Past-paper walk-through

Change in Momentum and Impulse ▪ 4.2

eXercise

Questions in this set

- 2026 Q2
- 2025 Q1
- 2024 Q2
- 2021 Q3

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.

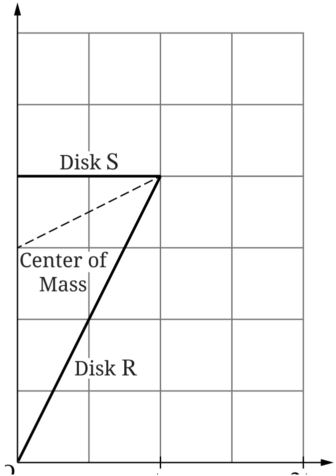
- Each arrow must start on, and point away from, each dot.
- If the momentum of either disk is zero, write "$p = 0$" next to the dot.

Question 2

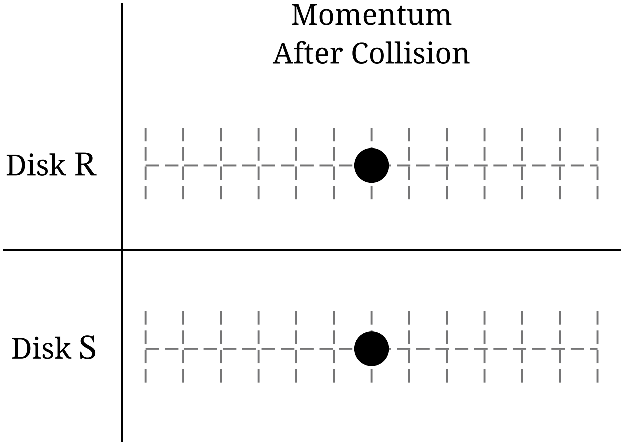
- Draw the length of each arrow to represent the magnitude of each momentum, consistent with the scale used in Figure 2.

[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.]

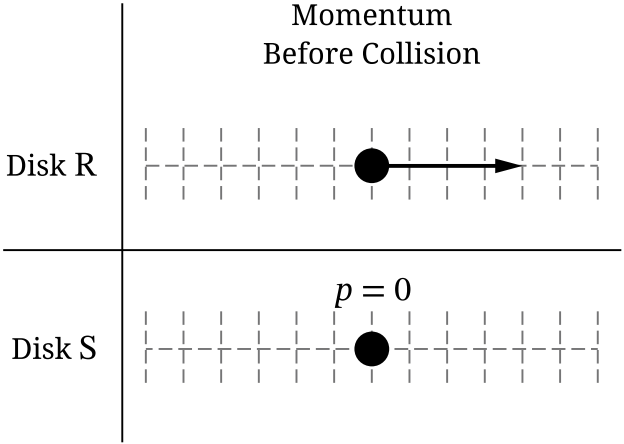
Question 2



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 $\frac{1}{2}v_0$ 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.]

(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.

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[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.]

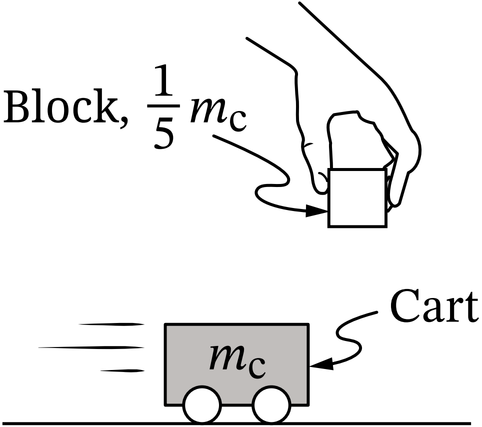
(a)(ii) **Derive** an expression for the speed v_f of the block-cart system after time $t = t_2$ in terms of m_c, v_c, and physical constants, as appropriate. Begin your derivation by writing a fundamental physics principle or an equation from the reference information.

(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 2

2024 ▪ Q2

[Figure 1: A stand with a horizontal support arm (labeled "Stand") has a spring hanging vertically from the arm, with a small loop at the bottom of the spring. To the right, a set of stacked cylindrical masses of various sizes (labeled "Cylinders") sits on the table, available for hanging on the spring's loop.]

A student hangs a spring of unknown spring constant k vertically by attaching one end to a stand, as shown in Figure 1. The other end of the spring has a small loop from which small cylinders can be hung. In addition to the spring, the student has access only to a variety of cylinders of unknown masses, a stopwatch, and a digital scale.

Question 2

(a) (a) Design an experimental procedure the student could use to determine the spring constant k of the spring.

In the following table, list the quantities that would be measured using only the provided equipment in your experiment. Define a symbol to represent each quantity.

