Past-paper walk-through

Linear Momentum ▪ 4.1

eXercise

Questions in this set

- 2026 Q2
- 2025 Q1
- 2024 Set 2 Q1
- 2022 Set 1 Q2
- 2022 Set 2 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

A projectile of total mass $4M$ is launched from the ground at position $x = 0$ and time $t = 0$. The projectile is launched with an initial speed v_0 at an angle θ above the horizontal. When the projectile is at the highest point in its trajectory, it breaks into Pieces Q and R of masses M and $3M$, respectively.
The motion of the projectile is described for the following times.
- At $t = t_1$, immediately after the projectile breaks apart, the two pieces are moving away from each other horizontally. - At $t = t_2$, Piece Q reaches the ground at $x = 0$ and Piece R reaches the ground at $x = x_2$, as shown in Figure 1.
[Figure 1: Three side-view snapshots labeled $t = 0$, $t = t_1$, $t = t_2$, with a note "Figure not drawn to scale." At $t = 0$: a $+y$ vertical axis and $+x$ horizontal axis are shown at the origin; a small box on the ground at $x = 0$ launches with velocity v_0 at angle θ above the horizontal, following a dashed parabolic path upward. At $t = t_1$: at the top

Question 2

of the dashed parabolic trajectory, two pieces are shown separating horizontally — "Piece Q, M" moving to the left and "Piece R, $3M$" moving to the right, connected by a wavy break symbol; the ground below is marked $x = 0$. At $t = t_2$: on the ground, a small box (Piece Q) sits at $x = 0$ and a larger box (Piece R) sits at $x = x_2$ to the right.]

(a) The horizontal and vertical components of a momentum vector are represented by p_x and p_y, respectively. The shaded bars in Figure 2 represent p_x and p_y of the projectile immediately after $t = 0$.

[Figure 2: "Figure 2, $t = 0$." A bar chart titled "Momentum" with vertical axis showing a dashed zero line labeled 0 and horizontal categories p_x and p_y, captioned "Complete Projectile." A shaded bar for p_x rises to a medium-large positive height above the zero line; a shaded bar for p_y rises to a smaller positive height above the zero line (shorter than the p_x bar).]

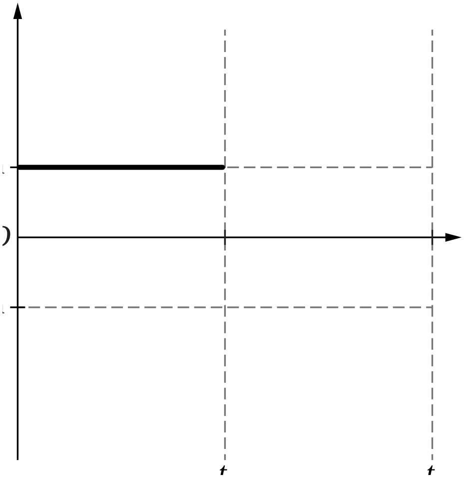
Question 2

[Figure 3: "Figure 3, $t = t_1$." Two blank bar charts titled "Momentum," each with a dashed zero line labeled 0 and horizontal categories p_x and p_y; the left one captioned "Piece Q" and the right one captioned "Piece R." Both are currently empty (no shaded bars drawn).]

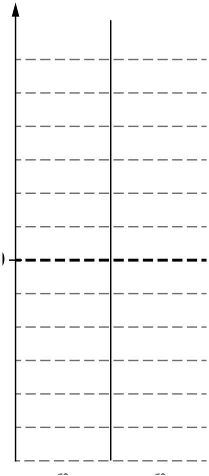
On Figure 3, **draw** shaded bars to represent p_x and p_y of Pieces Q and R at $t = t_1$.

- Start the shaded bars at the dashed line that represents zero momentum.
- Represent the magnitudes of the components of the momentum by using the heights of the shaded bars, consistent with the scale used in Figure 2.
- Represent any momentum component that is equal to zero by drawing a distinct line on the zero-momentum line.

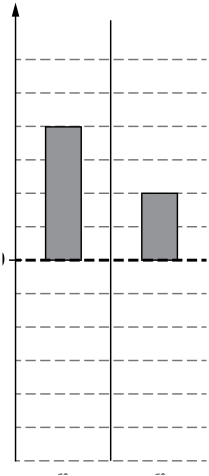
Question 2



Question 2



Question 2



Question 2

2026 ▪ Q2

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The motion of the projectile is described for the following times.

- At $t = t_1$, immediately after the projectile breaks apart, the two pieces are moving away from each other horizontally. - At $t = t_2$, Piece Q reaches the ground at $x = 0$ and Piece R reaches the ground at $x = x_2$, as shown in Figure 1.

[Figure 1: Three side-view snapshots labeled $t = 0$, $t = t_1$, $t = t_2$, with a note "Figure not drawn to scale." At $t = 0$: a $+y$ vertical axis and $+x$ horizontal axis are shown at the origin; a small box on the ground at $x = 0$ launches with velocity v_0 at angle θ above the horizontal, following a dashed parabolic path upward. At $t = t_1$: at the top of the dashed parabolic trajectory, two pieces are shown separating horizontally — "Piece Q, M" moving to the left and

Question 2

"Piece R, $3M$" moving to the right, connected by a wavy break symbol; the ground below is marked $x = 0$. At $t = t_2$: on the ground, a small box (Piece Q) sits at $x = 0$ and a larger box (Piece R) sits at $x = x_2$ to the right.]

(b) **Derive** an expression for x_2 in terms of v_0, θ, and physical constants, as appropriate. Begin your derivation by writing a fundamental physics principle or an equation from the reference information.

Question 2

2026 ▪ Q2

A projectile of total mass $4M$ is launched from the ground at position $x = 0$ and time $t = 0$. The projectile is launched with an initial speed v_0 at an angle θ above the horizontal. When the projectile is at the highest point in its trajectory, it breaks into Pieces Q and R of masses M and $3M$, respectively.

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(c) The horizontal component of a velocity vector is represented by v_x. Figure 4 shows the horizontal component $v_{x,\text{cm}}$ of the velocity of the center of mass of the projectile as a function of t during the time interval $0 < t < t_1$.

[Figure 4: A graph with vertical axis v_x and horizontal axis t (origin O). A horizontal dashed reference line is labeled $v_{x,\text{cm}}$ above the t-axis, and another horizontal dashed reference line is labeled $-v_{x,\text{cm}}$ below the t-axis (symmetric about the axis). A solid horizontal line segment at height $v_{x,\text{cm}}$ runs from $t = 0$ to $t = t_1$, representing v_x during $0 < t < t_1$. Vertical dashed lines mark $t = t_1$ and $t = t_2$ on the horizontal axis.]

On Figure 4, **sketch** a line or curve to represent v_x as a function of t for the time interval $t_1 < t < t_2$ for each of the following.

Question 2

- Piece Q - Piece R - The center of mass of the two-piece system
Clearly **label** all lines or curves.

Question 2

2026 ▪ Q2

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Question 2

"Piece R, $3M$" moving to the right, connected by a wavy break symbol; the ground below is marked $x = 0$. At $t = t_2$: on the ground, a small box (Piece Q) sits at $x = 0$ and a larger box (Piece R) sits at $x = x_2$ to the right.]

