is launched straight up from rest on level ground at time $t = 0$, as shown in Figure 1. While its engine fires, the rocket has a constant upward acceleration of magnitude $2g$. The engine stops firing at time $t = T$. After that, the rocket is in free fall until it returns to the ground at time $t = t_g$. Air resistance is negligible.

Figure 1

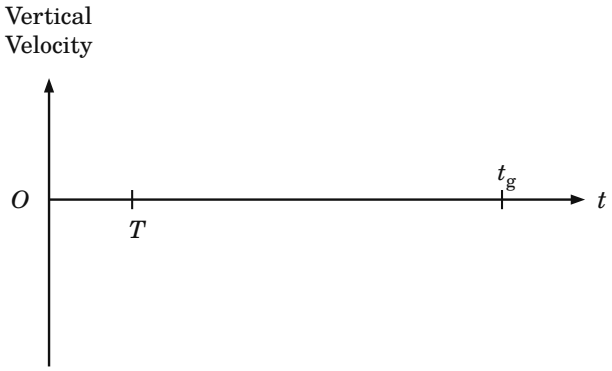


Note: Figure not drawn to scale.

Part A

i. On the axes in Figure 2, **sketch** a graph of the vertical velocity v_y of the rocket as a function of time t from $t = 0$ to $t = t_g$. Take upward as positive.

Figure 2



ii. **Derive** an expression for the maximum height H that the rocket reaches above the ground. Express your answer in terms of T 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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iii. **Derive** an expression for the speed of the rocket just before it reaches the ground. Express your answer in terms of T and physical constants, as appropriate. Begin with a fundamental physics principle or an equation from the reference information.

Part B

A second rocket is launched from rest in the same way. Its engine gives it a constant upward acceleration of magnitude $4g$ and fires for a time $\frac{1}{2}T$. After its engine stops, the second rocket is also in free fall. The second rocket reaches a maximum height H_2.

Indicate whether H_2 is greater than, less than, or equal to H by writing one of the following.

- $H_2 > H$
- $H_2 < H$
- $H_2 = H$

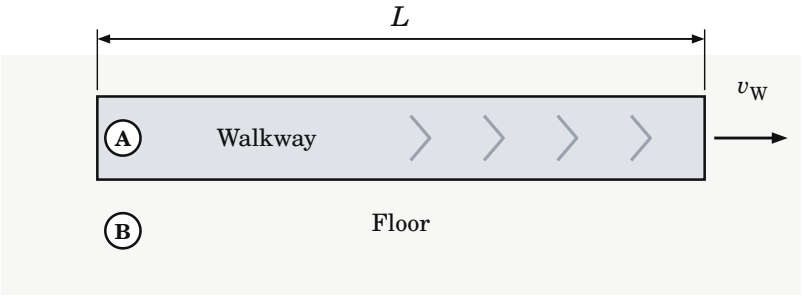
Justify your answer. Your justification must include reasoning in words, not only equations or derivations.

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Question 6: Translation Between Representations

6. A moving walkway of length L at an airport moves to the right with constant speed v_W relative to the floor. At time $t = 0$, Traveler A steps onto the left end of the walkway and walks to the right with constant speed $\frac{1}{2}v_W$ relative to the walkway. At the same instant, Traveler B starts beside the left end of the walkway and walks along the floor to the right with constant speed $\frac{1}{2}v_W$ relative to the floor, as shown in the top view in Figure 1. Traveler A reaches the right end of the walkway at time $t = t_A$.

Figure 1



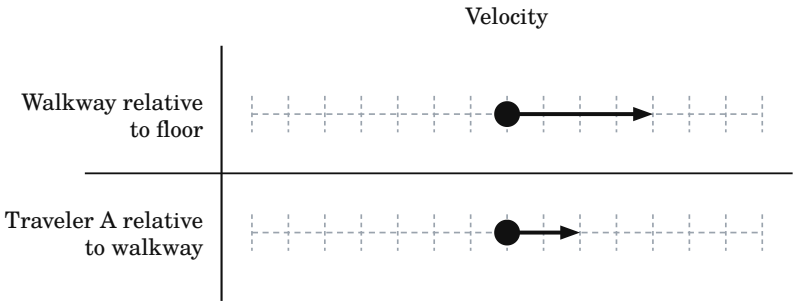
Top View

Note: Figure not drawn to scale.

Part A

The velocity diagram in Figure 2 represents the velocity of the walkway relative to the floor and the velocity of Traveler A relative to the walkway.

Figure 2

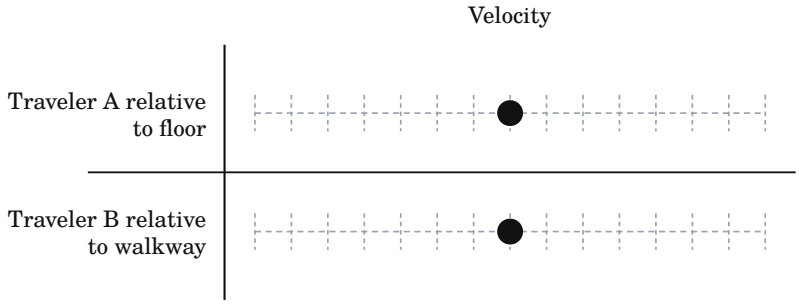


Draw arrows on Figure 3 to represent the velocity of Traveler A relative to the floor and the velocity of Traveler B relative to the walkway.

- Start each arrow on the dot and point it away from the dot.
- If the velocity is zero, write "$v = 0$" next to the dot.
- Make the length of each arrow represent the magnitude of the velocity, using the same scale as Figure 2.

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Figure 3



Part B

Derive an expression for the distance between Traveler A and Traveler B at time $t = t_A$. Express your answer in terms of L, v_W, and physical constants, as appropriate. Begin with a fundamental physics principle or an equation from the reference information.

