Past-paper walk-through

Conservation of Linear Momentum ▪ 4.3

eXercise

Questions in this set

- 2026 Q2
- 2025 Q1
- 2024 Q5
- 2022 Q4
- 2021 Q3
- 2019 Q1
- 2016 Q2

Reading the mark scheme

- **B1** a mark that stands on its own – the point is either made or not.
- **M1** a *method* mark: the right approach, even if the number is wrong.
- **A1** an *answer* mark, and it usually needs its M mark first.
- **C1** a working mark on the way to the answer.
- // separates answers the examiner accepts equally.
- **ecf** = error carried forward: a later part is marked on your own earlier answer.
- **owtte** = "or words to that effect" – the wording need not match.

Question 2

2026 ▪ Q2

Two small disks, R and S, are on a straight, horizontal track.
At time $t = 0$, Disk R of mass m_0 is located at position $x = 0$. Disk R is initially moving with speed v_0 in the $+x$-direction. Disk S of mass $3m_0$ is initially at rest, as shown in the top view in Figure 1. Frictional forces are negligible.
At $t = t_1$, the disks collide. Immediately after the collision, Disk R moves with speed $\frac{1}{2}v_0$ in the $-x$-direction.
[Figure 1 (Top View): A horizontal dashed track with two disks. On the left, a smaller shaded disk labeled m_0 ("Disk R") has an arrow above it labeled v_0 pointing right (in the $+x$-direction, with a $+x$ axis arrow shown above). On the right, a larger open disk labeled $3m_0$ ("Disk S") is labeled $v = 0$ above it. Note: Figure not drawn to scale.]

Question 2

(a) The momentum-vector diagram in Figure 2 represents the momentums of Disk R and Disk S before the collision.
[Figure 2: Two rows, each with a horizontal dashed number-line-style axis (light vertical tick marks along it) crossing a vertical axis at a central dot. Top row labeled "Disk R": a solid arrow starts at the central dot and points right, labeled with the heading "Momentum Before Collision" above both rows. Bottom row labeled "Disk S": just a dot with no arrow, labeled "$p = 0$" above it.]
Draw arrows on Figure 3 to represent the momentum vectors of Disk R and Disk S after the collision.

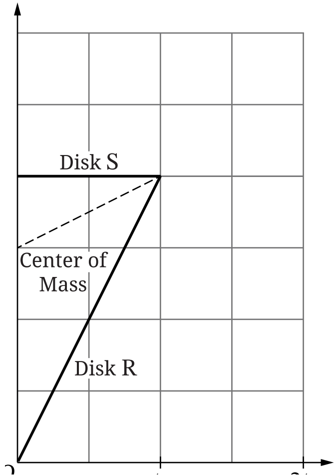
- Each arrow must start on, and point away from, each dot.
- If the momentum of either disk is zero, write "$p = 0$" next to the dot.

Question 2

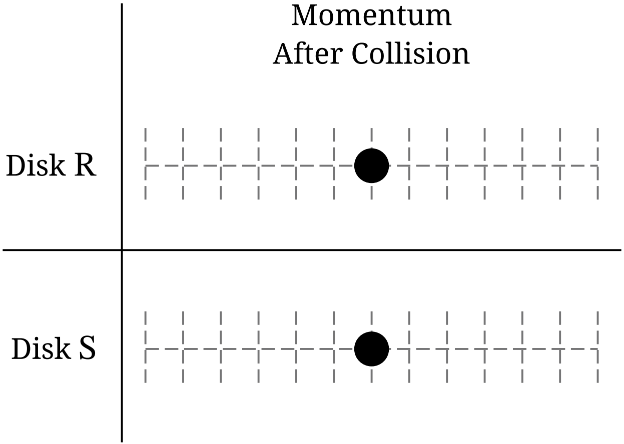
- Draw the length of each arrow to represent the magnitude of each momentum, consistent with the scale used in Figure 2.

[Figure 3: Same style as Figure 2 but blank — two rows each with a horizontal dashed axis and a central dot, headed "Momentum After Collision", one row labeled "Disk R" and one row labeled "Disk S", for the student to draw arrows on.]

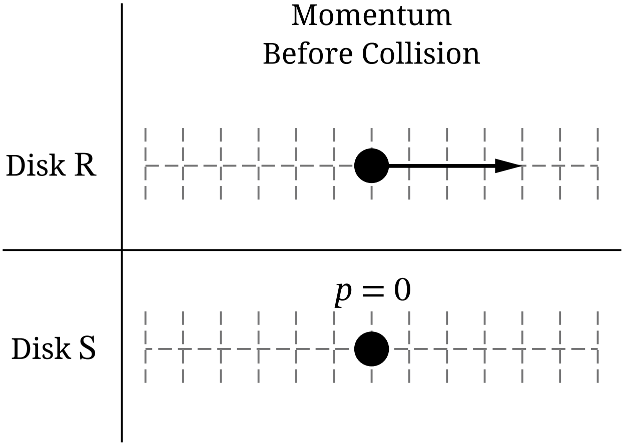
Question 2



Question 2



Question 2



Question 2

2026 ▪ Q2

Two small disks, R and S, are on a straight, horizontal track.

At time $t = 0$, Disk R of mass m_0 is located at position $x = 0$. Disk R is initially moving with speed v_0 in the $+x$-direction. Disk S of mass $3m_0$ is initially at rest, as shown in the top view in Figure 1. Frictional forces are negligible.

At $t = t_1$, the disks collide. Immediately after the collision, Disk R moves with speed $\dfrac{1}{2}v_0$ in the $-x$-direction.

[Figure 1 (Top View): A horizontal dashed track with two disks. On the left, a smaller shaded disk labeled m_0 ("Disk R") has an arrow above it labeled v_0 pointing right (in the $+x$-direction, with a $+x$ axis arrow shown above). On the right, a larger open disk labeled $3m_0$ ("Disk S") is labeled $v = 0$ above it. Note: Figure not drawn to scale.]

(b) Starting with conservation of linear momentum, **derive** an expression for the kinetic energy of Disk S immediately after the collision. Express your final answer in

Question 2

terms of m_0, v_0, and physical constants, as appropriate. Begin your derivation by writing the fundamental physics principle or an equation from the reference information.

Question 2

2026 ▪ Q2

Two small disks, R and S, are on a straight, horizontal track.

At time $t = 0$, Disk R of mass m_0 is located at position $x = 0$. Disk R is initially moving with speed v_0 in the $+x$-direction. Disk S of mass $3m_0$ is initially at rest, as shown in the top view in Figure 1. Frictional forces are negligible.