(d) Consider a case in which the projectile is launched at the same angle and initial speed as initially described. When the projectile breaks into Pieces Q and R, Piece Q falls straight down. In this case, Piece R reaches the ground at $x = x_{\text{new}}$.
Indicate whether x_{new} is greater than, less than, or equal to x_2 by writing one of the following.
- $x_{\text{new}} > x_2$ - $x_{\text{new}} < x_2$ - $x_{\text{new}} = x_2$
Briefly **justify** your answer either by referencing a feature of the representations you drew in part A or C or by using conceptual reasoning beyond algebraic solutions.

Question 1

2025 ▪ Q1

Two blocks, 1 and 2, slide toward each other on a horizontal surface. Block 1 has mass m and slides in the $+x$-direction with constant speed $2v_0$. Block 2 has mass $6m$ and slides in the $-x$-direction with constant speed v_0, as shown in Figure 1. The blocks then collide and stick together. The collision occurs from time $t = 0$ to $t = t_c$. After the collision, where $t > t_c$, the blocks move together with the same constant speed.
[Figure 1: Horizontal surface with a $+x$ arrow pointing right. Block 1 (mass m) on the left, moving in the $+x$-direction with speed $2v_0$ (arrow pointing right labeled $2v_0$). Block 2 (mass $6m$) on the right, moving in the $-x$-direction with speed v_0 (arrow pointing left labeled v_0).]
(a)(i) The diagrams in Figure 2 can be used to represent the momentum of blocks 1 and 2 before and after the collision. The momentum vector diagram for Block 1 before the collision is shown.

Question 1

[Figure 2: A table titled “Momentum Before Collision” / “Momentum After Collision” with rows for Block 1, Block 2, and Two-Block System. Each cell shows a horizontal zero-momentum grid line labeled “0”. The “Block 1, Before Collision” cell already shows an arrow starting at 0 and pointing right (+x-direction), representing the momentum of Block 1 before the collision. All other cells (Block 2 before collision; Block 1 after collision [shaded, not applicable]; Block 2 after collision [shaded, not applicable]; Two-Block System before collision; Two-Block System after collision) are blank grids to be filled in.]

Draw arrows on the grids to represent the momentum vectors of Block 2 before the collision and the two-block system before and after the collision.

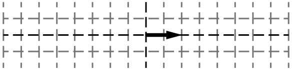
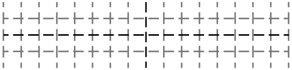
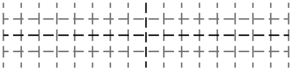
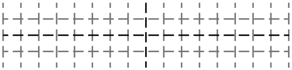
- Arrows should start at the zero-momentum line.
- The length of the arrows should be proportional to the relative magnitudes of the vectors.

Question 1

- Represent an arrow of zero length by drawing a dot at zero.

(a)(ii) During the time interval $0 \leq t \leq t_c$, a force F is exerted on Block 2 by Block 1 along the x-direction as a function of t that is modeled by $F(t) = F_{\max} \sin(At)$, where A is a positive constant and $F_{\max}$ is the magnitude of the maximum force exerted on Block 2 by Block 1 during the collision.
Derive an expression for $F_{\max}$. Express your answer in terms of m, v_0, A, t_c, and physical constants, as appropriate. Begin your derivation by writing a fundamental physics principle or an equation from the reference information.

Question 1

	Momentum Before Collision	Momentum After Collision
Block 1	 0	
Block 2	 0	
Two-Block System	 0	 0

Question 1

Question 1

2025 ▪ Q1

Two blocks, 1 and 2, slide toward each other on a horizontal surface. Block 1 has mass m and slides in the $+x$-direction with constant speed $2v_0$. Block 2 has mass $6m$ and slides in the $-x$-direction with constant speed v_0, as shown in Figure 1. The blocks then collide and stick together. The collision occurs from time $t = 0$ to $t = t_c$. After the collision, where $t > t_c$, the blocks move together with the same constant speed.

[Figure 1: Horizontal surface with a $+x$ arrow pointing right. Block 1 (mass m) on the left, moving in the $+x$-direction with speed $2v_0$ (arrow pointing right labeled $2v_0$). Block 2 (mass $6m$) on the right, moving in the $-x$-direction with speed v_0 (arrow pointing left labeled v_0).]

(b) Consider a new scenario where Block 1 initially slides in the $+x$-direction with a new constant speed v_1 and Block 2 again initially slides in the $-x$-direction with constant speed v_0. The blocks collide and stick together. In this new scenario, the two-block system has constant speed v_0 after the collision.

Question 1

Derive an expression for v_1 in terms of v_0. Begin your derivation by writing a fundamental physics principle or an equation from the reference information.

Solution 1

(a)(i) Mark scheme

- Momentum vector diagram (Figure 2). Using the scale already set by the given Block 1 arrow (2 units right, i.e. magnitude $2v_0$ for mass m, since Block 1's momentum is $m(2v_0)$): draw ONE arrow for Block 2's momentum before the collision pointing in the $-x$ direction (leftward) and 6 units long (magnitude $6mv_0$, consistent with Block 2's mass $6m$ and speed v_0) [Point A1]. Draw identical arrows – same length and direction – for the momentum of the two-block system both BEFORE and AFTER the collision, since total momentum is conserved; the length equals the vector sum of the Block 1 and Block 2 arrows: 2 units right + 6 units left = 4 units left, i.e. pointing in the $-x$ direction with magnitude $4mv_0$ (matches $m(2v_0) + 6m(-v_0) = -4mv_0 = 7m(-\frac{4}{7}v_0)$) [Point

Solution 1

A2]. Award A1 for the correctly-directed 6-unit Block 2 arrow; award A2 for two IDENTICAL two-block-system arrows (before and after) of the correct length/direction, independent of A1.

Solution 1

(a)(ii) Mark scheme

- Derive $F_{\max}$. Begin with the impulse-momentum theorem or Newton's second law: $\vec{J} = \int_{t_1}^{t_2} \vec{F}_{net}(t)\, dt = \Delta\vec{p}$, or equivalently $\vec{F}_{net} = \dfrac{d\vec{p}}{dt}$ [Point A3: multistep derivation using the integral form of impulse or the differential form of N2L]. Apply conservation of momentum to the original collision: $\sum \vec{p}_0 = \sum \vec{p}_f \Rightarrow (m)(2v_0) + (6m)(-v_0) = (m + 6m)(v_f) \Rightarrow v_f = -\frac{4}{7}v_0$ [Point A4: award for stating any ONE equivalent fact – final speed of Block 1 or 2 is $\frac{4}{7}v_0$, $\Delta p_{Block2} = +\frac{18}{7}mv_0$, $\Delta p_{Block1} = -\frac{18}{7}mv_0$, $\Delta v_{Block2} = +\frac{3}{7}v_0$, or $\Delta v_{Block1} = -\frac{18}{7}v_0$]. Then $\Delta p_{Block2} = -\Delta p_{Block1} = 6m\left(-\frac{4}{7}v_0 - (-v_0)\right) = \frac{18}{7}mv_0$. Substitute the given force into the impulse integral:

Solution 1

$\Delta p_{Block2} = \int_0^{t_c} F_{\max} \sin(At)\, dt$ [Point A5: substituting F(t) into the impulse/N2L expression]. Evaluate: $\frac{18}{7} m v_0 = \dfrac{F_{\max}}{A}\left[-\cos(At)\right]_0^{t_c} = \dfrac{F_{\max}}{A}\left[1 - \cos(At_c)\right]$ [Point A6: definite integral with correct limits, or an equivalent indefinite integral plus a constant of integration]. Solve: $F_{\max} = \dfrac{18}{7}\left(\dfrac{Amv_0}{1 - \cos(At_c)}\right)$ [Point A7: final correct expression in terms of m, v_0, A, t_c].