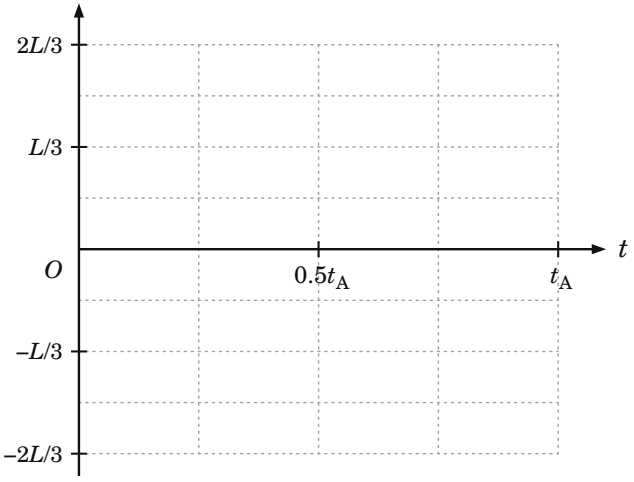
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Part C

A person who stands still on the walkway, riding along with it, measures the positions of both travelers. The person uses a position coordinate x' that is positive to the right and equal to zero at the point on the walkway where Traveler A stepped on.

On the axes in Figure 4, **draw** two lines that represent x' for Traveler A and for Traveler B as functions of time t from $t = 0$ to $t = t_A$. Distinctly **label** each line.

Figure 4



Part D

Indicate whether the speed of Traveler A relative to Traveler B is greater than, less than, or equal to v_W by writing one of the following.

- Speed of A relative to B > v_W
- Speed of A relative to B < v_W
- Speed of A relative to B = v_W

Briefly **justify** your answer by referring to how velocities measured in different reference frames are related.

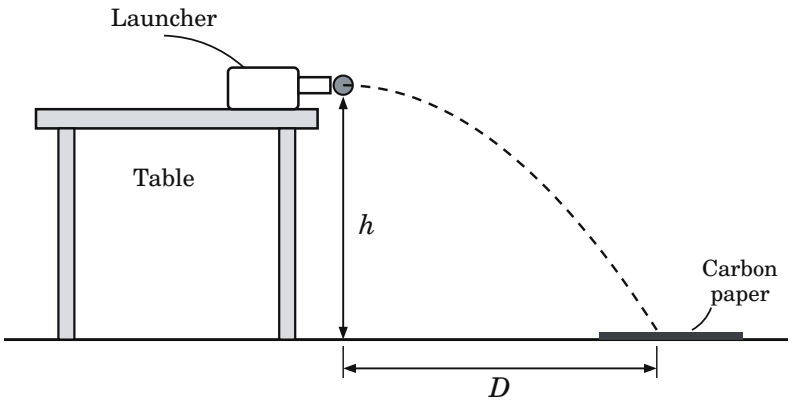
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Question 7: Experimental Design and Analysis

The following information applies to Parts A and B.

7. Students want to determine the launch speed v_L of a small ball fired by a spring-loaded launcher. The launcher fires the ball horizontally and gives it the same launch speed every time. The launcher can be clamped to the edge of tables of different heights, and a sheet of carbon paper on the floor marks where the ball lands, as shown in Figure 1.

Figure 1



Note: Figure not drawn to scale.

The students must design an experiment in which they vary one quantity and collect data that can be graphed to determine v_L. The only measuring tool available is a meterstick.

Part A

i. **Indicate** the quantities the students should measure so that they can determine v_L from a linear graph.

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

Part B

i. **Indicate** the quantities the students could plot on the horizontal and vertical axes to produce a linear graph from which v_L can be determined. State clearly which quantity goes on each axis.

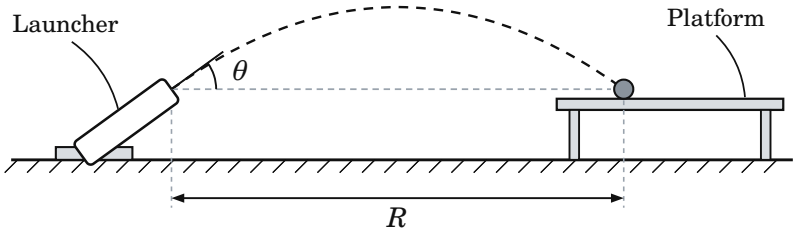
ii. Briefly **describe** how v_L is related to a feature of the graph from Part B(i). You may include an equation that relates v_L to that feature.

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The following information applies to Parts C and D.

In a different experiment, the students place the same launcher on the floor and fire the ball at several angles θ above the horizontal. For each angle, they set the top of a level platform at the height where the ball leaves the launcher, so the ball lands at the same height from which it was launched, as shown in Figure 2. The students measure the horizontal distance R from the launch point to the landing point. Table 1 shows the data.

Figure 2



Note: Figure not drawn to scale.

Table 1

θ (degrees)	R (m)
10	0.32
15	0.45
20	0.60
25	0.70
30	0.78
35	0.87

The students correctly determine that $R = \frac{{v_L}^2}{g} \sin 2\theta$. The students make a graph with R plotted on the horizontal axis.

Part C

i. **Label** the vertical axis of Figure 3 with a measured or calculated quantity, with units if it has any. Choose a quantity that makes the graph linear and lets you determine v_L.

ii. On the grid in Figure 3, make a graph that can be used to determine v_L.

- Add a numerical scale to the vertical axis.
- **Plot** the data points.
- Table 2 gives space for calculations and is not scored.