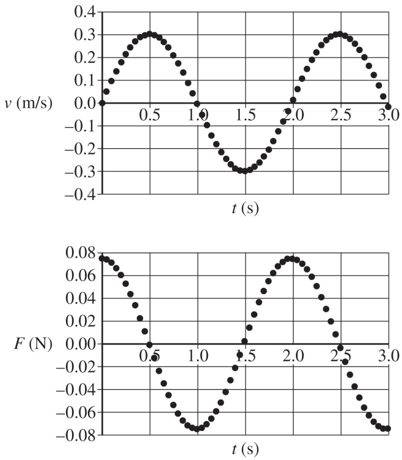
In the space below the table, **describe** the overall procedure. Provide enough detail so that another student could replicate the experiment, including any steps necessary to reduce experimental uncertainty. As needed, use the symbols defined in the table. If needed, you may include a simple diagram with your procedure.

Quantity to Be Measured	Symbol for Quantity	Equipment for Measurement
		Stopwatch Digital scale

Question 2

Procedure (and diagram, if needed):

Question 2



0.4
0.3
0.2
0.1
0.0
–0.1
–0.2
–0.3
–0.4
v (m/s)
0.5
1.0
1.5
2.0
2.5
3.0
t (s)
0.08
0.06
0.04
0.02
0.00
–0.02
–0.04
–0.06
–0.08
F (N)
0.5
1.0
1.5
2.0
2.5
3.0
t (s)

Question 2

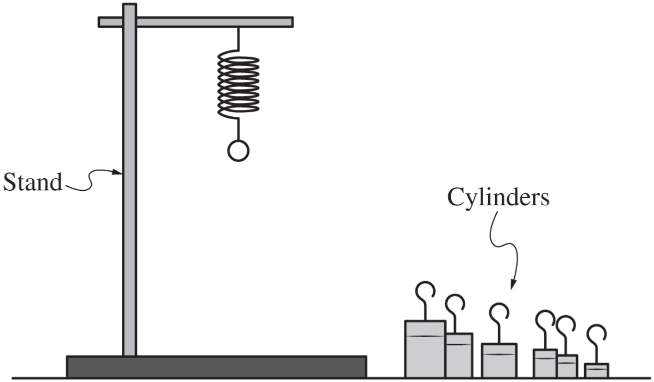


Figure 1

Question 2

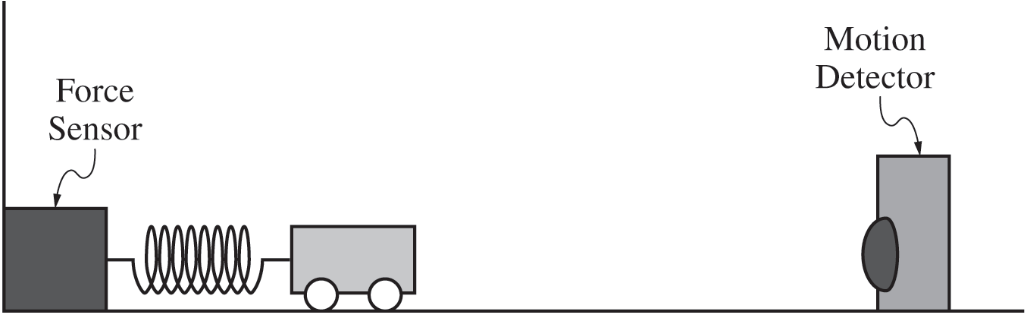


Figure 2

Question 2

2024 ▪ Q2

[Figure 1: A stand with a horizontal support arm (labeled "Stand") has a spring hanging vertically from the arm, with a small loop at the bottom of the spring. To the right, a set of stacked cylindrical masses of various sizes (labeled "Cylinders") sits on the table, available for hanging on the spring's loop.]

A student hangs a spring of unknown spring constant k vertically by attaching one end to a stand, as shown in Figure 1. The other end of the spring has a small loop from which small cylinders can be hung. In addition to the spring, the student has access only to a variety of cylinders of unknown masses, a stopwatch, and a digital scale.

(b)(i) (b)

i. **Indicate** the quantities that could be plotted to produce a linear graph whose slope can be used to determine the spring constant k of the spring.

Vertical axis: ____________________ Horizontal axis: ____________________

Question 2

(b)(ii) ii. Briefly **describe** how the slope of the graph would be analyzed to determine the spring constant k of the spring.

Question 2

2024 ▪ Q2

[Figure 1: A stand with a horizontal support arm (labeled "Stand") has a spring hanging vertically from the arm, with a small loop at the bottom of the spring. To the right, a set of stacked cylindrical masses of various sizes (labeled "Cylinders") sits on the table, available for hanging on the spring's loop.]

A student hangs a spring of unknown spring constant k vertically by attaching one end to a stand, as shown in Figure 1. The other end of the spring has a small loop from which small cylinders can be hung. In addition to the spring, the student has access only to a variety of cylinders of unknown masses, a stopwatch, and a digital scale.