Solution 1

(b) Mark scheme

- New scenario: Block 1 (mass m) slides at speed v_1 in the $+x$ direction, Block 2 (mass $6m$) slides at speed v_0 in the $-x$ direction; they collide and stick, and the combined system moves afterward at constant speed v_0. Using conservation of momentum (a multistep derivation) [Point B1]: $\sum \vec{p}_0 = \sum \vec{p}_f$. The final momentum magnitude of the combined $7m$ system is $7mv_0$ [Point B2]. $mv_1 + 6m(-v_0) = 7m(v_0) \Rightarrow mv_1 = 13mv_0 \Rightarrow v_1 = 13v_0$ [Point B3: correct final expression for v_1 in terms of v_0].

Question 1

2024 Set 2 ▪ Q1

Blocks A and B of masses $2m$ and m, respectively, are arranged in a setup consisting of a ramp that makes an angle θ with a smooth horizontal table and an ideal spring of spring constant k fixed to a wall, as shown. Block A is held at rest a distance D up the ramp, and Block B is at rest on the horizontal table. The coefficient of kinetic friction between Block A and the rough ramp is μ in the region of length D, and there is negligible friction between the blocks and the smooth table.

[Figure: A ramp inclined at angle θ to a horizontal table. Block A (mass $2m$) sits on the ramp at a distance D up the incline, with the region of length D on the ramp labeled with friction coefficient μ. The ramp meets the table at the origin 0. On the horizontal table, Block B (mass m) rests at position x_1. Further right along the table, a spring of constant k is fixed to a wall, with its uncompressed (equilibrium) position at x_3; a distance x_c is marked from x_3 back toward the wall/spring, near the wall. The

Question 1

horizontal axis is labeled with positions 0, x_1, x_3 increasing to the right toward the wall.]
Note: Figure not drawn to scale.
Continue your response to QUESTION 1 on this page.
At time $t = 0$, Block A is located at horizontal position $x = 0$ and is released from rest. After the block is released, the following occurs.
- At time $t = t_1$, Block A has traveled a distance D down the ramp, has transitioned to the table, and is moving with speed v at $x = x_1$. - At time $t = t_2$, Block A is at $x = x_2$ when it collides with and sticks to Block B. - At time $t = t_3$, the combined blocks A and B are at $x = x_3$ when they collide with and stick to the spring in its equilibrium position. - At time $t = t_4$, the combined blocks A and B are instantaneously at rest and the spring is compressed a distance x_c from its equilibrium position.

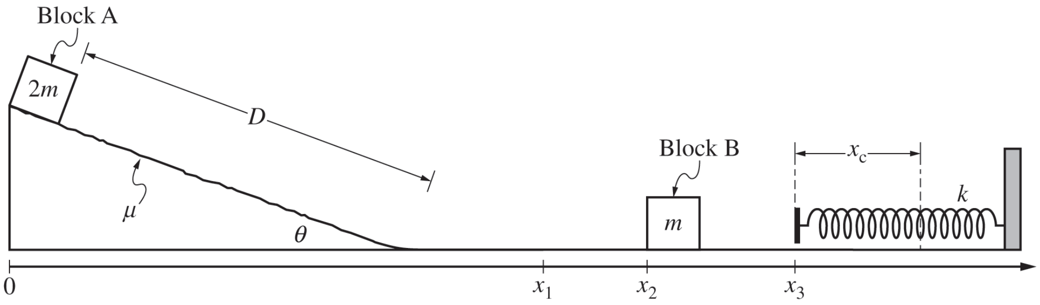
Question 1

For parts (a)(i) and (a)(ii), express your answer in terms of m, θ, D, μ, x_c, and physical constants, as appropriate.

(a)(i) Derive an expression for the speed v of Block A at time t_1.

(a)(ii) Derive an expression for the spring constant k of the spring.

Question 1



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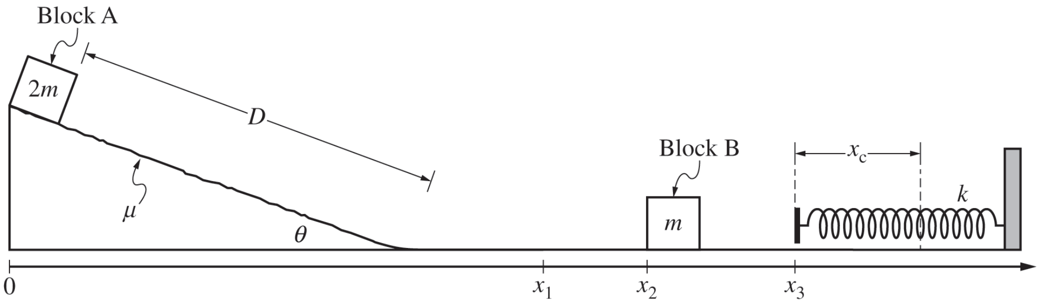
Question 1



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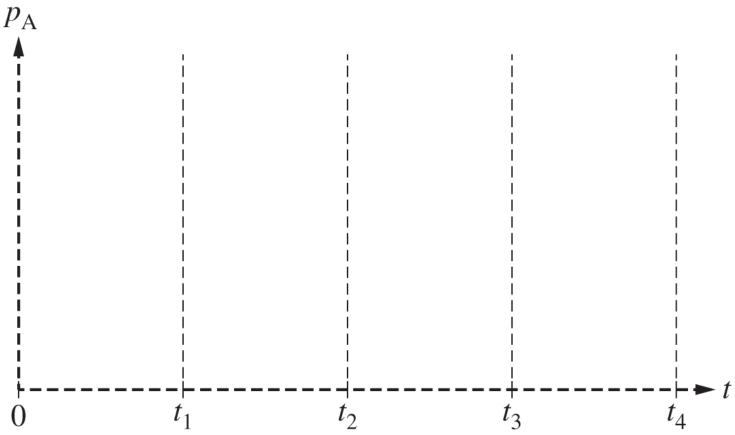
Question 1



Question 1

2024 Set 2 ▪ Q1

Blocks A and B of masses $2m$ and m, respectively, are arranged in a setup consisting of a ramp that makes an angle θ with a smooth horizontal table and an ideal spring of spring constant k fixed to a wall, as shown. Block A is held at rest a distance D up the ramp, and Block B is at rest on the horizontal table. The coefficient of kinetic friction between Block A and the rough ramp is μ in the region of length D, and there is negligible friction between the blocks and the smooth table.

[Figure: A ramp inclined at angle θ to a horizontal table. Block A (mass $2m$) sits on the ramp at a distance D up the incline, with the region of length D on the ramp labeled with friction coefficient μ. The ramp meets the table at the origin 0. On the horizontal table, Block B (mass m) rests at position x_1. Further right along the table, a spring of constant k is fixed to a wall, with its uncompressed (equilibrium) position at x_3; a distance x_c is marked from x_3 back toward the wall/spring, near the wall. The horizontal axis is labeled with positions 0, x_1, x_3 increasing to the right toward the wall.]

Question 1

Note: Figure not drawn to scale.

Continue your response to QUESTION 1 on this page.