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Figure 3

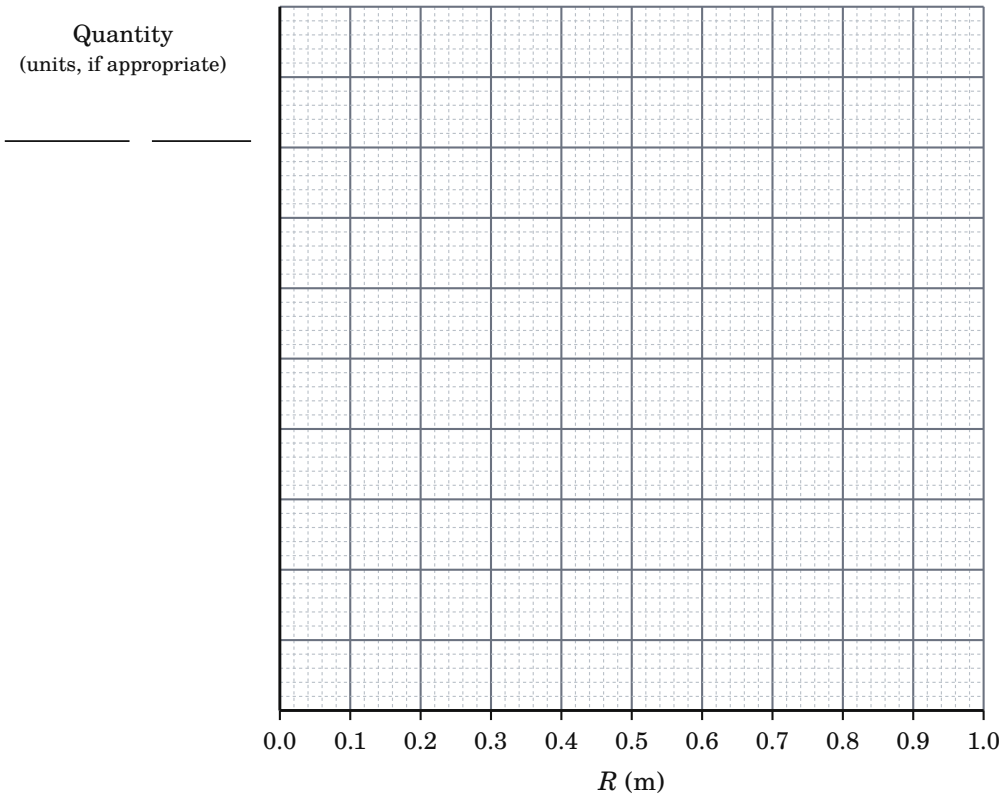


Table 2

θ (degrees)	R (m)	
10	0.32	
15	0.45	
20	0.60	
25	0.70	
30	0.78	
35	0.87	

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

Part D

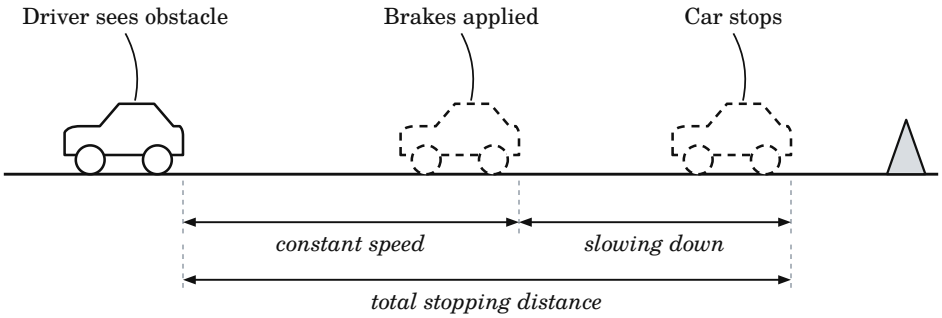
Use your best-fit line from Part C(iii) to **calculate** an experimental value for v_L.

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Question 8: Qualitative/Quantitative Translation

8. A driver traveling at constant speed on a straight, level road sees an obstacle ahead. During the driver's reaction time t_r, the car keeps moving at the same constant speed. The driver then applies the brakes, and the car slows down with constant acceleration of magnitude a_0 until it stops, as shown in Figure 1. The total stopping distance is the distance the car travels from the instant the driver sees the obstacle until the car stops.

Figure 1



Note: Figure not drawn to scale.

Car A travels at speed v before its driver sees the obstacle, and Car B travels at speed $2v$. Both drivers have the same reaction time t_r, and both cars slow down with acceleration of the same magnitude a_0. The total stopping distances of Car A and Car B are d_A and d_B, respectively.

Part A

Indicate whether d_B is greater than, less than, or equal to $2d_A$ by writing one of the following.

- $d_B > 2d_A$
- $d_B < 2d_A$
- $d_B = 2d_A$

Justify your answer in words, without relying on equations.

Part B

Starting with a kinematic equation or the work-energy theorem, **derive** an expression for d_A. Express your answer in terms of v, t_r, a_0, and physical constants, as appropriate. Begin with a fundamental physics principle or an equation from the reference information.

Part C

Justify whether 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.

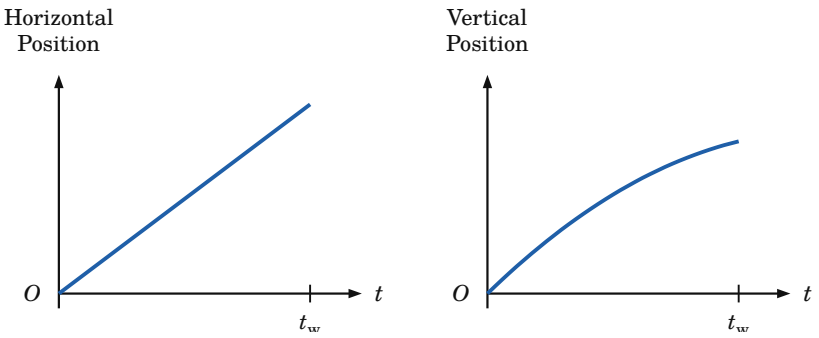
General scoring note. Equivalent physics reasoning and derivations earn the same points as the example responses. When a criterion names one method, the matching step in another correct method earns that point. For example, conservation of energy can replace a kinematic equation for the free-fall stage of the rocket in Question 5, and relative motion can replace separate position equations in Questions 4 and 6. In Questions 3 and 7, any quantity that makes the graph linear earns credit, as long as the slope is then related to the unknown correctly for that quantity.

Question 1: Mathematical Routines (MR) — 10 points

Part A(i) — 2 points

A1	For a horizontal position graph that is a straight line with positive slope, starting at the origin.	1 point
A2	For a vertical position graph that starts at the origin and curves with a decreasing slope that is still positive at t_w.	1 point

EXAMPLE RESPONSE



Scoring note: A vertical position graph that levels off or turns down before t_w does not earn point A2, because the ball is still rising when it strikes the wall.

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Part A(ii)		3 points
A3	For a multistep derivation that applies a kinematic equation to the horizontal motion and to the vertical motion, connected by the time t_w.	1 point
A4	For using $v_0 \cos \theta_0$ as the horizontal component and $v_0 \sin \theta_0$ as the vertical component of the initial velocity.	1 point
A5	For a correct expression for y_w.	1 point

EXAMPLE RESPONSE

Horizontal, with $a_x = 0$: $x = x_0 + v_{x0}t + \frac{1}{2}a_x t^2 \rightarrow L = (v_0 \cos \theta_0)t_w$, so $t_w = \frac{L}{v_0 \cos \theta_0}$

Vertical, with $a_y = -g$: $y_w = (v_0 \sin \theta_0)t_w - \frac{1}{2}g t_w^2$

$y_w = L \tan \theta_0 - \frac{gL^2}{2v_0^2 \cos^2 \theta_0}$

Scoring note: A correct final expression written with no supporting work earns point A5 but not point A3.