At $t = t_1$, the disks collide. Immediately after the collision, Disk R moves with speed $\frac{1}{2}v_0$ in the $-x$-direction.

[Figure 1 (Top View): A horizontal dashed track with two disks. On the left, a smaller shaded disk labeled m_0 ("Disk R") has an arrow above it labeled v_0 pointing right (in the $+x$-direction, with a $+x$ axis arrow shown above). On the right, a larger open disk labeled $3m_0$ ("Disk S") is labeled $v = 0$ above it. Note: Figure not drawn to scale.]

(c) The graph shown in Figure 4 represents the positions x as functions of time t from $t = 0$ until $t = t_1$ for each of the following:

Question 2

- Disk R
- Disk S
- The center of mass of the two-disk system

On the graph shown in Figure 4, **draw** three lines that represent the positions x of Disk R, Disk S, and the center of mass of the two-disk system as functions of t from $t = t_1$ to $t = 2t_1$. Distinctly **label** each line.

[Figure 4: A position (x, vertical axis) vs. time (t, horizontal axis) grid. From $t = 0$ to $t = t_1$, three straight lines rise from the origin O: the steepest line (largest slope) is labeled "Disk S", a shallower line is labeled "Center of Mass" (shown as a dashed line), and the shallowest line is labeled "Disk R". The horizontal axis is marked with tick values t_1 and $2t_1$ (blank beyond t_1 for the student to continue the lines).]

Question 2

2026 ▪ Q2

Two small disks, R and S, are on a straight, horizontal track.
At time $t = 0$, Disk R of mass m_0 is located at position $x = 0$. Disk R is initially moving with speed v_0 in the $+x$-direction. Disk S of mass $3m_0$ is initially at rest, as shown in the top view in Figure 1. Frictional forces are negligible.

At $t = t_1$, the disks collide. Immediately after the collision, Disk R moves with speed $\frac{1}{2}v_0$ in the $-x$-direction.

[Figure 1 (Top View): A horizontal dashed track with two disks. On the left, a smaller shaded disk labeled m_0 ("Disk R") has an arrow above it labeled v_0 pointing right (in the $+x$-direction, with a $+x$ axis arrow shown above). On the right, a larger open disk labeled $3m_0$ ("Disk S") is labeled $v = 0$ above it. Note: Figure not drawn to scale.]

(d) During the collision, the magnitudes of the changes in momentum of Disk R and Disk S are $|\Delta p_R|$ and $|\Delta p_S|$, respectively.

Question 2

Indicate whether $|\Delta p_R|$ is greater than, less than, or equal to $|\Delta p_S|$ by writing one of the following.
- $|\Delta p_R| > |\Delta p_S|$ - $|\Delta p_R| < |\Delta p_S|$ - $|\Delta p_R| = |\Delta p_S|$
Briefly **justify** your response by referencing a fundamental physics principle.

Question 1

2025 ▪ Q1

A student has a cart of mass m_c and a block of mass $\frac{1}{5}m_c$, as shown in Figure 1.
- At time $t = 0$, the cart is moving to the right across a horizontal surface with constant speed v_c, and the student releases the block from rest. - At $t = t_1$, the block collides with and sticks to the top of the cart. The block does not slide on the cart. - At $t = t_2$, the block-cart system continues to move to the right with constant speed v_f.
Figure 1
[Figure 1: Three snapshots of a cart of mass m_c on a horizontal surface. At $t = 0$, a hand holds a block of mass $\frac{1}{5}m_c$ above the moving cart labeled "Cart"; the cart moves to the right with speed lines shown. At $t = t_1$, the block is shown just above/contacting the top of the cart (falling onto it), cart still moving right. At $t = t_2$, the block rests on top of the cart, and the block-cart system moves to the right together.]

Question 1

(a)(i) On the axes shown in Figure 2, **sketch** a graph of the magnitude p_x of the x-component of the momentum of the block-cart system as a function of time t from $t = 0$ until $t > t_2$.

Figure 2

[Figure 2: A blank set of axes with vertical axis labeled p_x and horizontal axis labeled t, origin O. Two vertical dashed reference lines are drawn at $t = t_1$ and $t = t_2$. The student is to sketch the momentum curve on these axes.]

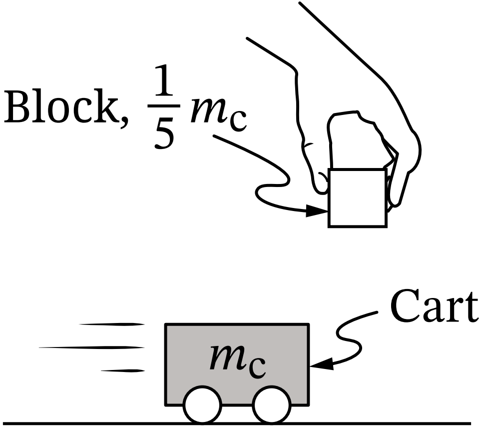
(a)(ii) **Derive** an expression for the speed v_f of the block-cart system after time $t = t_2$ in terms of m_c, v_c, and physical constants, as appropriate. Begin your derivation by writing a fundamental physics principle or an equation from the reference information.

(a)(iii) **Derive** an expression for the change in the kinetic energy ΔK in the block-cart system from $t = 0$ to $t = t_2$ in terms of m_c, v_c, and physical constants, as

Question 1

appropriate. Begin your derivation by writing a fundamental physics principle or an equation from the reference information.

Question 1



Question 1

2025 ▪ Q1

A student has a cart of mass m_c and a block of mass $\frac{1}{5}m_c$, as shown in Figure 1.
- At time $t = 0$, the cart is moving to the right across a horizontal surface with constant speed v_c, and the student releases the block from rest. - At $t = t_1$, the block collides with and sticks to the top of the cart. The block does not slide on the cart. - At $t = t_2$, the block-cart system continues to move to the right with constant speed v_f.
Figure 1
[Figure 1: Three snapshots of a cart of mass m_c on a horizontal surface. At $t = 0$, a hand holds a block of mass $\frac{1}{5}m_c$ above the moving cart labeled "Cart"; the cart moves to the right with speed lines shown. At $t = t_1$, the block is shown just above/contacting the top of the cart (falling onto it), cart still moving right. At $t = t_2$, the block rests on top of the cart, and the block-cart system moves to the right together.]

Question 1

(b) Consider the case where a new block is dropped and collides with the top of the cart. The new block slides along the cart during the collision but does not slide off the cart. The time interval from when the new block collides with the cart and moves together with the cart is Δt. During Δt there is a frictional force between the new block and the cart.
Indicate whether the x-component of the momentum of the new block-cart system increases, decreases, or remains constant during Δt.