At time $t = 0$, Block A is located at horizontal position $x = 0$ and is released from rest. After the block is released, the following occurs.

- At time $t = t_1$, Block A has traveled a distance D down the ramp, has transitioned to the table, and is moving with speed v at $x = x_1$. - At time $t = t_2$, Block A is at $x = x_2$ when it collides with and sticks to Block B. - At time $t = t_3$, the combined blocks A and B are at $x = x_3$ when they collide with and stick to the spring in its equilibrium position. - At time $t = t_4$, the combined blocks A and B are instantaneously at rest and the spring is compressed a distance x_c from its equilibrium position.

For parts (a)(i) and (a)(ii), express your answer in terms of m, θ, D, μ, x_c, and physical constants, as appropriate.

(b)(i) [Figure repeated: the same ramp-table-spring setup with Block A (mass $2m$) on the ramp, Block B (mass m) on the table, and the spring of constant k near the wall;

Question 1

axis positions 0, x_1, x_2, x_3 marked left to right, with x_c marked near the spring. Note: Figure not drawn to scale.]

On the following axes, sketch a graph of the magnitude of the momentum p_A of Block A as a function of time t from $t = 0$ to t_4.

[Graph: vertical axis labeled p_A (unlabeled scale), horizontal axis labeled t with tick marks at 0, t_1, t_2, t_3, t_4 (unlabeled scale/blank grid for the student to draw on).]

(b)(ii) Use principles of forces to justify the graph drawn in part (b)(i) for the time interval $t = t_3$ to $t = t_4$. Explicitly reference features of the shape of the graph you drew in part (b)(i).

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2024 Set 2 ▪ Q1

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Question 1

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For parts (a)(i) and (a)(ii), express your answer in terms of m, θ, D, μ, x_c, and physical constants, as appropriate.

Question 1

(c) For times $t > t_4$, the two-block-spring system oscillates with period T_O. The procedure is then repeated using a new ramp, where there is negligible friction between Block A and the ramp.

Indicate how the new period of oscillation T_N in the procedure that uses the new ramp compares with the period of oscillation T_O from the original procedure.

_____ $T_N > T_O$ _____ $T_N < T_O$ _____ $T_N = T_O$

Briefly justify your answer.

Solution 1

(a)(i) Mark scheme

- Using energy conservation for Block A sliding down the ramp (mass $2m$, ramp length D, angle θ, coefficient of friction μ): $U_g - \Delta E_{friction} = K$, i.e. $m_A g D \sin\theta - \mu m_A g D \cos\theta = \frac{1}{2} m_A v^2$, giving $v = \sqrt{2gD(\sin\theta - \mu\cos\theta)}$. (Equivalently via kinematics: Newton's second law gives $a = g\sin\theta - \mu g\cos\theta$, then $v^2 = v_0^2 + 2a\Delta x = 2(g\sin\theta - \mu g\cos\theta)D$.) Points: 1 for a correct multi-step derivation start (energy-conservation statement with U_g, or Newton's second law including the signed friction force), 1 for a consistent next step (friction-energy expression with correct sign, or substituting acceleration into a kinematics equation), 1 for the final correct expression $v = \sqrt{2gD(\sin\theta - \mu\cos\theta)}$.

Solution 1

(a)(ii) Mark scheme

- Momentum conservation for the collision between Block A (mass $2m$, speed v from part (a)(i)) and Block B (mass m, at rest): $2mv = (2m + m)v_{A,B}$, so $v_{A,B} = \frac{2}{3}v = \frac{2}{3}\sqrt{2gD(\sin\theta - \mu\cos\theta)}$. Then energy conservation from just after the collision to maximum spring compression: $K_{after\ collision} = U_{s,max}$, i.e. $\frac{1}{2}(3m)v_{A,B}^2 = \frac{1}{2}kx_c^2$ (using that the combined blocks' speed just before contacting the spring equals $v_{A,B}$). Solving: $k = \dfrac{3m}{x_c^2}v_{A,B}^2 = \dfrac{8}{3}\dfrac{mgD(\sin\theta - \mu\cos\theta)}{x_c^2}$. Points: 1 for using momentum conservation to find $v_{A,B}$, 1 for equating post-collision kinetic energy to the maximum elastic potential energy of the spring

Solution 1

$(K_{after\ collision} = U_{s,max})$, 1 for indicating the speed just before the spring contact equals $v_{A,B}$.

Solution 1

(b)(i) Mark scheme

- Sketch of p_A (magnitude of Block A's momentum) vs. t from $t = 0$ to t_4, with four required features: (1) a straight line increasing from 0 at $t = 0$ to a value $p_1 = m_A v$ at $t = t_1$ (Block A accelerates down the ramp under the net gravity-minus-friction force); (2) a horizontal line from t_1 to t_2 at the same level p_1, continuous at t_1 (Block A crosses the frictionless table at constant velocity before the collision); (3) a horizontal line from t_2 to t_3 at a smaller constant level $p_2 = m_A v_{A,B} < p_1$ (the perfectly inelastic collision with Block B at t_2 reduces Block A's speed to $v_{A,B} = \frac{2}{3}v$, then A+B move together at constant velocity toward the spring); (4) a concave-down curve from t_3 to t_4, continuous with level p_2 at t_3, decreasing to 0 at t_4 (the spring's restoring force grows as compression

Solution 1

increases, decelerating the blocks at an increasing rate until they momentarily stop at maximum compression).

Solution 1

(b)(ii) Mark scheme

- For $t_3 \leq t \leq t_4$: the momentum of Block A decreases because the spring exerts a force on the blocks directed opposite to their velocity, decelerating them toward rest. As the spring compresses further, the spring force increases in magnitude, so the rate of decrease of momentum (the magnitude of the slope of the p_A-vs-t graph) increases with time – this is why the curve is concave down, becoming steeper as $t \to t_4$, consistent with the sketch in part (b)(i). Points: 1 for a statement about the change in momentum consistent with the (b)(i) graph, 1 for identifying that a decreasing graph means the net force on Block A is opposite its motion, 1 for explicitly relating the changing steepness of the curve to the increasing magnitude of the spring force.

Solution 1

(c)

Mark scheme

- $T_N = T_O$ (the period is unchanged). Justification: the period of a spring-block oscillator depends only on the oscillating mass and the spring constant ($T = 2\pi\sqrt{m/k}$), not on friction, amplitude, velocity, or compression distance. Removing friction on the new ramp changes only the compression distance/amplitude of the oscillation, not m or k, so the period stays the same.

Question 2

2022 Set 1 ▪ Q2

[Diagram, Figure setup: Cart 1 of mass m_1 sits at the top of an incline (marked "Cart 1"), held at rest at a height H above the bottom of the incline. The incline descends and transitions smoothly into a horizontal section. Cart 2, of mass m_2, sits at rest on the horizontal section further along, marked "Cart 2". A Motion Detector is mounted vertically at the far right end of the horizontal track, facing left toward the carts. A second diagram below shows the two-cart system, now combined, moving to the right with velocity v (arrow labeled "v" pointing right) toward the Motion Detector.]
Cart 1 of mass m_1 is held at rest above the bottom of the incline. Cart 2 has mass m_2, where $m_2 > m_1$, and is at rest at the bottom of the incline. At time $t = 0$, Cart 1 is released and then travels down the incline and transitions to the horizontal section. The center of mass of Cart 1 moves a vertical distance H, as shown. At time t_C, Cart 1 reaches the bottom of the incline and immediately collides with and sticks to Cart 2.