Part A(iii)		2 points
A6	For a correct method for the vertical velocity component at the wall, such as applying $v_y = v_{y0} + a_y t$ with $v_{y0} = v_0 \sin \theta_0$ and $a_y = -g$ at $t = t_w$.	1 point
A7	For a correct expression for the vertical velocity component at the wall.	1 point

EXAMPLE RESPONSE

$v_y = v_0 \sin \theta_0 - g t_w = v_0 \sin \theta_0 - \frac{gL}{v_0 \cos \theta_0}$

Scoring note: This value is positive, which matches the statement that the ball is still rising at the wall.

Scoring note: An equivalent expression earns point A7, such as the positive root of $v_y^2 = v_0^2 \sin^2 \theta_0 - 2g y_w$ with y_w replaced by the result of Part A(ii).

Part B		3 points
B1	For indicating $y_2 > y_w$.	1 point
B2	For explaining that the faster ball has a larger horizontal velocity component, so it reaches the wall in less time.	1 point
B3	For explaining that a ball with less time in the air falls a shorter distance below the straight line of its launch direction, and both balls are launched along the same line, so the faster ball strikes the wall higher.	1 point

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EXAMPLE RESPONSE

$y_2 > y_w$. Both balls leave along the same straight line at angle θ_0. Without gravity, each would follow that line and hit the wall at height $L \tan \theta_0$. Gravity pulls each ball below the line by an amount that grows with its time in the air. The faster ball has a larger horizontal velocity component, so it covers the horizontal distance L in less time. It falls a shorter distance below the line, so it strikes the wall higher. This agrees with Part A(ii): the term subtracted from $L \tan \theta_0$ gets smaller as the launch speed increases.

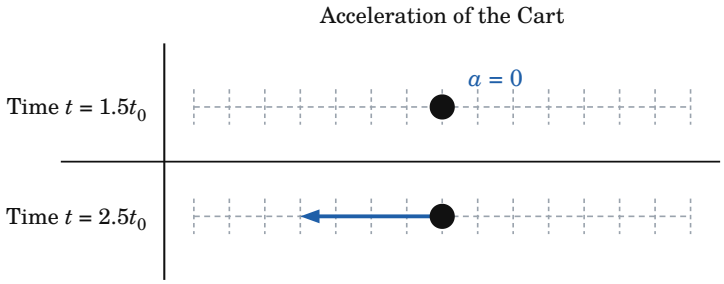
Scoring note: Reasoning from the expression in Part A(ii) also earns points B2 and B3 if it explains in words that the term subtracted from $L \tan \theta_0$ is inversely proportional to v_0^2, so a faster kick subtracts less and the ball strikes the wall higher.

Review: Splitting a launch into horizontal and vertical motion is covered in free fall and projectile motion in the AP Physics 1 kinematics study guide. Its projectile simulator lets you hold the angle fixed and raise the launch speed to see how the path changes.

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

Part A		3 points
A1	For writing "$a = 0$" beside the dot for $t = 1.5t_0$, with no arrow.	1 point
A2	For a single arrow pointing left from the dot for $t = 2.5t_0$.	1 point
A3	For drawing the arrow at $t = 2.5t_0$ four units long, twice the length of the arrow in Figure 2.	1 point

EXAMPLE RESPONSE



Scoring note: From $2t_0$ to $3t_0$ the velocity changes by $-2v_0$ in a time t_0, so the acceleration is $-2v_0/t_0$, twice the magnitude of the acceleration from 0 to t_0. The velocity is zero at $2.5t_0$, but it is still changing, so the acceleration is not zero.

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Part B		4 points
B1	For a multistep derivation that uses kinematic equations or areas under the velocity-time graph.	1 point
B2	For identifying that the cart is at its maximum position when its velocity becomes zero, at $t = 2.5t_0$.	1 point
B3	For a correct displacement for a time interval in which the cart accelerates, such as $\frac{1}{2}v_0t_0$ from 0 to t_0 or $\frac{1}{4}v_0t_0$ from $2t_0$ to $2.5t_0$.	1 point
B4	For a correct expression for x_{max}.	1 point

EXAMPLE RESPONSE

From 0 to t_0: $a = v_0/t_0$, so $\Delta x_1 = \frac{1}{2}at_0^2 = \frac{1}{2}v_0t_0$

From t_0 to $2t_0$: $\Delta x_2 = v_0t_0$

From $2t_0$ on: $a = -2v_0/t_0$. The velocity is zero when $v_0 - (2v_0/t_0)\Delta t = 0$, so $\Delta t = \frac{1}{2}t_0$, at $t = 2.5t_0$.

$\Delta x_3 = v_0(\frac{1}{2}t_0) + \frac{1}{2}(-2v_0/t_0)(\frac{1}{2}t_0)^2 = \frac{1}{4}v_0t_0$

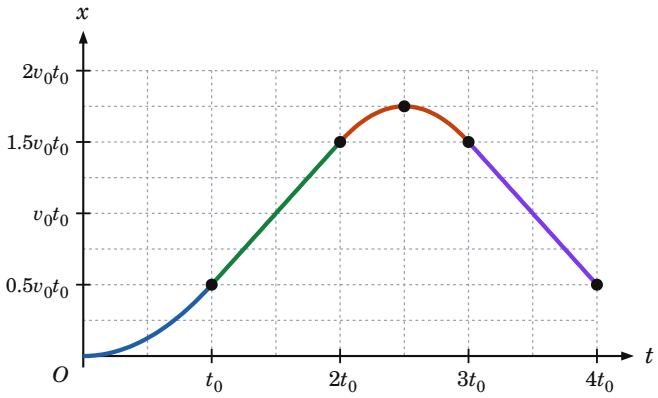
$x_{max} = \frac{1}{2}v_0t_0 + v_0t_0 + \frac{1}{4}v_0t_0 = \frac{7}{4}v_0t_0$

Scoring note: The areas under the velocity graph give the same result: a triangle, a rectangle, and a second triangle that ends where the line crosses the time axis.