$I^{ncreases}$

$D^{ecreases}$

$R^{emainsconstant}$
Justify your response.

Solution 1

(a)(i)

Mark scheme

- Sketch a single continuous, nonzero, horizontal line for p_x across the whole graph from $t = 0$ through $t = t_2$ (and beyond). Since no net external horizontal force acts on the block-cart system, the x-momentum is conserved throughout — constant before the collision $(t < t_1)$, unchanged during the collision, and constant after $(t > t_1)$, at the same height. Point A1: sketch a constant, nonzero p_x segment for $t < t_1$ OR for $t > t_1$. Point A2: sketch a continuous, nonzero, horizontal line from $t = 0$ to $t = t_2$ (or beyond), showing momentum stays constant the entire time.

Solution 1

(a)(ii) Mark scheme

- Begin with conservation of momentum: $p_i = p_f$. The falling block (mass $m_b = \frac{1}{5}m_c$) collides with the cart (mass m_c, speed v_c) and they move together afterward: $m_c v_c = (m_c + m_b)v_f = \left(m_c + \frac{1}{5}m_c\right) v_f = \frac{6}{5}m_c v_f$. Solving gives $v_f = \frac{5}{6}v_c$. Point A3 is earned for including a conservation-of-momentum equation; Point A4 for setting $m_c v_c$ equal to the post-collision momentum $(m_c + m_b)v_f$. A correct, isolated final expression $v_f = \frac{5}{6}v_c$ earns both A3 and A4.

Solution 1

(a)(iii) Mark scheme

- $\Delta K = K_f - K_0$, with $K_0 = \frac{1}{2} m_c v_c^2$, and using $v_f = \frac{5}{6} v_c$ from part A(ii) with final mass $\frac{6}{5} m_c$: $K_f = \frac{1}{2}\left(\frac{6}{5} m_c\right)\left(\frac{5}{6} v_c\right)^2 = \frac{5}{12} m_c v_c^2$. So $\Delta K = \frac{5}{12} m_c v_c^2 - \frac{1}{2} m_c v_c^2 = -\frac{1}{12} m_c v_c^2$ (kinetic energy decreases in the collision). Point A5 for a multistep derivation using $K = \frac{1}{2} m v^2$ (minimum: show an expression for K or ΔK that goes beyond the given reference equation); Point A6 for identifying m_c and $\frac{6}{5} m_c$ as the initial and final masses moving horizontally; Point A7 for using a v_f expression consistent with part A(ii). A correct, isolated final expression $\Delta K = -\frac{1}{12} m_c v_c^2$ earns points A3, A4, A6, and A7 as well.

Solution 1

(b) Mark scheme

- The x-momentum of the new block-cart system remains constant throughout Δt (Point B1). Justification: the frictional force between the new block and the cart is an internal force — it acts equally and oppositely on the two objects, so it produces no net external force on the system (Point B2: e.g. "the frictional force is internal to the new block-cart system" or "the net external force is still zero"). Consequently, the change in momentum of the new block is equal in magnitude and opposite in direction to the change in momentum of the cart — the impulses on each are equal and opposite (Point B3). Example response: "The momentum of the new block-cart system will remain constant because the frictional force

Solution 1

exerted on the new block by the cart is internal to the system and only a net external force will cause a change in momentum of the system."

Question 5

2024 ▪ Q5

[Figure 1: Block A (mass 6 kg) is shown on the left with three horizontal arrows/lines behind it indicating motion to the right, sitting on a horizontal surface. Block B (mass 2 kg), smaller, sits at rest to the right of Block A on the same horizontal surface. The label "$t = 0$" is below the figure.]
At time $t = 0$, Block A slides along a horizontal surface toward Block B, which is initially at rest, as shown in Figure 1. The masses of blocks A and B are 6 kg and 2 kg, respectively. The blocks collide elastically at $t = 1.0$ s, and as a result, the magnitude of the change in kinetic energy of Block B is 9 J. All frictional forces are negligible.
(a) (a) **Determine** the speed of Block B immediately after the collision.

Question 5

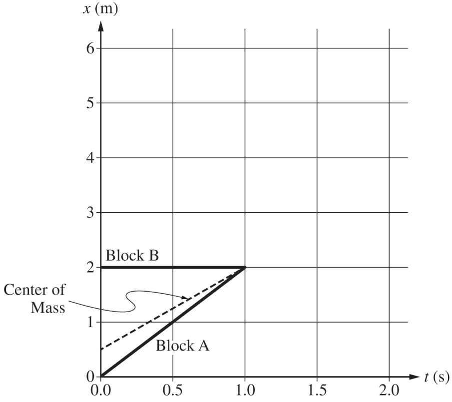


Figure 2

Question 5

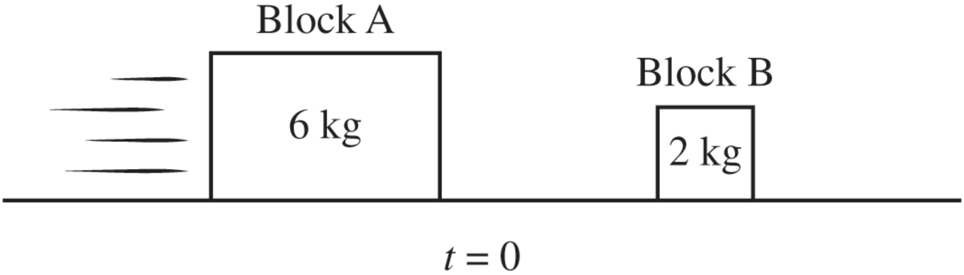


Figure 1

Question 5

2024 ▪ Q5

[Figure 1: Block A (mass 6 kg) is shown on the left with three horizontal arrows/lines behind it indicating motion to the right, sitting on a horizontal surface. Block B (mass 2 kg), smaller, sits at rest to the right of Block A on the same horizontal surface. The label "$t = 0$" is below the figure.]

At time $t = 0$, Block A slides along a horizontal surface toward Block B, which is initially at rest, as shown in Figure 1. The masses of blocks A and B are 6 kg and 2 kg, respectively. The blocks collide elastically at $t = 1.0$ s, and as a result, the magnitude of the change in kinetic energy of Block B is 9 J. All frictional forces are negligible.