Question 2

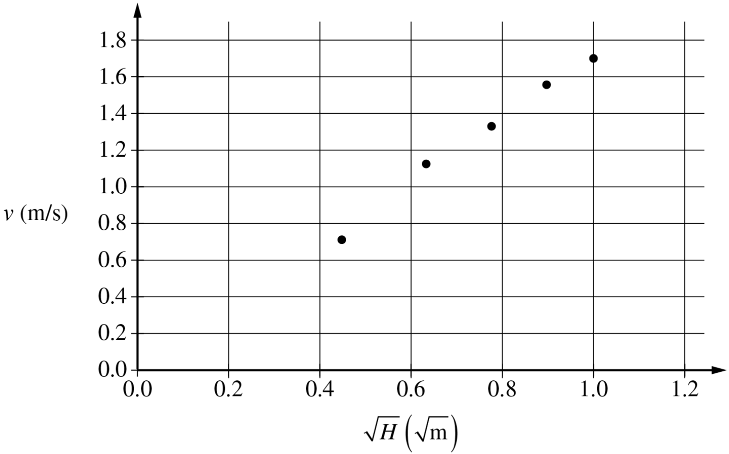
After the collision, the two-cart system moves with constant speed v. Frictional and rotational effects are negligible.

(a) During the collision, is the impulse on Cart 1 from Cart 2 greater than, less than, or equal to the magnitude of the impulse on Cart 2 from Cart 1 ?

______ Greater than ______ Less than ______ Equal to

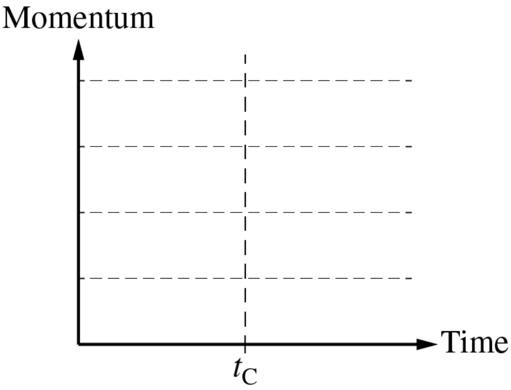
Justify your answer.

Question 2

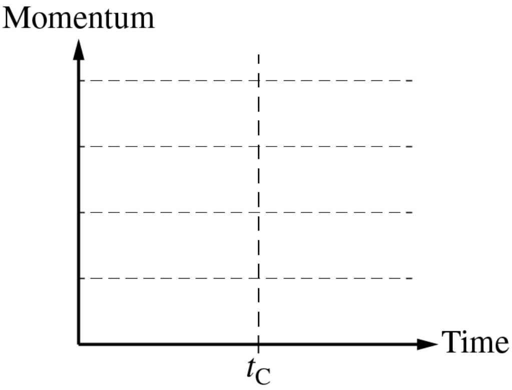


1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
v (m/s)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
$\sqrt{H}\left(\sqrt{\mathrm{m}}\right)$

Question 2

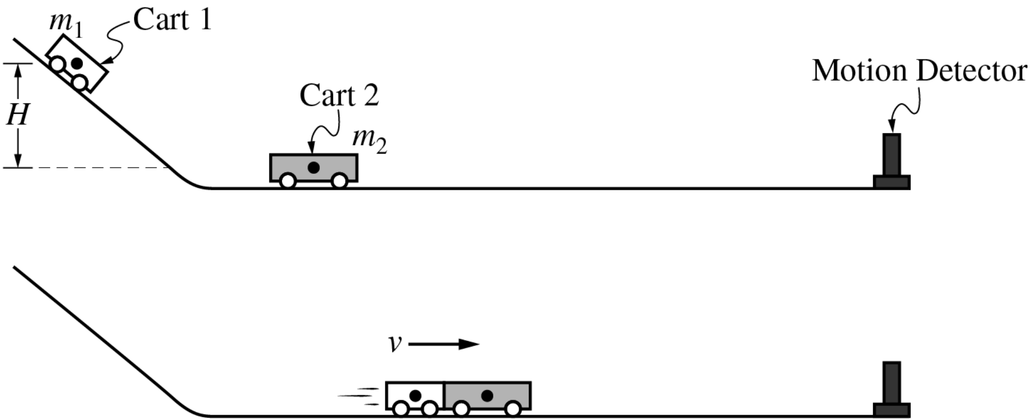


Cart 1



Cart 2

Question 2



Question 2

2022 Set 1 ▪ Q2

[Diagram, Figure setup: Cart 1 of mass m_1 sits at the top of an incline (marked "Cart 1"), held at rest at a height H above the bottom of the incline. The incline descends and transitions smoothly into a horizontal section. Cart 2, of mass m_2, sits at rest on the horizontal section further along, marked "Cart 2". A Motion Detector is mounted vertically at the far right end of the horizontal track, facing left toward the carts. A second diagram below shows the two-cart system, now combined, moving to the right with velocity v (arrow labeled "v" pointing right) toward the Motion Detector.]

Cart 1 of mass m_1 is held at rest above the bottom of the incline. Cart 2 has mass m_2, where $m_2 > m_1$, and is at rest at the bottom of the incline. At time $t = 0$, Cart 1 is released and then travels down the incline and transitions to the horizontal section. The center of mass of Cart 1 moves a vertical distance H, as shown. At time t_C, Cart 1 reaches the bottom of the

Question 2

incline and immediately collides with and sticks to Cart 2. After the collision, the two-cart system moves with constant speed v. Frictional and rotational effects are negligible.

(b) On the following axes, draw graphs of the magnitude of the momentum of each cart as a function of time t, before and after t_C. The collision occurs in a negligible amount of time. The grid lines on each graph are drawn to the same scale.

[Graph 1, titled "Cart 1": axes labeled "Momentum" (vertical) vs. "Time" (horizontal); a dashed vertical gridline is marked at t_C on the time axis; horizontal dashed gridlines are evenly spaced on the momentum axis; no data plotted, blank axes for the student to draw on.]

[Graph 2, titled "Cart 2": axes labeled "Momentum" (vertical) vs. "Time" (horizontal); a dashed vertical gridline is marked at t_C on the time axis; horizontal dashed gridlines are evenly spaced on the momentum axis; no data plotted, blank axes for the student to draw on.]

Question 2

2022 Set 1 ▪ Q2

[Diagram, Figure setup: Cart 1 of mass m_1 sits at the top of an incline (marked "Cart 1"), held at rest at a height H above the bottom of the incline. The incline descends and transitions smoothly into a horizontal section. Cart 2, of mass m_2, sits at rest on the horizontal section further along, marked "Cart 2". A Motion Detector is mounted vertically at the far right end of the horizontal track, facing left toward the carts. A second diagram below shows the two-cart system, now combined, moving to the right with velocity v (arrow labeled "v" pointing right) toward the Motion Detector.]

Cart 1 of mass m_1 is held at rest above the bottom of the incline. Cart 2 has mass m_2, where $m_2 > m_1$, and is at rest at the bottom of the incline. At time $t = 0$, Cart 1 is released and then travels down the incline and transitions to the horizontal section. The center of mass of Cart 1 moves a vertical distance H, as shown. At time t_C, Cart 1 reaches the bottom of the

Question 2

incline and immediately collides with and sticks to Cart 2. After the collision, the two-cart system moves with constant speed v. Frictional and rotational effects are negligible.