Part C		3 points
C1	For a curve from the origin that bends upward (slope increasing) from 0 to t_0, followed by a straight line with positive slope from t_0 to $2t_0$.	1 point
C2	For a curve from $2t_0$ to $3t_0$ that bends downward and has its maximum at $2.5t_0$.	1 point
C3	For a straight line with negative slope from $3t_0$ to $4t_0$, with positions that match the grid: $0.5v_0t_0$ at t_0, $1.5v_0t_0$ at $2t_0$ and at $3t_0$, and $0.5v_0t_0$ at $4t_0$.	1 point

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EXAMPLE RESPONSE



KEY

- 0 to t_0: speeding up, curve bends upward
- t_0 to $2t_0$: constant velocity v_0, straight line
- $2t_0$ to $3t_0$: slowing until $2.5t_0$, then speeding up to the left; curve bends downward throughout
- $3t_0$ to $4t_0$: constant velocity $-v_0$, straight line

Scoring note: The graph has no sharp corners, because its slope is the velocity, and the velocity never jumps from one value to another.

Part D		2 points
D1	For indicating that the average speed is greater than the magnitude of the average velocity.	1 point
D2	For explaining that the cart reverses direction at $2.5t_0$, so the distance it travels is greater than the magnitude of its displacement, and both are divided by the same time interval.	1 point

EXAMPLE RESPONSE

Average speed > magnitude of average velocity. Average speed is the distance traveled divided by the time, and average velocity is the displacement divided by the time. The cart moves right until $2.5t_0$ and then moves left. The leftward motion adds to the distance but cancels part of the displacement: the distance is $3v_0t_0$, while the displacement is $0.5v_0t_0$, over the same $4t_0$.

Review: The slope and area rules for motion graphs in the kinematics study guide cover Parts B and C, and the same guide defines average speed and average velocity in its first section.

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

Part A		2 points
A(i)	For indicating that the students measure the distance d the cart rolls from rest and the time t it takes to roll that distance, for several different distances.	1 point
A(ii)	For a valid way to reduce uncertainty, such as timing several trials at each distance and averaging the times, or using distances long enough that reaction time is a small part of each time.	1 point

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Part B		2 points
B(i)	For a pair of quantities that gives a linear graph, such as d on the vertical axis and t^2 on the horizontal axis.	1 point
B(ii)	For relating a feature of the graph to a, such as: for d versus t^2, the slope equals $\frac{1}{2}a$, so $a = 2 \times$ slope.	1 point

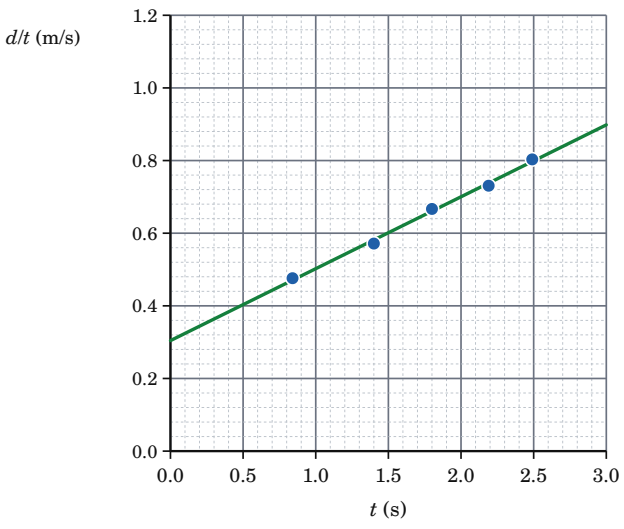
EXAMPLE RESPONSE

Starting from rest, $d = \frac{1}{2}at^2$. A graph of d (vertical axis) versus t^2 (horizontal axis) is a straight line through the origin with slope $\frac{1}{2}a$, so $a = 2 \times$ slope.

Scoring note: Other linear choices earn credit with a matching relationship, such as t^2 versus d (slope = $2/a$) or $2d$ versus t^2 (slope = a).

Part C		4 points
C(i)	For labeling the vertical axis with a quantity that makes the graph linear with t on the horizontal axis, such as d/t or $2d/t$, in m/s.	1 point
C(ii)	For a linear numerical scale on the vertical axis.	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 (t, d/t)

Best-fit line: slope about 0.20 m/s², vertical intercept about 0.30 m/s

Values plotted

t (s)	d/t (m/s)
0.84	0.476
1.40	0.571
1.80	0.667
2.19	0.731
2.49	0.803

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Part D		2 points
D(i)	For relating the slope to a correctly for the quantity plotted in Part C. For d/t versus t, the slope is $\frac{1}{2}a$, so $a = 2 \times$ slope. For $2d/t$ versus t, the slope is a.	1 point
D(ii)	For a value of a between 0.36 m/s² and 0.44 m/s².	1 point

EXAMPLE RESPONSE

Dividing $d = ut + \frac{1}{2}at^2$ by t gives $d/t = u + \frac{1}{2}at$, so the slope of the graph is $\frac{1}{2}a$.

Two points on the best-fit line: (0.50 s, 0.40 m/s) and (2.50 s, 0.80 m/s)

slope = (0.80 m/s − 0.40 m/s) ÷ (2.50 s − 0.50 s) = 0.20 m/s²

$a = 2 \times$ slope = 0.40 m/s²

Scoring note: A student who plotted $2d/t$ reads a slope of about 0.40 m/s², which is a itself, and earns both points.

Scoring note: The vertical intercept, about 0.30 m/s on the d/t graph, is the speed u at Photogate 1. It is not needed to find a.

Review: The section on motion diagrams and measured data in the kinematics study guide shows why distance plotted against time squared is a straight line for an object that starts from rest.

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

Part A		3 points
A1	For indicating $D_2 > D_1$.	1 point
A2	For explaining that both stones gain speed at the same rate, but Stone 1 has been falling longer, so at every instant after t_0 it is moving faster than Stone 2.	1 point
A3	For connecting the difference in speeds to the separation: Stone 1 covers more distance than Stone 2 in every time interval, so the distance between them keeps growing.	1 point

EXAMPLE RESPONSE

$D_2 > D_1$. Both stones speed up at the same rate. Stone 1 started falling earlier, so at any instant after Stone 2 is released, Stone 1 has been falling longer and is moving faster. It falls farther than Stone 2 during each interval, so the gap between them grows.