(b) [Figure 2: A graph of position x (m) vs. time t (s), with y-axis from 0 to 6 in increments of 1, and x-axis from 0.0 to 2.0 in increments of 0.5, gridlines at $0.0, 0.5, 1.0, 1.5, 2.0$. Three lines are drawn from $t = 0$ to $t = 1.0$ s: a solid line labeled "Block A" starting at $x = 0$ at $t = 0$ and rising linearly to about $x = 2$ at $t = 1.0$ s; a

Question 5

solid horizontal line labeled "Block B" at constant $x = 2$ from $t = 0$ to $t = 1.0$ s (block B at rest); and a dashed line labeled "Center of Mass" starting at about $x = 0.5$ at $t = 0$ and rising linearly to $x = 2$ at $t = 1.0$ s, in between the Block A and Block B lines.]

The graph shown in Figure 2 represents the positions x of Block A, Block B, and the center of mass of the two-block system as functions of t between $t = 0$ and $t = 1.0$ s.

(b) On the graph in Figure 2, **draw** and **label** three lines to represent the positions of Block A, Block B, and the center of mass of the two-block system as functions of t between $t = 1.0$ s and $t = 2.0$ s. Each line should be distinctly labeled.

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2024 ▪ Q5

[Figure 1: Block A (mass 6 kg) is shown on the left with three horizontal arrows/lines behind it indicating motion to the right, sitting on a horizontal surface. Block B (mass 2 kg), smaller, sits at rest to the right of Block A on the same horizontal surface. The label "$t = 0$" is below the figure.]

At time $t = 0$, Block A slides along a horizontal surface toward Block B, which is initially at rest, as shown in Figure 1. The masses of blocks A and B are 6 kg and 2 kg, respectively. The blocks collide elastically at $t = 1.0$ s, and as a result, the magnitude of the change in kinetic energy of Block B is 9 J. All frictional forces are negligible.

(c) (c) Consider if in the original scenario, instead of colliding elastically, the blocks collided and stuck together. **Describe** how the line drawn for the center of mass in part (b) would change, if at all. Briefly **justify** your response.

Solution 5

(a)

Mark scheme

- Determine the speed of Block B immediately after the (elastic) collision from its kinetic energy: $\frac{1}{2}(2\text{ kg})v_f^2 = 9\text{ J} \Rightarrow v_f = 3\text{ m/s}$. Full credit (1 point) for determining the speed of Block B to be 3 m/s.

Solution 5

(b) Mark scheme

- On the position-vs-time graph (which already shows both blocks colliding at $t = 1.0$ s, $x = 2$ m), draw post-collision lines: Block A's line should have a positive slope that is smaller (less steep) than its pre-collision slope; Block B's line should have a positive, nonvertical slope; and the center-of-mass line should be a straight line with the same slope as the pre-collision (single) center-of-mass line, since momentum (and hence the center-of-mass velocity) is unchanged by the collision. In the example response, Block A's post-collision line has slope 1 m/s (rising from $(1.0, 2)$ toward $(2.0, 3)$) and Block B's post-collision line has slope 3 m/s (rising from $(1.0, 2)$ toward $(2.0, 5)$), both starting at $t = 1.0$ s, $x = 2$ m; the dashed center-of-mass line continues through this point with the same slope as

Solution 5

before the collision. Points: Block A drawn with a lesser positive slope than its pre-collision line (correct value not required) (1 point); Block B drawn with a positive, nonvertical slope (correct value not required) (1 point); the center-of-mass line drawn with the same slope as the pre-collision line (1 point); Block A and Block B lines drawn with the correct slopes, 1 m/s and 3 m/s respectively, both starting at $t = 1.0$ s, $x = 2$ m (1 point).

Solution 5

(c) Mark scheme

- If the blocks instead collided and stuck together (perfectly inelastic collision), the line drawn for the center of mass in part (b) would NOT change — it would have the same slope as in the elastic-collision case, because momentum is conserved in the collision regardless of whether it is elastic or inelastic, and no external forces act on the two-block system, so the center-of-mass velocity is unaffected. (After a perfectly inelastic collision, the individual position-time lines for Block A and Block B would now coincide with — lie along — this same center-of-mass line, since the blocks move together.) Points: indicating that the line drawn for the center of mass is the same for both scenarios (1 point); an explanation that

Solution 5

indicates one of — momentum is conserved in an inelastic collision, or no external forces are exerted on the two-block system (1 point).

Question 4

2022 ▪ Q4

A student has a piece of clay and a rubber sphere, both of the same mass. Both objects are thrown horizontally at the same speed at identical blocks that are at rest at the edge of identical tables, as shown, where friction between the blocks and the table is negligible. After the collisions, both blocks fall to the floor.

In Case A, the clay sticks to Block A after the collision. In Case B, the rubber sphere bounces off of Block B after the collision.

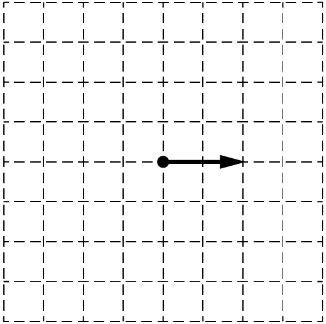
[Figure: Two setups side by side. Left: "Case A: Clay and Block A Before Collision" — a piece of Clay is shown moving horizontally (arrow) toward Block A resting at the edge of a table. Right: "Case B: Rubber Sphere and Block B Before Collision" — a Rubber Sphere is shown moving horizontally (arrow) toward Block B resting at the edge of an identical table.]

Question 4

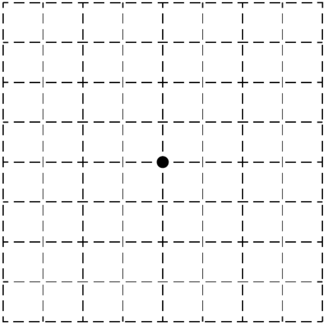
[Figure: Two grid diagrams below, each with a dot at center. Left: “Case A: Momentum of Clay-Block System Immediately After Collision” — the dot has a solid arrow pointing to the right, representing nonzero momentum. Right: “Case B: Momentum of Sphere-Block System Immediately After Collision” — just a dot shown, no arrow (to be completed by the student).]

(a) In the figure at left above, the arrow represents the momentum immediately after the collision for the clay-block system in Case A. In the figure at right above, draw an arrow starting on the dot to represent the momentum of the sphere-block system immediately after the collision in Case B. If the momentum is zero, write “zero” next to the dot. The momentum, if it is not zero, must be represented by an arrow starting on, and pointing away from, the dot. The length of the vector, if not zero, should reflect the magnitude of the momentum relative to Case A.