(c) Show that the velocity v of the two-cart system after the collision is given by the equation

$$v = \sqrt{2g}\left(\frac{m_1}{m_1 + m_2}\right)\sqrt{H}.$$

Question 2

2022 Set 1 ▪ Q2

[Diagram, Figure setup: Cart 1 of mass m_1 sits at the top of an incline (marked "Cart 1"), held at rest at a height H above the bottom of the incline. The incline descends and transitions smoothly into a horizontal section. Cart 2, of mass m_2, sits at rest on the horizontal section further along, marked "Cart 2". A Motion Detector is mounted vertically at the far right end of the horizontal track, facing left toward the carts. A second diagram below shows the two-cart system, now combined, moving to the right with velocity v (arrow labeled "v" pointing right) toward the Motion Detector.]

Cart 1 of mass m_1 is held at rest above the bottom of the incline. Cart 2 has mass m_2, where $m_2 > m_1$, and is at rest at the bottom of the incline. At time $t = 0$, Cart 1 is released and then travels down the incline and transitions to the horizontal section. The center of mass of Cart 1 moves a vertical distance H, as shown. At time t_C, Cart 1 reaches the bottom of the

Question 2

incline and immediately collides with and sticks to Cart 2. After the collision, the two-cart system moves with constant speed v. Frictional and rotational effects are negligible.

(d)(i) A group of students use the setup to perform an experiment. They measure the mass of Cart 1 to be $m_1 = 0.250$ kg. The mass of Cart 2 is unknown. The students perform several trials and in each trial, Cart 1 is released from a different height H and the final velocity of the two-cart system is measured. The students graph v as a function of $\sqrt{H}$, as shown below.

[Graph: scatter plot; vertical axis "v (m/s)" ranges from 0.0 to 1.8 in increments of 0.2; horizontal axis "$\sqrt{H}$ ($\sqrt{\text{m}}$)" ranges from 0.0 to 1.2 in increments of 0.2; plotted points approximately at $(0.45, 0.75)$, $(0.65, 1.05)$, $(0.65, 1.25)$, $(0.85, 1.35)$, $(1.0, 1.55)$, $(1.0, 1.65)$, showing a roughly linear increasing trend; no line drawn yet.]

Draw a line that represents the best fit to the data points shown.

(d)(ii) Use the best-fit line to calculate the mass of Cart 2.

Question 2

2022 Set 1 ▪ Q2

[Diagram, Figure setup: Cart 1 of mass m_1 sits at the top of an incline (marked "Cart 1"), held at rest at a height H above the bottom of the incline. The incline descends and transitions smoothly into a horizontal section. Cart 2, of mass m_2, sits at rest on the horizontal section further along, marked "Cart 2". A Motion Detector is mounted vertically at the far right end of the horizontal track, facing left toward the carts. A second diagram below shows the two-cart system, now combined, moving to the right with velocity v (arrow labeled "v" pointing right) toward the Motion Detector.]

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Question 2

incline and immediately collides with and sticks to Cart 2. After the collision, the two-cart system moves with constant speed v. Frictional and rotational effects are negligible.

(e) After the experiment, the students use a balance to measure the mass of Cart 2 and find it to be less than what was determined in part (d). To explain this discrepancy, one of the students proposes that the mass of Cart 1 was incorrectly measured at the beginning of the experiment. The students measure the mass of Cart 1 again and record a new value, m_1'.

Should the students expect that m_1' will be greater than 0.250 kg, less than 0.250 kg, or equal to 0.250 kg?

$\mathrm{m}_1' > 0.250$ kg $\mathrm{m}_1' < 0.250$ kg $\mathrm{m}_1' = 0.250$ kg

Justify your answer.

Solution 2

(a)

Mark scheme

- Answer: Equal to (1 point for selecting this with an attempted justification). Justification: By Newton's third law, the force Cart 2 exerts on Cart 1 and the force Cart 1 exerts on Cart 2 are equal in magnitude (and opposite in direction) at every instant during the collision; since both carts experience the collision over the same time interval, the impulses ($\int F\,dt$) on each cart must be equal in magnitude (1 point).

Solution 2

(b) Mark scheme

- Momentum (p) vs. time (t) graphs, before/after t_C (collision assumed instantaneous). Cart 1: for $0 < t < t_C$, a straight line increasing linearly from zero (Cart 1 accelerates down the incline); at t_C its momentum drops abruptly to a smaller constant (horizontal) value for $t > t_C$ (1 point for the $0 < t < t_C$ portion: linear increasing for Cart 1 and zero for Cart 2; 1 point for Cart 1's post-collision horizontal line being smaller in magnitude than its momentum at $t = t_C$). Cart 2: zero (flat on the axis) for $0 < t < t_C$, then jumps at t_C to a constant (horizontal) value for $t > t_C$ that is GREATER in magnitude than Cart 1's post-collision momentum (1 point). The magnitude of Cart 1's momentum loss at the collision

Solution 2

must equal the magnitude of Cart 2's momentum gain (equal and opposite changes), consistent with the equal-impulse answer in part (a) (1 point).

Solution 2

(c) Mark scheme

- Derivation of $v = \sqrt{2g}\left(\frac{m_1}{m_1 + m_2}\right)\sqrt{H}$. Conservation of energy (or equivalently kinematics) gives Cart 1's speed at the bottom of the incline: $m_1 gH = \frac{1}{2}m_1 v_1^2 \Rightarrow v_1 = \sqrt{2gH}$ (1 point). Conservation of momentum for the perfectly inelastic collision: $m_1 v_1 = (m_1 + m_2)v \Rightarrow v = \frac{m_1}{m_1 + m_2} v_1$ (1 point). Combining: $v = \frac{m_1}{m_1 + m_2}\sqrt{2gH} = \sqrt{2g}\left(\frac{m_1}{m_1 + m_2}\right)\sqrt{H}$, as required (1 point).

Solution 2

(d)(i)

Mark scheme

- Draw a straight best-fit line through the v vs. $\sqrt{H}$ scatter plot with approximately equal numbers of data points above and below the line (through or near the origin).

Solution 2

(d)(ii) Mark scheme

- Use the best-fit line to find m_2. Calculate the slope using two well-separated points on the best-fit line, e.g. slope $= \dfrac{(1.20 - 0.60)\ \text{m/s}}{(0.70 - 0.35)\sqrt{\text{m}}} = 1.72\ \sqrt{\text{m}}/\text{s}$ (1 point). Relate the slope to the masses via the part (c) result, $\mathit{slope} = \dfrac{m_1}{m_1 + m_2}\sqrt{2g}$, and solve for m_2: $m_2 = \dfrac{m_1\sqrt{2g}}{\mathit{slope}} - m_1$ (1 point). Substituting $m_1 = 0.250$ kg and $g = 9.8\ \text{m/s}^2$: $m_2 = \dfrac{(0.25\ \text{kg})\sqrt{2(9.8)}}{1.72} - 0.25\ \text{kg} \approx 0.39\ \text{kg}$ (1 point). Any value in the range 0.30–0.60 kg is acceptable given a valid best-fit slope.

Solution 2

(e)

Mark scheme

- Answer: $m_1' < 0.250$ kg (1 point for selecting this with an attempted justification). Justification: The directly-measured mass of Cart 2 came out smaller than the value calculated in part (d). A smaller true m_2 corresponds to a smaller initial energy/momentum for the same drop height H; since the best-fit slope (and hence the computed relationship) stays the same, this discrepancy is explained if the actual mass of Cart 1 is smaller than the recorded 0.250 kg — i.e., $m_1' < 0.250$ kg (1 point).