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Part B		3 points
B1	For a multistep derivation that applies a kinematic equation to each stone, or to the motion of Stone 1 relative to Stone 2.	1 point
B2	For accounting correctly for the later release of Stone 2, such as its fall distance $\frac{1}{2}g(t - t_0)^2$, or a separation of $\frac{1}{2}gt_0^2$ at $t = t_0$ that then grows at the relative speed gt_0.	1 point
B3	For a correct expression for D.	1 point

EXAMPLE RESPONSE

Distance fallen from rest (down taken as positive): $\Delta y = v_{y0}t + \frac{1}{2}gt^2 = \frac{1}{2}gt^2$

Stone 1: $\Delta y_1 = \frac{1}{2}gt^2$ Stone 2: $\Delta y_2 = \frac{1}{2}g(t - t_0)^2$

$D = \Delta y_1 - \Delta y_2 = \frac{1}{2}g[t^2 - (t - t_0)^2] = gt_0t - \frac{1}{2}gt_0^2$

Scoring note: Alternate solution (relative motion): when Stone 2 is released, Stone 1 has fallen $\frac{1}{2}gt_0^2$ and is moving at gt_0. After that both stones have the same acceleration, so Stone 1 moves away from Stone 2 at the constant relative speed gt_0: $D = \frac{1}{2}gt_0^2 + gt_0(t - t_0) = gt_0t - \frac{1}{2}gt_0^2$.

Part C		2 points
C1	For describing the functional dependence: D increases linearly with t, at a constant rate gt_0.	1 point
C2	For applying it to Part A: since D grows as t grows, D at $2t_0$ ($\frac{3}{2}gt_0^2$) is greater than D at t_0 ($\frac{1}{2}gt_0^2$), which agrees with Part A.	1 point

EXAMPLE RESPONSE

Consistent. The expression $D = gt_0t - \frac{1}{2}gt_0^2$ increases linearly with time, so the stones get farther apart.

The rate gt_0 is the difference in the stones' speeds, which stays the same because both speed up at the same rate. That is the reasoning in Part A.

Review: The free fall guide works through objects dropped from rest, including the distance fallen after a given time.

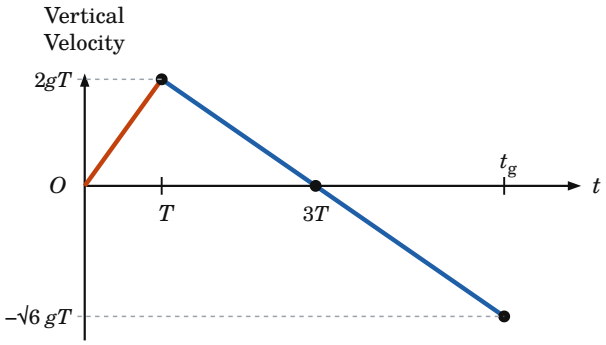
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Question 5: Mathematical Routines (MR) — 10 points

Part A(i) — 2 points

A1	For a straight line with positive slope from the origin to $t = T$.	1 point
A2	For a straight line with negative slope from T to t_g that crosses the time axis and is less steep than the first line.	1 point

EXAMPLE RESPONSE



KEY

- Engine firing: slope $2g$
- Free fall: slope $-g$, crossing zero at the highest point

Scoring note: The line crosses zero at $3T$ and ends at $-\sqrt{6}\,gT$, which is larger in magnitude than $2gT$. These details are not required.

Part A(ii) — 3 points

A3	For a multistep derivation that treats the powered stage and the free-fall stage separately.	1 point
A4	For a correct speed ($2gT$) or height (gT^2) at the instant the engine stops.	1 point
A5	For a correct expression for H, using a vertical velocity of zero at the highest point.	1 point

EXAMPLE RESPONSE

Powered stage, $a_y = 2g$: $v_1 = 0 + (2g)T = 2gT$, $y_1 = \frac{1}{2}(2g)T^2 = gT^2$

Free fall, $a_y = -g$, with $v_y = 0$ at the top: $0 = v_1^2 - 2g(H - y_1)$

$H - y_1 = \frac{(2gT)^2}{2g} = 2gT^2$

$H = gT^2 + 2gT^2 = 3gT^2$

Scoring note: Alternate solution (energy): after the engine stops, only gravity does work on the rocket, so its mechanical energy is constant. With the ground as the zero of gravitational potential energy, $\frac{1}{2}m(2gT)^2 + mg(gT^2) = mgH$, which gives $H = 3gT^2$. This earns points A3, A4, and A5.

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Part A(iii)		2 points
A6	For applying a kinematic equation or conservation of energy to the fall, such as $v_y^2 = v_{y0}^2 + 2a_y\Delta y$ from the highest point with $v_{y0} = 0$ and $\Delta y = -H$, or $mgH = \frac{1}{2}mv^2$.	1 point
A7	For a correct expression for the speed just before the rocket reaches the ground.	1 point

EXAMPLE RESPONSE

From the highest point: $v^2 = 0 + 2gH = 2g(3gT^2) = 6g^2T^2$

$v = \sqrt{6}\,gT$ (about $2.4gT$)

Scoring note: Other correct methods give the same result. From the moment the engine stops, $v^2 = (2gT)^2 + 2g(gT^2) = 6g^2T^2$. With energy, $mgH = \frac{1}{2}mv^2$ gives $v = \sqrt{(2gH)} = \sqrt{6}\,gT$. The three-ball race on the free fall page shows why, in free fall, the rocket passes the cutoff height on the way down with the same speed, $2gT$, that it had there on the way up.

Part B		3 points
B1	For indicating $H_2 < H$.	1 point
B2	For explaining that both rockets have the same speed when their engines stop ($4g \times \frac{1}{2}T = 2g \times T$), so after cutoff both rise the same additional height.	1 point
B3	For explaining why the second rocket is lower when its engine stops, such as: it reaches the same speed in half the time, so with the same average speed it rises half as far; or the area under its velocity-time graph during the powered stage is half as large.	1 point

EXAMPLE RESPONSE

$H_2 < H$. Both rockets are moving at $2gT$ when their engines stop, because $4g \times \frac{1}{2}T = 2g \times T$. From that moment both are in free fall with the same speed, so each rises the same extra height. While the engines fire, each rocket speeds up steadily from 0 to $2gT$, so both have the same average speed. The second rocket fires for only half as long, so it covers half the height before cutoff, and its highest point is lower. (For comparison, $H_2 = \frac{5}{2}gT^2$ and $H = 3gT^2$.)