Question 4

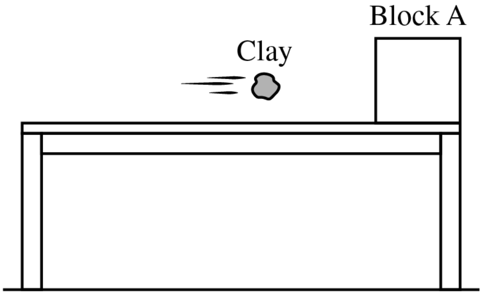


Case A: Momentum of Clay-Block System Immediately After Collision

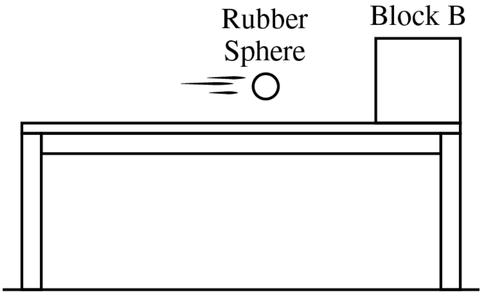


Case B: Momentum of Sphere-Block System Immediately After Collision

Question 4



Case A: Clay and Block A
Before Collision



Case B: Rubber Sphere and Block B
Before Collision

Question 4

2022 ▪ Q4

A student has a piece of clay and a rubber sphere, both of the same mass. Both objects are thrown horizontally at the same speed at identical blocks that are at rest at the edge of identical tables, as shown, where friction between the blocks and the table is negligible. After the collisions, both blocks fall to the floor.

In Case A, the clay sticks to Block A after the collision. In Case B, the rubber sphere bounces off of Block B after the collision.

[Figure: Two setups side by side. Left: "Case A: Clay and Block A Before Collision" — a piece of Clay is shown moving horizontally (arrow) toward Block A resting at the edge of a table. Right: "Case B: Rubber Sphere and Block B Before Collision" — a Rubber Sphere is shown moving horizontally (arrow) toward Block B resting at the edge of an identical table.]

[Figure: Two grid diagrams below, each with a dot at center. Left: "Case A: Momentum of Clay-Block System Immediately After Collision" — the dot has a solid arrow pointing to the

Question 4

right, representing nonzero momentum. Right: "Case B: Momentum of Sphere-Block System Immediately After Collision" — just a dot shown, no arrow (to be completed by the student).]

(b) After the clay and Block A collide, Block A lands a horizontal distance d_A from the edge of the table. Does Block B land on the floor at a horizontal distance from the edge of the table that is greater than, less than, or equal to d_A? In a clear, coherent, paragraph-length response that may also contain equations and/or drawings, explain your reasoning. Neglect any frictional effects due to the table or air resistance.

Solution 4

(a)

Mark scheme

- Draw an arrow starting on the dot for the sphere-block system in Case B, pointing to the right (same direction as Case A), with length two grid units (twice the length of the Case A arrow), since the sphere transfers more momentum than the clay. Scoring: 1 point for drawing an arrow representing the sphere-block momentum, two grid units in length and pointing to the right.

Solution 4

(b) Mark scheme

- Block B lands a greater horizontal distance from the edge of the table than d_A. Reasoning: momentum is conserved in each collision and is the same before both collisions; since the sphere in Case B bounces off Block B rather than sticking like the clay in Case A, the sphere transfers more momentum to Block B than the clay transfers to Block A, so Block B has greater momentum (and hence greater speed) immediately after the collision than Block A. A larger momentum means a greater launch speed. Both blocks fall from the same height off the table, so they are in the air for the same amount of time. A block moving faster horizontally therefore travels a greater horizontal distance in that same fall time – so Block B lands farther than d_A. Scoring (1 point each): indicating momentum is

Solution 4

conserved; indicating either why more momentum is transferred by the rubber sphere or why Block B has greater momentum than Block A after the collision; indicating a larger momentum leads to a greater speed; indicating the blocks fall for the same amount of time; indicating a block moving at a faster speed lands at a greater horizontal distance; an overall logical, relevant, internally consistent paragraph-length argument following the required argument format.

Question 3

2021 ▪ Q3

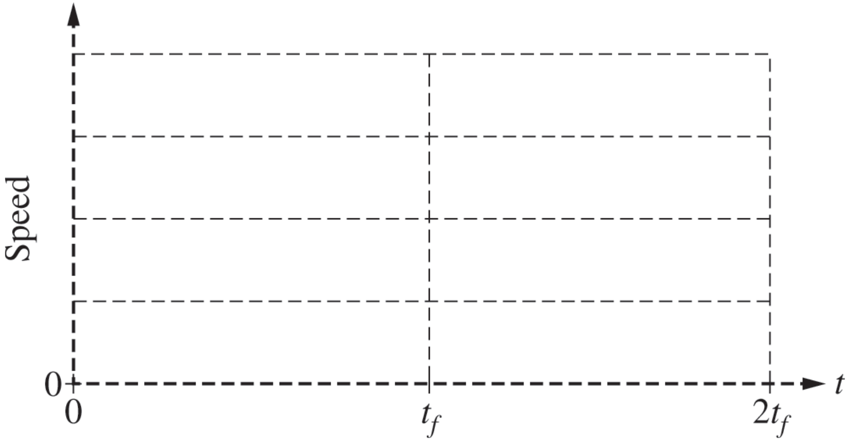
(12 points, suggested time 25 minutes)

(a)(i) A student of mass M_S, standing on a smooth surface, uses a stick to push a disk of mass M_D. The student exerts a constant horizontal force of magnitude F_H over the time interval from time $t = 0$ to $t = t_f$ while pushing the disk. Assume there is negligible friction between the disk and the surface.

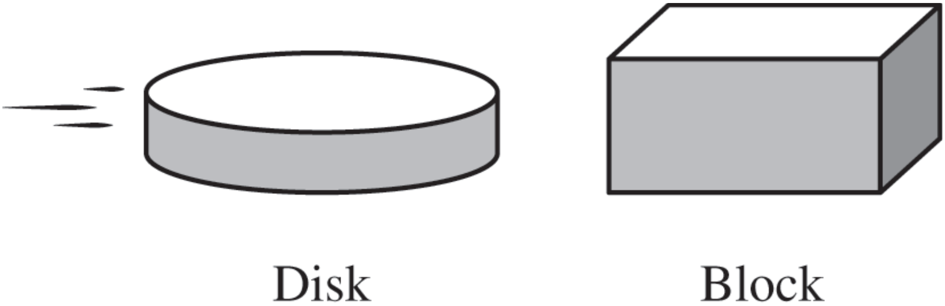
Assuming the disk begins at rest, determine an expression for the final speed v_D of the disk relative to the surface. Express your answer in terms of F_H, t_f, M_S, M_D, and physical constants, as appropriate.