Question 2

2022 Set 2 ▪ Q2

[Figure (top): A spring with spring constant k is attached to a wall on the left, compressed by an amount Δx from its natural length, holding Block 1 (mass m_1). Block 2 (mass m_2) sits at rest at position $x = 0$, to the right of Block 1, in front of a Motion Detector mounted on a wall at the far right.]
[Figure (bottom): After release, the spring is no longer compressed (uncompressed length shown), and the combined Block 1 + Block 2 system moves to the right with speed v, starting from $x = 0$.]
Block 1 of mass m_1 is held at rest while compressing an ideal spring an amount Δx. The spring constant of the spring is k. Block 2 has mass m_2, where $m_2 < m_1$. At time $t = 0$, Block 1 is released. At time t_C, the spring is no longer compressed and Block 1 immediately collides with and sticks to Block 2. The blocks stick together and the

Question 2

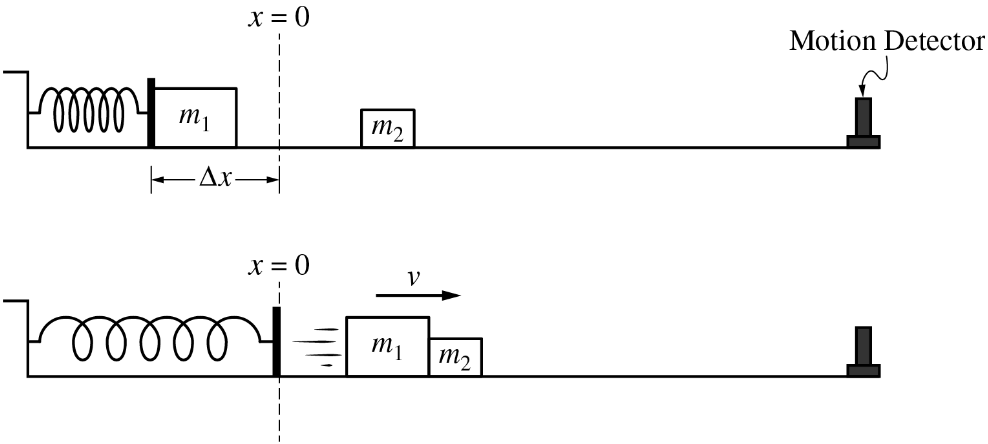
two-block system moves with constant speed v, as shown. Frictional effects are negligible.

(a) The impulse on Block 1 from the spring during the time interval $0 < t < t_C$ is J_S. The impulse on Block 1 from Block 2 during the collision is J_2. Which of the following expressions correctly compares the magnitudes of J_S and J_2 ?

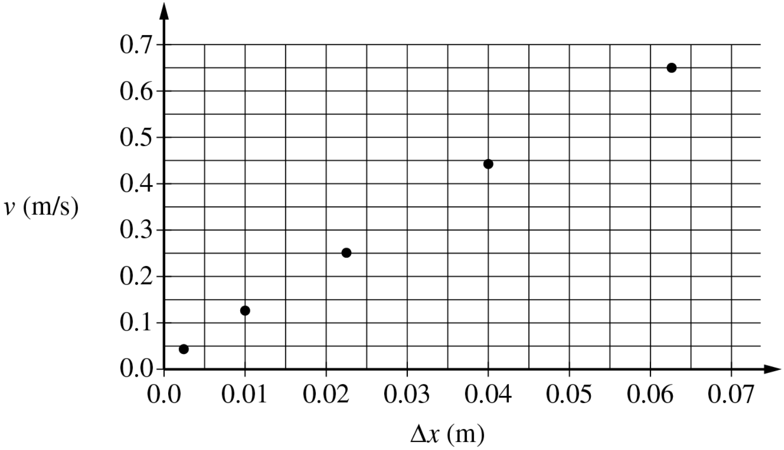
____ $J_S > J_2$ ____ $J_S < J_2$ ____ $J_S = J_2$

Justify your answer.

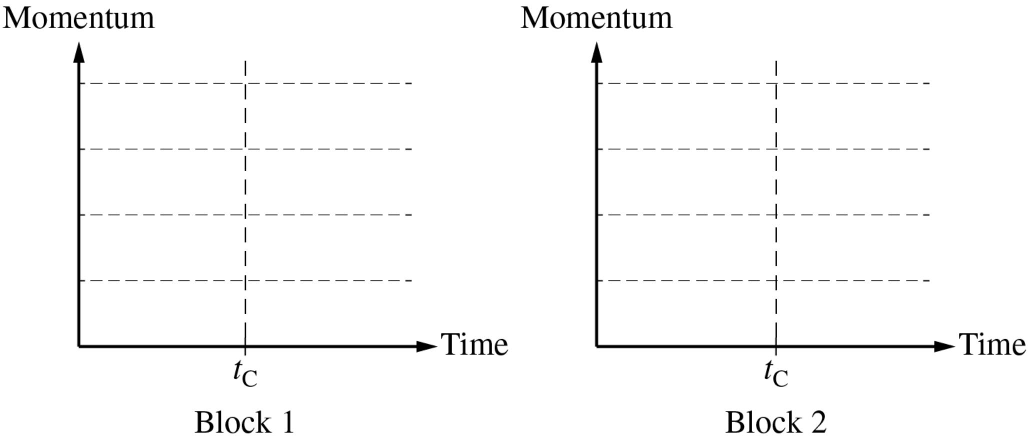
Question 2



Question 2



Question 2



Question 2

2022 Set 2 ▪ Q2

[Figure (top): A spring with spring constant k is attached to a wall on the left, compressed by an amount Δx from its natural length, holding Block 1 (mass m_1). Block 2 (mass m_2) sits at rest at position $x = 0$, to the right of Block 1, in front of a Motion Detector mounted on a wall at the far right.]
[Figure (bottom): After release, the spring is no longer compressed (uncompressed length shown), and the combined Block 1 + Block 2 system moves to the right with speed v, starting from $x = 0$.]
Block 1 of mass m_1 is held at rest while compressing an ideal spring an amount Δx. The spring constant of the spring is k. Block 2 has mass m_2, where $m_2 < m_1$. At time $t = 0$, Block 1 is released. At time t_C, the spring is no longer compressed and Block 1 immediately collides with and sticks to Block 2. The blocks stick together and the two-block system moves with constant speed v, as shown. Frictional effects are negligible.

Question 2

(b) On the following axes, draw graphs of the magnitude of the momentum of each block as a function of time, before and after t_C. The collision occurs in a negligible amount of time. The grid lines on each graph are drawn to the same scale.
[Two blank graphs labeled "Momentum" on the vertical axis and "Time" on the horizontal axis, each with a marked point t_C on the time axis and dashed gridlines; left graph labeled "Block 1", right graph labeled "Block 2", for the student to sketch momentum vs. time before and after t_C.]