Review: Once the engine stops, the rocket moves like a ball thrown straight up, starting with the speed it had at engine cutoff. The free fall guide works through that case in objects thrown straight up.

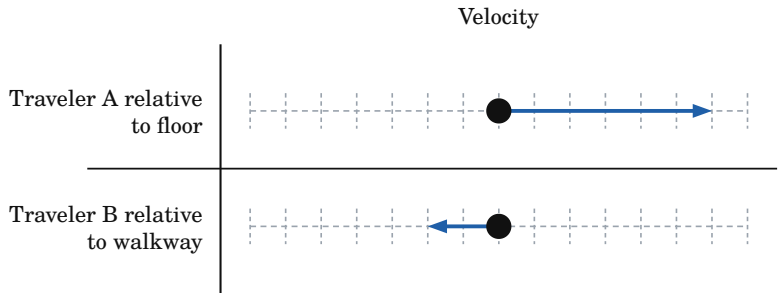
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Question 6: Translation Between Representations (TBR) — 12 points

Part A — 3 points

A1	For a single arrow pointing right for Traveler A relative to the floor.	1 point
A2	For a single arrow pointing left for Traveler B relative to the walkway.	1 point
A3	For arrow lengths of six units for Traveler A relative to the floor and two units for Traveler B relative to the walkway.	1 point

EXAMPLE RESPONSE



Scoring note: A velocity measured relative to the floor equals the velocity relative to the walkway plus the walkway's velocity relative to the floor. Traveler A: $\frac{1}{2}v_W + v_W = \frac{3}{2}v_W$, six units. Traveler B relative to the walkway: $\frac{1}{2}v_W - v_W = -\frac{1}{2}v_W$, two units to the left.

Part B — 4 points

B1	For a multistep derivation that applies $x = x_0 + vt$ to both travelers, or to the motion of Traveler A relative to Traveler B, over the time t_A.	1 point
B2	For a correct velocity of Traveler A relative to the floor, $\frac{3}{2}v_W$.	1 point
B3	For a correct time $t_A = \frac{2L}{3v_W}$, or a correct position $L/3$ for Traveler B at that time.	1 point
B4	For a correct expression for the distance between the travelers.	1 point

EXAMPLE RESPONSE

Relative to the floor: $v_A = \frac{1}{2}v_W + v_W = \frac{3}{2}v_W$ and $v_B = \frac{1}{2}v_W$

Traveler A reaches the end when $L = \frac{3}{2}v_W t_A$, so $t_A = \frac{2L}{3v_W}$

Traveler B is then at $x_B = \frac{1}{2}v_W t_A = \frac{L}{3}$

Distance between them: $L - \frac{L}{3} = \frac{2L}{3}$

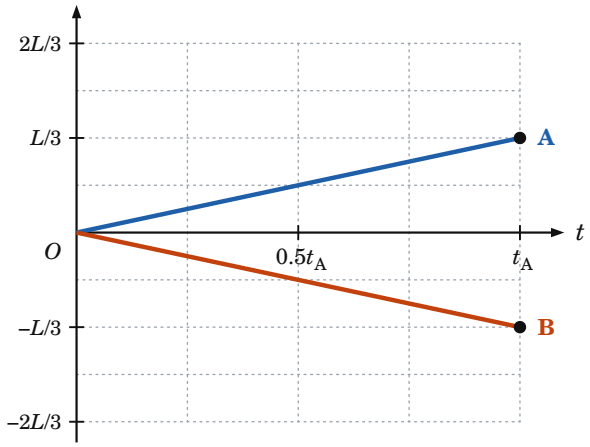
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Scoring note: Alternate solution (relative motion): relative to Traveler B, Traveler A moves at $\frac{3}{2}v_W - \frac{1}{2}v_W = v_W$. The travelers start side by side, so at $t_A = \frac{2L}{3v_W}$ they are $v_W t_A = \frac{2L}{3}$ apart. This earns all four points.

Scoring note: The answer does not depend on v_W. A faster walkway shortens the time Traveler A needs to reach the end, and the gap between the travelers grows faster by the same factor.

Part C		3 points
C1	For a straight line through the origin with positive slope, labeled A.	1 point
C2	For a straight line through the origin with negative slope, labeled B.	1 point
C3	For lines that end at $x' = L/3$ (A) and $x' = -L/3$ (B) at $t = t_A$.	1 point

EXAMPLE RESPONSE



KEY

Traveler A: moves at $+\frac{1}{2}v_W$ relative to the walkway

Traveler B: moves at $-\frac{1}{2}v_W$ relative to the walkway

Part D		2 points
D1	For indicating that the speed of Traveler A relative to Traveler B equals v_W.	1 point
D2	For a valid justification, such as: relative to the floor, A moves at $\frac{3}{2}v_W$ and B at $\frac{1}{2}v_W$, so A gains on B at v_W; or each traveler walks at $\frac{1}{2}v_W$ relative to the surface underfoot, so their velocities differ by the walkway's velocity.	1 point

EXAMPLE RESPONSE

Equal to v_W. Velocities measured in two frames differ by the velocity of one frame relative to the other. Each traveler walks at $\frac{1}{2}v_W$ relative to the surface under their feet, so the only difference between their velocities is the walkway's velocity, v_W. The graph in Part C shows the same thing: relative to the walkway, A moves at $+\frac{1}{2}v_W$ and B at $-\frac{1}{2}v_W$, a difference of v_W. It also matches Part B, since a gap that grows at v_W for a time $\frac{2L}{3v_W}$ reaches $\frac{2L}{3}$.

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Review: Positive and negative velocities along a chosen axis are set up in position, velocity, and acceleration, the first section of the kinematics study guide.