(a)(ii) Assume there is negligible friction between the student's shoes and the surface. After time t_f, the student slides with speed v_S. Derive an equation for the ratio v_D/v_S. Express your answer in terms of M_S, M_D, and physical constants, as appropriate.

Question 3



Question 3



Question 3

2021 ▪ Q3

(12 points, suggested time 25 minutes)

(b) Assume that the student's mass is greater than that of the disk ($M_S > M_D$). On the grid below, sketch graphs of the speeds of both the student and the disk as functions of time t between $t = 0$ and $t = 2t_f$. Assume that neither the disk nor the student collides with anything after $t = t_f$. On the vertical axis, label v_D and v_S. Label the graphs "S" and "D" for the student and the disk, respectively.
[Graph grid: vertical axis labeled "Speed" (dashed gridlines, unlabeled numeric scale); horizontal axis labeled "t" with marked points at 0, t_f, and $2t_f$; empty dashed grid for the student to sketch on.]

Question 3

2021 ▪ Q3

(12 points, suggested time 25 minutes)

(c) [Figure: A disk (shown as a cylinder with motion lines indicating it moves to the right) and a rectangular block, shown side by side and labeled "Disk" and "Block" respectively.]

The disk is now moving at a constant speed v_1 on the surface toward a block of mass M_B, which is at rest on the surface, as shown above. The disk and block collide head-on and stick together, and the center of mass of the disk-block system moves with speed v_{cm}.

(c)(i) Suppose the mass of the disk is much greater than the mass of the block. Estimate the velocity of the center of mass of the disk-block system. Explain how you arrived at your prediction without deriving it mathematically.

Question 3

(c)(ii) Suppose the mass of the disk is much less than the mass of the block. Estimate the velocity of the center of mass of the disk-block system. Explain how you arrived at your prediction without deriving it mathematically.

(c)(iii) Now suppose that neither object's mass is much greater than the other but that they are not necessarily equal. Derive an equation for v_{cm}. Express your answer in terms of v_1, M_D, M_B, and physical constants, as appropriate.

(c)(iv) Consider the scenario from part (c)(i), where the mass of the disk was much greater than the mass of the block. Does your equation for v_{cm} from part (c)(iii) agree with your reasoning from part (c)(i)?

______ Yes ______ No

Explain your reasoning by addressing why, according to your equation, v_{cm} becomes (or approaches) a certain value when M_D is much greater than M_B.

Solution 3

(a)(i)

Mark scheme

- By the impulse-momentum theorem on the disk (starting from rest): $F_H t_f = M_D v_D - 0$, so $v_D = \dfrac{F_H t_f}{M_D}$.

Solution 3

(a)(ii) Mark scheme

- By conservation of momentum for the student-disk system (zero total momentum before and after, since it starts at rest and the two move in opposite directions): $0 = M_S v_S - M_D v_D$, giving $\dfrac{v_D}{v_S} = \dfrac{M_S}{M_D}$. Points: (1) indicating total momentum of the system is the same before and after (an answer of just M_S/M_D alone also earns this point but not the next), (2) correctly substituting into a conservation-of-momentum equation and expressing the answer in the form $v_D/v_S = \ldots$ (need not be numerically correct to earn this point).

Solution 3

(b) Mark scheme

- Sketch two lines from the origin for $0 < t < t_f$: both straight segments starting at the origin with two different positive slopes (steeper for the disk D, shallower for the student S, since $M_S > M_D$ makes $v_D > v_S$); for $t_f < t < 2t_f$ both become horizontal (constant speed) lines, continuous with their values at t_f (no discontinuity or collision after t_f). Label the higher horizontal line 'D' (value v_D) and the lower 'S' (value v_S), with $v_D > v_S$ clearly indicated. Points: (1) two straight segments for $t < t_f$ beginning at the origin with two different positive slopes, (2) two horizontal, continuous functions for $t > t_f$, (3) $v_D > v_S$ indicated (via vertical-axis labels or the D curve drawn above the S curve for all $t > 0$).

Solution 3

(c)

Mark scheme

- No separate points are allocated to this stem - it sets up the scenario (a disk moving at constant speed v_1 collides head-on with a stationary block of mass M_B and sticks, the disk-block system's center of mass then moving at speed v_{cm}) for parts (c)(i)-(c)(iv), which carry the point allocations below.

Solution 3

(c)(i)

Mark scheme

- When $M_D \gg M_B$, the light block has little effect on the massive disk's motion, so $v_{cm} \approx v_1$ (the pre-collision speed of the disk).

(c)(ii)

Mark scheme

- When $M_D \ll M_B$, the light disk sticking to the much more massive (initially at rest) block barely moves it, so $v_{cm} \approx 0$.

Solution 3

(c)(iii)

Mark scheme

- Using conservation of momentum for the perfectly inelastic collision: $M_D v_1 = (M_D + M_B) v_{cm}$, so $v_{cm} = \dfrac{M_D v_1}{M_D + M_B}$. Points: (1) using conservation of momentum, (2) a correct final expression.

Solution 3

(c)(iv)

Mark scheme

- Yes, the equation agrees with part (c)(i). When $M_D \gg M_B$, M_B is negligible in the denominator, so $M_D + M_B \approx M_D$ and the equation simplifies to $v_{cm} = \dfrac{M_D v_1}{M_D} = v_1$, matching the part (c)(i) reasoning that $v_{cm} \approx v_1$ in that limit. Points: (1) an attempt to use limiting-case reasoning or functional dependence on the part (c)(iii) equation, (2) correctly recognizing the equation reduces to a simpler form that matches the part (c)(i) answer.

Question 1

2019 ▪ Q1

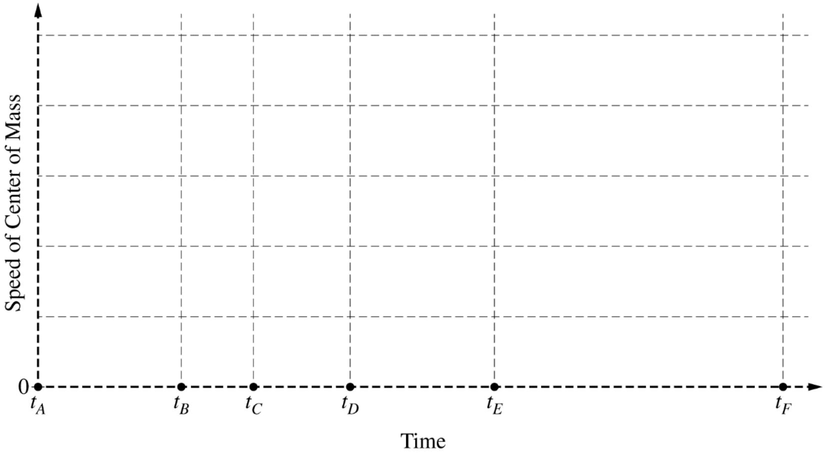
Identical blocks 1 and 2 are placed on a horizontal surface at points A and E, respectively, as shown. The surface is frictionless except for the region between points C and D, where the surface is rough. Beginning at time t_A, block 1 is pushed with a constant horizontal force from point A to point B by a mechanical plunger. Upon reaching point B, block 1 loses contact with the plunger and continues moving to the right along the horizontal surface toward block 2. Block 1 collides with and sticks to block 2 at point E, after which the two-block system continues moving across the surface, eventually passing point F.