Question 2

2022 Set 2 ▪ Q2

[Figure (top): A spring with spring constant k is attached to a wall on the left, compressed by an amount Δx from its natural length, holding Block 1 (mass m_1). Block 2 (mass m_2) sits at rest at position $x = 0$, to the right of Block 1, in front of a Motion Detector mounted on a wall at the far right.]
[Figure (bottom): After release, the spring is no longer compressed (uncompressed length shown), and the combined Block 1 + Block 2 system moves to the right with speed v, starting from $x = 0$.]
Block 1 of mass m_1 is held at rest while compressing an ideal spring an amount Δx. The spring constant of the spring is k. Block 2 has mass m_2, where $m_2 < m_1$. At time $t = 0$, Block 1 is released. At time t_C, the spring is no longer compressed and Block 1 immediately collides with and sticks to Block 2. The blocks stick together and the two-block system moves with constant speed v, as shown. Frictional effects are negligible.

Question 2

(c) Show that the velocity v of the two-block system after the collision is given by the equation $v = \dfrac{\sqrt{km_1}}{m_1 + m_2}\Delta x$.

Question 2

2022 Set 2 ▪ Q2

[Figure (top): A spring with spring constant k is attached to a wall on the left, compressed by an amount Δx from its natural length, holding Block 1 (mass m_1). Block 2 (mass m_2) sits at rest at position $x = 0$, to the right of Block 1, in front of a Motion Detector mounted on a wall at the far right.]

[Figure (bottom): After release, the spring is no longer compressed (uncompressed length shown), and the combined Block 1 + Block 2 system moves to the right with speed v, starting from $x = 0$.]

Block 1 of mass m_1 is held at rest while compressing an ideal spring an amount Δx. The spring constant of the spring is k. Block 2 has mass m_2, where $m_2 < m_1$. At time $t = 0$, Block 1 is released. At time t_C, the spring is no longer compressed and Block 1 immediately collides with and sticks to Block 2. The blocks stick together and the two-block system moves with constant speed v, as shown. Frictional effects are negligible.

Question 2

(d)(i) A group of students use the setup to perform an experiment. They measure the mass of Block 1 to be $m_1 = 0.500$ kg, and the spring constant k of the spring to be 150 N/m. The mass of Block 2 is unknown. They perform several trials and in each trial the spring is compressed a different distance Δx and the final velocity v of the two-block system is measured. They graph v as a function of Δx, as shown below. Draw a line that represents the best fit to the data points shown.
[Scatter plot: vertical axis v (m/s) from 0.0 to 0.7 in increments of 0.1; horizontal axis Δx (m) from 0.0 to 0.07 in increments of 0.01. Data points approximately at $(0.01, 0.08)$, $(0.02, 0.16)$, $(0.035, 0.28)$, $(0.05, 0.45)$, $(0.06, 0.58)$, $(0.065, 0.62)$, for the student to draw a best-fit line through.]
(d)(ii) Use the best-fit line to calculate the mass of Block 2.

Question 2

2022 Set 2 ▪ Q2

[Figure (top): A spring with spring constant k is attached to a wall on the left, compressed by an amount Δx from its natural length, holding Block 1 (mass m_1). Block 2 (mass m_2) sits at rest at position $x = 0$, to the right of Block 1, in front of a Motion Detector mounted on a wall at the far right.]
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Question 2

(e) After the experiment, the students use a balance to measure the mass of Block 2 and find it to be greater than what was determined in part (d). To explain this discrepancy, one of the students proposes that the spring constant was incorrectly measured at the beginning of the experiment. The students measure the spring constant again and record a new value, k'.
Should the students expect that k' be greater than 150 N/m, less than 150 N/m, or equal to 150 N/m ?
k' $>$ 150 N/m k' $<$ 150 N/m k' $=$ 150 N/m
Justify your answer.

Solution 2

(a) Mark scheme

- Answer: $J_S > J_2$ — select this choice with an attempt at a relevant justification (1 point), plus a fully correct justification (1 point). Example justification: By Newton's third law, the impulse Block 2 exerts on Block 1 during the collision has the same magnitude as the impulse Block 1 exerts on Block 2. Since Block 1 is still moving forward (nonzero momentum) after the collision, the impulse from the spring J_S (which accelerated Block 1 from rest up to its pre-collision speed) must be greater in magnitude than the impulse J_2 from the collision (which only reduces, not zeroes, Block 1's momentum).

Solution 2

(b) Mark scheme

- Full-credit sketch, 1 point per criterion: (1) For $0 < t < t_C$: Block 1's momentum rises along a concave-down (decreasing-slope) curve up to its maximum at $t = t_C$, while Block 2's momentum stays at zero (flat on the time axis) throughout. (2) For $t > t_C$: Block 1's momentum is a horizontal line at a value smaller in magnitude than its momentum at $t = t_C$ (it lost momentum in the collision). (3) For $t > t_C$: Block 2's momentum is a horizontal line at a value smaller in magnitude than Block 1's momentum at $t = t_C$ (Block 2 now moves, but with less momentum than Block 1 had just before the collision). (4) Blocks 1 and 2 have an equal-magnitude change in momentum at t_C — Block 1's drop equals Block 2's rise (momentum conservation in the collision).

Solution 2

(c) Mark scheme

- Use conservation of energy (spring PE converts to KE of Block 1) to find Block 1's speed at $x = 0$ — 1 point: $\frac{1}{2}k(\Delta x)^2 = \frac{1}{2}m_1 v_1^2 \Rightarrow v_1 = \sqrt{\frac{k}{m_1}}\Delta x$. Use conservation of momentum for the perfectly inelastic collision to find the speed of the combined two-block system — 1 point: $m_1 v_1 = (m_1 + m_2)v \Rightarrow v = \dfrac{m_1 v_1}{m_1 + m_2}$. Combine the two equations — 1 point: $v = \dfrac{\Delta x\sqrt{km_1}}{m_1 + m_2}$, as required to show.

Solution 2

(d)(i)

Mark scheme

- Draw a straight best-fit line through the plotted v vs. Δx data, with approximately the same number of data points above the line as below it (need not pass exactly through any single point). 1 point for a reasonable best-fit line satisfying this balance criterion.

Solution 2

(d)(ii) Mark scheme

- Calculate the slope of the best-fit line using two well-separated points on it — 1 point, e.g. slope $= \dfrac{(0.60 - 0.02)\ \mathrm{m/s}}{(0.055 - 0.0175)\ \mathrm{m}} \approx 10.67\ \mathrm{s}^{-1}$. Correctly relate the slope to m_2 using the part (c) result $v = \dfrac{\sqrt{km_1}}{m_1 + m_2}\Delta x$ — 1 point: slope $= \dfrac{\sqrt{km_1}}{m_1 + m_2} \Rightarrow m_2 = \dfrac{\sqrt{km_1}}{\text{slope}} - m_1$. Compute a correct numeric mass — 1 point: $m_2 = \dfrac{\sqrt{(150\ \mathrm{N/m})(0.500\ \mathrm{kg})}}{10.67\ \mathrm{s}^{-1}} - 0.500\ \mathrm{kg} \approx 0.31\ \mathrm{kg}$ (acceptable range $0.27\ \mathrm{kg}$ to $0.37\ \mathrm{kg}$, since it depends on the student's own graph read).

Solution 2

(e) Mark scheme

- Answer: $k' > 150$ N/m — select this choice with an attempt at relevant justification (1 point), plus a fully correct justification (1 point). Example justification: A balance shows the true mass of Block 2 is greater than the value determined in part (d). From slope $= \dfrac{\sqrt{k' m_1}}{m_1 + m_2}$, the measured slope of the graph (an experimental result) stays the same, so for a larger true m_2 the spring constant k' needed to keep that same slope must be greater than the originally assumed 150 N/m.