(c)(i) [Figure 2: A force sensor is mounted on a wall on the left. A spring connects the force sensor to a cart of mass $m = 0.25$ kg on wheels, sitting on a horizontal track. To the right of the cart is a motion detector facing the cart.]

Question 2

In a different experiment, the student attaches one end of a spring to a force sensor that is attached to a wall. The other end of the spring is attached to a cart with mass $m = 0.25$ kg. The student places a motion detector to the right of the cart, as shown in Figure 2, and pulls the cart to the right a small distance so that the spring is stretched. The student releases the cart from rest, and the cart-spring system oscillates.

The following graphs show the velocity v of the cart and the force F exerted on the cart by the spring as functions of time t.

[Graph 1: velocity v (m/s) vs. time t (s); y-axis from -0.4 to 0.4 in increments of 0.1; x-axis from 0 to 3.0 s with gridlines at $0.5, 1.0, 1.5, 2.0, 2.5, 3.0$. The curve is a smooth cosine-like oscillation: starting near $v \approx 0$ at $t = 0$, rising to a positive peak near $v \approx 0.3$–0.35 around $t \approx 0.5$ s, back down through zero near $t \approx 1.0$–1.2 s, down to a negative peak near $v \approx -0.3$–-0.35 around $t \approx 1.7$ s, back up through zero near

Question 2

$t \approx 2.2$–2.4 s, and up to another positive peak near $t \approx 2.9$–3.0 s. Period of oscillation is approximately 1.7–1.8 s.]

[Graph 2: force F (N) vs. time t (s); y-axis from -0.08 to 0.08 in increments of 0.02; x-axis from 0 to 3.0 s with gridlines at $0.5, 1.0, 1.5, 2.0, 2.5, 3.0$. The curve is a smooth oscillation with the same period as the velocity graph, appearing approximately $90°$ out of phase with $v(t)$: starting near $F \approx 0.06$–0.07 (near a peak) at $t = 0$, decreasing through zero around $t \approx 0.4$–0.5 s, reaching a negative peak near $F \approx -0.07$ around $t \approx 0.8$–0.9 s, back through zero near $t \approx 1.3$ s, reaching a positive peak near $t \approx 1.7$–1.8 s, and continuing to oscillate with the same period through $t = 3.0$ s.]

i. Using the data in the velocity-time graph, **calculate** the change in kinetic energy of the cart from $t = 0.5$ s to $t = 2.0$ s. Show your steps and substitutions.

Question 2

(c)(ii) ii. Using the data in the force-time graph, **estimate** the change in momentum of the cart from $t = 0.5$ s to $t = 2.5$ s. Briefly **explain** how you arrived at your estimation.

(c)(iii) iii. Do the data from the velocity-time graph confirm your estimation from part (c)(ii)? Briefly **explain**.

Solution 2

(a) Mark scheme

- Procedure: place a cylinder on the digital scale and record its mass. Hang the cylinder from the spring and pull it down a small distance so the spring is stretched, then release it so it oscillates. Use the stopwatch to measure the time for the cylinder to complete many (e.g. ten) full cycles (from maximum stretch back to maximum stretch), then divide by the number of oscillations to get the period. Repeat the procedure for cylinders of different masses. Points (4 total, 1 each): measuring the mass of at least one cylinder with the digital scale; measuring the period of oscillation with the stopwatch; a procedure that indicates the cylinder is set into oscillatory motion; a procedure that reduces experimental uncertainty (accept any one of: using multiple masses, doing multiple trials with a

Solution 2

single mass, or measuring multiple oscillations and dividing by the number of oscillations).

Solution 2

(b)(i) Mark scheme

- List a linear-izing pair of axes whose slope gives k, e.g. Vertical axis: m, Horizontal axis: T^2 (from $T = 2\pi\sqrt{m/k}$, so $m = \frac{k}{4\pi^2}T^2$). Any of the following pairs earns the point: m vs. T^2; T^2 vs. m; $4\pi^2 m$ vs. T^2; T^2 vs. $4\pi^2 m$; $\frac{T^2}{4\pi^2}$ vs. m; m vs. $\frac{T^2}{4\pi^2}$; T vs. $\sqrt{m}$; $\sqrt{m}$ vs. T; $\frac{T}{2\pi}$ vs. $\sqrt{m}$; $\sqrt{m}$ vs. $\frac{T}{2\pi}$; T vs. $2\pi\sqrt{m}$; $2\pi\sqrt{m}$ vs. T (any bullet may also substitute $1/f$ for T).