[Diagram: A plunger (with block 1 loaded against it) sits at the left, followed by a horizontal line marked with points A, B, C, D, E, F from left to right. Block 2 sits at point E. The region between C and D is hatched, indicating it is rough (roughened surface). The plunger pushes block 1 from A to B.]

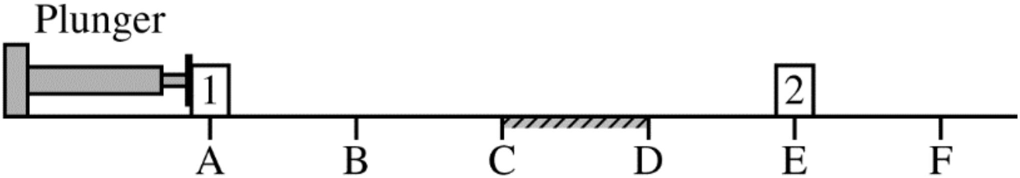
Question 1

(a) On the axes below, sketch the speed of the center of mass of the two-block system as a function of time, from time t_A until the blocks pass point F at time t_F. The times at which block 1 reaches points A through F are indicated on the time axis.
[Graph: y-axis "Speed of Center of Mass" starting at 0, no numeric scale shown; x-axis "Time" with labeled tick marks at t_A, t_B, t_C, t_D, t_E, t_F (unevenly spaced, t_E noticeably farther from t_D than the others); axes are otherwise blank dashed gridlines for the student to sketch on.]

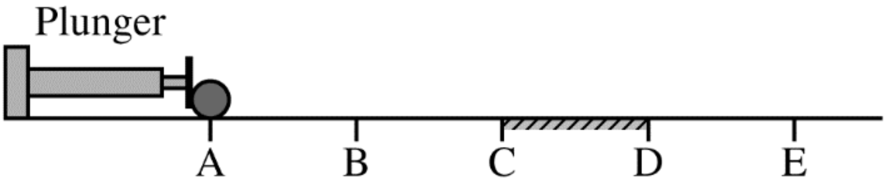
Question 1



Question 1



Question 1



Question 1

2019 ▪ Q1

Identical blocks 1 and 2 are placed on a horizontal surface at points A and E, respectively, as shown. The surface is frictionless except for the region between points C and D, where the surface is rough. Beginning at time t_A, block 1 is pushed with a constant horizontal force from point A to point B by a mechanical plunger. Upon reaching point B, block 1 loses contact with the plunger and continues moving to the right along the horizontal surface toward block 2. Block 1 collides with and sticks to block 2 at point E, after which the two-block system continues moving across the surface, eventually passing point F.

[Diagram: A plunger (with block 1 loaded against it) sits at the left, followed by a horizontal line marked with points A, B, C, D, E, F from left to right. Block 2 sits at point E. The region between C and D is hatched, indicating it is rough (roughened surface). The plunger pushes block 1 from A to B.]

Question 1

(b) The plunger is returned to its original position, and both blocks are removed. A uniform solid sphere is placed at point A, as shown. The sphere is pushed by the plunger from point A to point B with a constant horizontal force that is directed toward the sphere's center of mass. The sphere loses contact with the plunger at point B and continues moving across the horizontal surface toward point E. In which interval(s), if any, does the sphere's angular momentum about its center of mass change? Check all that apply.
[Diagram: A plunger with a sphere loaded against it sits at the left, followed by a horizontal line marked with points A, B, C, D, E from left to right. The region between C and D is hatched, indicating it is rough.]
_____ A to B _____ B to C _____ C to D _____ D to E _____ None
Briefly explain your reasoning.

Solution 1

(a) Mark scheme

- Correct graph of center-of-mass speed vs time has 5 required features (1 pt each): (1) a straight line beginning at 0 at t_A and increasing to t_B (block 1 accelerates under the plunger's constant external force, block 2 stationary, so $v_{cm} = v_1/2$ rises linearly); (2) a horizontal, nonzero segment from t_B to t_C (frictionless surface, block 1 moves at constant velocity, so v_{cm} constant); (3) a segment decreasing linearly from t_C to t_D (friction between C and D is an external force decelerating block 1, so v_{cm} decreases); (4) a horizontal, nonzero, constant segment from t_D through t_F at a DIFFERENT (lower) value than the t_B-t_C plateau, with NO change at t_E; (5) a curve continuous from t_A through t_F, with the only possible exception being a jump at t_E. Note: if the speed changes at t_E, point (4) is not

Solution 1

earned but point (5) may still be earned. No credit for a flat line along the time axis. Physical reasoning: the collision between block 1 and block 2 at E is an INTERNAL interaction of the two-block system, so it does not change the system's center-of-mass velocity (momentum conservation) – the correct graph shows the D-to-F plateau passing smoothly through t_E with no jump, at a lower speed than the B-to-C plateau because the mass tracked (2 blocks) is now effectively combined.

Solution 1

(b) Mark scheme

- Correct answer: the sphere's angular momentum about its center of mass changes ONLY in the interval C to D (not A-B, not B-C, not D-E). Point 1: for reasoning that a change in angular momentum is caused by a net external torque. Point 2: for correctly identifying that friction acting between C and D is the only force producing an external torque over the entire interval A to E. Full reasoning: the plunger's force (A to B) is directed toward the sphere's center of mass, so it produces zero torque about the center of mass; the surface is frictionless everywhere except C to D, so no other external force can exert a torque about the center of mass; therefore only the friction force acting in the rough region C to D changes the sphere's angular momentum about its center of mass (this point is

Solution 1

NOT earned if the response claims angular momentum/angular speed decreases between C and D or that the sphere stops rotating at D – friction here INcreases/changes the spin from zero, since the sphere arrives at C already translating without spin).