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

Part A		2 points
A(i)	For indicating that the students measure the launch height h (from the floor to the ball as it leaves the launcher) and the horizontal distance D from the point on the floor directly below the launch point to the landing mark, for several table heights.	1 point
A(ii)	For a valid way to reduce uncertainty, such as firing several times at each height and averaging the landing distances, or measuring D to the center of the cluster of marks.	1 point

Part B		2 points
B(i)	For a pair of quantities that gives a linear graph, such as D^2 on the vertical axis and h on the horizontal axis.	1 point
B(ii)	For relating a feature of the graph to v_L, such as: for D^2 versus h, the slope equals $\frac{2v_L^2}{g}$, so $v_L = \sqrt{(g \times \text{slope} \div 2)}$.	1 point

EXAMPLE RESPONSE

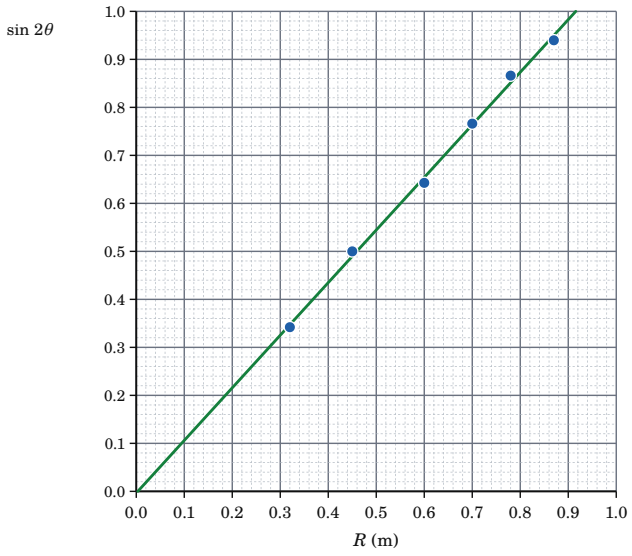
The fall time comes from $h = \frac{1}{2}gt^2$, and the horizontal distance is $D = v_L t$. Eliminating t gives $D^2 = \frac{2v_L^2}{g}h$. A graph of D^2 (vertical axis) versus h (horizontal axis) is a straight line through the origin, and $v_L = \sqrt{(g \times \text{slope} \div 2)}$.

Scoring note: D versus $\sqrt{h}$ also works, with slope = $v_L\sqrt{(2/g)}$.

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 $\sin 2\theta$ (no units) or $(\sin 2\theta)/g$ in s^2/m.	1 point
C(ii)	For a linear numerical scale on the vertical axis.	1 point
C(iii)	For plotting the six 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

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EXAMPLE RESPONSE



KEY

Data points (R, sin 2θ)

Best-fit line: slope about 1.09 per meter, passing close to the origin

Values plotted

θ (degrees)	sin 2θ	R (m)
10	0.342	0.32
15	0.500	0.45
20	0.643	0.60
25	0.766	0.70
30	0.866	0.78
35	0.940	0.87

Part D		**2 points**
D(i)	For relating the slope to v_L correctly for the quantity plotted in Part C. For sin 2θ versus R, the slope is $\frac{g}{{v_L}^2}$, so $v_L = \sqrt{(g \div \text{slope})}$. For (sin 2θ)/g versus R, the slope is $\frac{1}{{v_L}^2}$, so $v_L = 1 \div \sqrt{\text{slope}}$.	1 point
D(ii)	For a value of v_L between 2.85 m/s and 3.15 m/s.	1 point

EXAMPLE RESPONSE

Rearranging $R = \frac{{v_L}^2}{g} \sin 2\theta$ gives $\sin 2\theta = \frac{g}{{v_L}^2} R$, so the slope of the graph is $\frac{g}{{v_L}^2}$.

Two points on the best-fit line: (0.20 m, 0.22) and (0.90 m, 0.98)

slope = (0.98 – 0.22) ÷ (0.90 m – 0.20 m) = 1.09 m^{-1}

$v_L = \sqrt{(9.8\ m/s^2 \div 1.09\ m^{-1})} = 3.0$ m/s

Scoring note: A student who plotted (sin 2θ)/g reads a slope of about 0.11 s^2/m^2, which gives $v_L = 1 \div \sqrt{0.11} =$ 3.0 m/s and earns both points.

Review: The horizontal launch in Parts A and B is the same setup as the worked example of a ball rolling off a platform in the kinematics study guide.

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

Part A		3 points
A1	For indicating $d_B > 2d_A$.	1 point
A2	For explaining that Car B has twice as much speed to lose at the same rate, so it brakes for twice as long as Car A.	1 point
A3	For explaining that Car B's average speed while braking is also twice Car A's, so its braking distance is four times as large; with the reaction distance only doubled, the total more than doubles.	1 point

EXAMPLE RESPONSE

$d_B > 2d_A$. During the reaction time both cars move at constant speed for the same time, so Car B goes twice as far. While braking, both cars lose speed at the same rate. Car B has twice as much speed to lose, so it brakes for twice as long, and its average speed while braking is also twice as large. Twice the average speed for twice the time gives four times the braking distance, so the total is more than twice Car A's.

Scoring note: Reasoning about energy also earns points A2 and A3, for example: each kilogram of Car B has four times as much kinetic energy to remove, and braking removes the same energy per kilogram for each meter traveled, so Car B's braking distance is four times Car A's.

Part B		3 points
B1	For a multistep derivation that treats the reaction interval (constant speed) and the braking interval (constant acceleration) separately.	1 point
B2	For a correct reaction distance vt_r or a correct braking distance $\frac{v^2}{2a_0}$.	1 point
B3	For a correct expression for d_A.	1 point

EXAMPLE RESPONSE

Reaction: $\Delta x_1 = vt_r$

Braking, with final speed 0 and $a_x = -a_0$: $v_x^2 = v_{x0}^2 + 2a_x\Delta x \rightarrow 0 = v^2 - 2a_0\Delta x_2$, so $\Delta x_2 = \frac{v^2}{2a_0}$

$d_A = vt_r + \frac{v^2}{2a_0}$

Scoring note: Alternate solution (work-energy theorem): during braking the net force on the car has magnitude ma_0, so $-ma_0\Delta x_2 = 0 - \frac{1}{2}mv^2$, which gives $\Delta x_2 = \frac{v^2}{2a_0}$. The mass cancels.

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Part C		2 points
C1	For describing the functional dependence: the reaction distance is proportional to the speed, and the braking distance is proportional to the square of the speed.	1 point
C2	For applying it: doubling the speed doubles the first term and quadruples the second, so d_B exceeds $2d_A$, which agrees with Part A.	1 point

EXAMPLE RESPONSE

$$d_B = (2v)t_r + \frac{(2v)^2}{2a_0} = 2vt_r + \frac{2v^2}{a_0}$$

$$2d_A = 2vt_r + \frac{v^2}{a_0}$$

$$d_B - 2d_A = \frac{v^2}{a_0} > 0, \text{ consistent with Part A.}$$

Review: The braking stage uses the equation that leaves out time, listed with the other constant-acceleration equations in the kinematics study guide.

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