Solution 2

(b)(ii) Mark scheme

- Describe how the slope relates to k, consistent with the axes chosen in (b)(i). Using $T = 2\pi\sqrt{m/k}$: e.g. for m (vertical) vs. T^2 (horizontal), slope $= \dfrac{k}{4\pi^2}$, so $k = (\text{slope})\,4\pi^2$. (Other axis choices give the corresponding relation, e.g. T^2 vs. m gives slope $= 4\pi^2/k$ so $k = 4\pi^2/\text{slope}$; $4\pi^2 m$ vs. T^2 gives slope $= k$; etc.) Full credit (1 point) for correctly relating the slope of the best-fit line to k given the student's chosen axes.

Solution 2

(c)(i)

Mark scheme

- Estimate the change in kinetic energy of the cart using $K = \frac{1}{2}mv^2$:
  $\Delta K = K_f - K_i = \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2 = \frac{1}{2}(0.25)(0)^2 - \frac{1}{2}(0.25)(0.3)^2 \approx -0.0113$ J.
  Points: using the kinetic energy equation $K = \frac{1}{2}mv^2$ (1 point); substituting one of the given values — mass 0.25 kg or initial velocity 0.3 m/s (1 point); an answer that approximates $\Delta K \approx -0.0113$ J (unit and sign not required) — a correct numeric answer with no supporting work earns this point alone (1 point).

Solution 2

(c)(ii)

Mark scheme

- Because the cart's speed returns to the same value (0.3 m/s) before and after the interaction, the magnitude of the change in momentum is zero. This is estimated from the force-time graph: the area under a force-vs-time curve equals the impulse, i.e. the change in momentum; the area under the curve from $t = 0.5$ s to $t = 2.5$ s is zero (equal positive and negative areas cancel), so $\Delta p \approx 0$. Points: indicating the magnitude of the change in momentum is zero (1 point); indicating that the area under the force-time graph represents the value of the change in momentum (1 point).

Solution 2

(c)(iii)

Mark scheme

- Yes — the velocity-time graph confirms the estimate from (c)(ii): it shows the velocity is 0.3 m/s at both $t = 0.5$ s and $t = 2.5$ s, and since momentum is mass times velocity, the momentum is the same at both times, giving a change in momentum of zero. This agrees with the (c)(ii) estimate that $\Delta p \approx 0$. Full credit (1 point) for an explanation that compares the (c)(ii) estimate to the velocity-time data in this way.

Question 3

2021 ▪ Q3

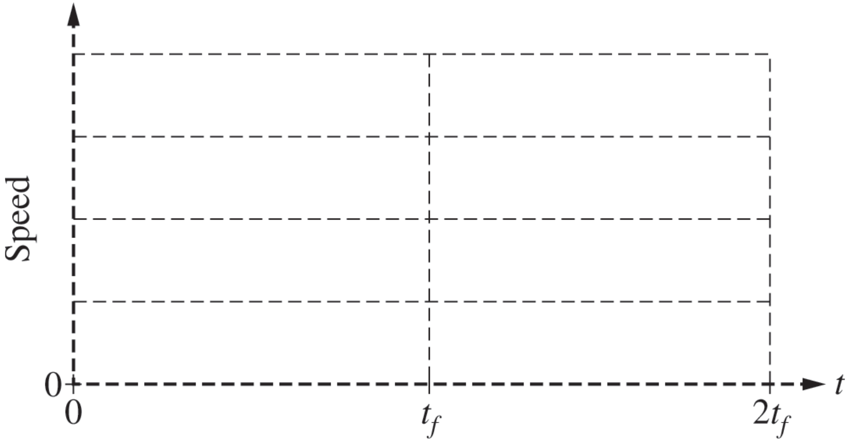
(12 points, suggested time 25 minutes)

(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.

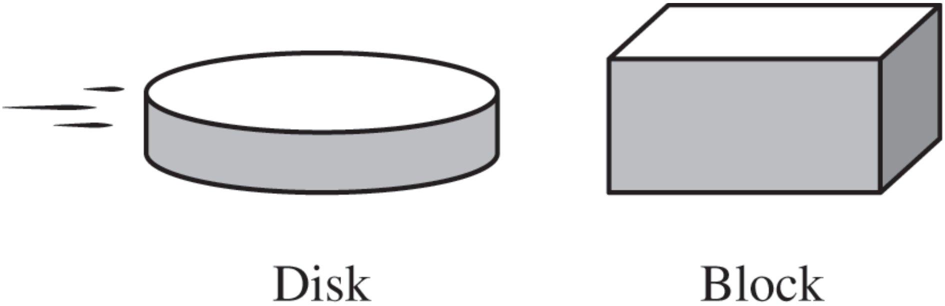
Assuming the disk begins at rest, determine an expression for the final speed v_D of the disk relative to the surface. Express your answer in terms of F_H, t_f, M_S, M_D, and physical constants, as appropriate.

(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.

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(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).

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(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.