Question 2

2016 ▪ Q2

A new kind of toy ball is advertised to “bounce perfectly elastically” off hard surfaces. A student suspects, however, that no collision can be perfectly elastic. The student hypothesizes that the collisions are very close to being perfectly elastic for low-speed collisions but that they deviate more and more from being perfectly elastic as the collision speed increases.

(a) Design an experiment to test the student’s hypothesis about collisions of the ball with a hard surface. The student has equipment that would usually be found in a school physics laboratory.

(a)(i) What quantities would be measured?

(a)(ii) What equipment would be used for the measurements, and how would that equipment be used?

Question 2

(a)(iii) Describe the procedure to be used to test the student's hypothesis. Give enough detail so that another student could replicate the experiment.

Question 2

2016 ▪ Q2

A new kind of toy ball is advertised to "bounce perfectly elastically" off hard surfaces. A student suspects, however, that no collision can be perfectly elastic. The student hypothesizes that the collisions are very close to being perfectly elastic for low-speed collisions but that they deviate more and more from being perfectly elastic as the collision speed increases.

(b) Describe how you would represent the data in a graph or table. Explain how that representation would be used to determine whether the data are consistent with the student's hypothesis.

Question 2

2016 ▪ Q2

A new kind of toy ball is advertised to "bounce perfectly elastically" off hard surfaces. A student suspects, however, that no collision can be perfectly elastic. The student hypothesizes that the collisions are very close to being perfectly elastic for low-speed collisions but that they deviate more and more from being perfectly elastic as the collision speed increases.

(c) A student carries out the experiment and analysis described in parts (a) and (b). The student immediately concludes that something went wrong in the experiment because the graph or table shows behavior that is elastic for low-speed collisions but appears to violate a basic physics principle for high-speed collisions.

(c)(i) Give an example of a graph or table that indicates nearly elastic behavior for low-speed collisions but appears to violate a basic physics principle for high-speed collisions.

Question 2

(c)(ii) State one physics principle that appears to be violated in the graph or table given in part (c)i. Several physics principles might appear to be violated, but you only need to identify one.
Briefly explain what aspect of the graph or table indicates that the physics principle is violated, and why.

Solution 2

(a)

Mark scheme

- Context only, no response scored on this leaf: instructs the student to design an experiment to test the student's hypothesis about collisions of the ball with a hard surface, using equipment usually found in a school physics laboratory. This is the setup for parts (a)(i)–(iii), which the College Board scores jointly as a 4-point unit (see 2ai/2aii/2aiii).

Solution 2

(a)(i)

Mark scheme

- What quantities would be measured: quantities that could be used to compare the ball's mechanical energy before and after a collision with the hard surface. Example 1: the drop height and the bounce height of the ball. Example 2: the ball's speed immediately before and immediately after it bounces. [Note: parts (a)(i)-(iii) are scored as a single 4-point unit in the official guidelines; this leaf carries the point for 'an overall plan in which quantities are measured that could be used to compare mechanical energy before and after a collision with a hard surface.']

Solution 2

(a)(ii)

Mark scheme

- What equipment would be used, and how: Example 1 — a meterstick placed upright against the wall and a video camera to record the ball's motion (drop height and bounce height read off the meterstick from the video). Example 2 — a photogate positioned near the floor, at a height just above the ball's diameter, to measure the ball's speed as it passes through, used just before and just after the bounce. [Note: scored jointly with 2ai/2aiii as a 4-point unit; this leaf carries the point for 'having lab equipment and measurement procedures well specified.']

Solution 2

(a)(iii) Mark scheme

- Procedure, with enough detail for another student to replicate it, including trials across a range of pre-collision speeds from low to high (needed to test the hypothesis). Example 1: drop the ball from 10 different heights, using the video camera to record the bounce height at each. Example 2: drop the ball through the photogate; record the speeds measured before and after the bounce; repeat for at least five different drop heights, covering a range from low to high. Scoring: 1 pt for a conceptually plausible plan to measure pre-/post-collision positions and/or speeds, without extraneous equipment or measurements; 1 pt for a procedure that includes trials of different pre-collision speeds ranging from low to high.

Solution 2

(b) Mark scheme

- Describe how to represent the data and how that representation tests the hypothesis. Example 1: make a graph of the bounce height h_f as a function of the drop height h_i. If the data are consistent with the hypothesis, they will (1) lie close to the line $h_f = h_i$ for low drop heights, and (2) lie below this line for high drop heights. Example 2: make a graph of $v_f^2 - v_i^2$ as a function of v_i, where v_f and v_i are the ball's speed just after and just before the bounce. If the data are consistent with the hypothesis, $v_f^2 - v_i^2$ will (1) be close to zero for low speeds, and (2) be negative for high speeds. Scoring: 1 pt for describing how to plot or otherwise represent the data in a way usable to test the hypothesis; 1 pt for describing how to compare post-collision to pre-collision mechanical energy (or a

Solution 2

plausible alternative) to quantify the elasticity of the collision; 1 pt for comparing the low-speed versus high-speed results; 1 pt for addressing the hypothesis with an analysis such as a slope, ratio, or difference.

Solution 2

(c)

Mark scheme

- Context only, no response scored on this leaf: describes that a student who carried out the experiment and analysis of parts (a)-(b) immediately concludes something went wrong, because the resulting graph or table shows behavior that is nearly elastic for low-speed collisions but appears to violate a basic physics principle for high-speed collisions. This is the setup for parts (c)(i)-(c)(ii).

Solution 2

(c)(i) Mark scheme

- Give an example of a graph or table showing nearly elastic behavior at low collision speed but an apparent violation of a physics principle at high speed. Example (energy-conservation framing): a graph of the ratio $\frac{\text{post-collision mechanical energy}}{\text{pre-collision mechanical energy}}$ as a function of pre-collision speed, where the ratio stays close to 1.0 for low initial speeds but rises above 1.0 for high-speed collisions. Scoring: 1 pt for a graph/table showing the low-speed collisions are nearly perfectly elastic; 1 pt for a graph/table showing a violation of a physics principle for the higher-speed collisions.

Solution 2

(c)(ii) Mark scheme

- State one physics principle that appears violated (several may apply; only one is required), and explain what aspect of the graph/table shows the violation and why. Example, using the energy-ratio graph from (c)(i): the principle is conservation of energy; the graph shows a violation because the energy ratio rises above 1.0 for high-speed collisions, and the final (post-collision) mechanical energy cannot legitimately be greater than the initial (pre-collision) mechanical energy. Scoring: 1 pt for a correct description of the aspect of the graph/table that shows a violation of the stated principle; 1 pt for a correct explanation of why that representation shows a violation of the stated principle.