Past-paper walk-through

Systems and Center of Mass ▪ 2.1

eXercise

Questions in this set

- 2026 Q2
- 2024 Q5
- 2023 Q1
- 2021 Q3
- 2019 Q1
- 2015 Q1

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.

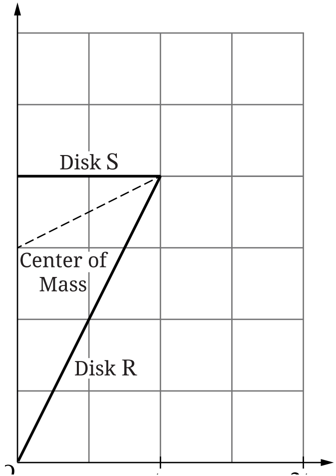
- Each arrow must start on, and point away from, each dot.
- If the momentum of either disk is zero, write "$p = 0$" next to the dot.

Question 2

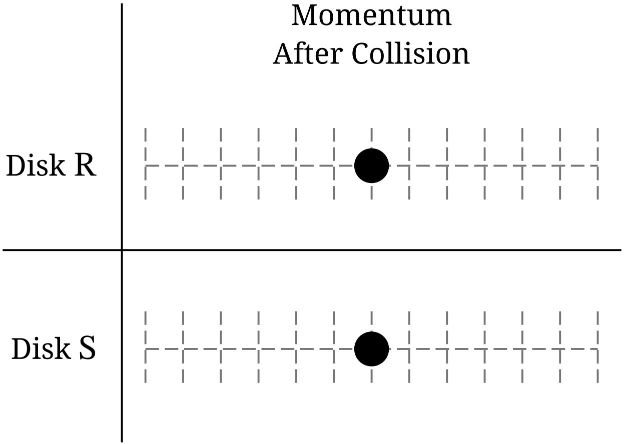
- Draw the length of each arrow to represent the magnitude of each momentum, consistent with the scale used in Figure 2.

[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.]

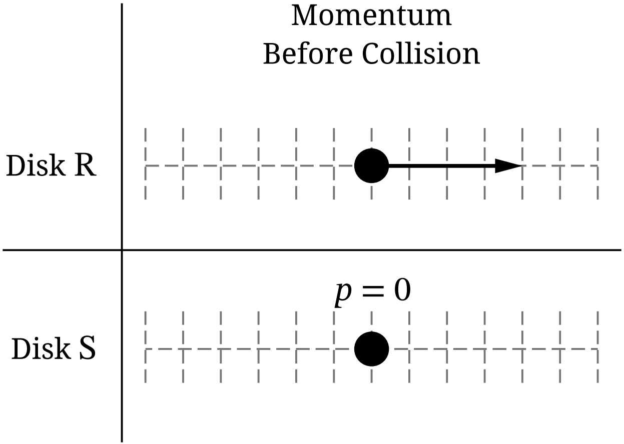
Question 2



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.

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 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

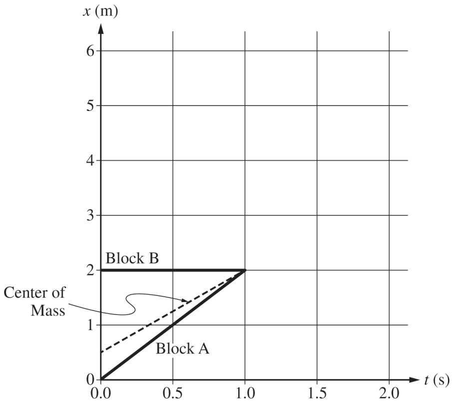


Figure 2

Question 5

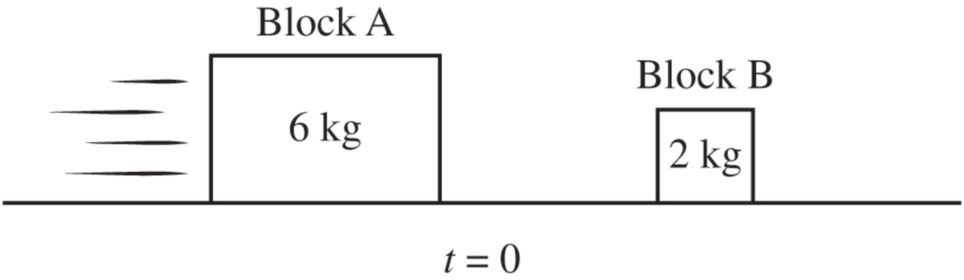


Figure 1

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.

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.

(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 1

2023 ▪ Q1

A cart on a horizontal surface is attached to a spring. The other end of the spring is attached to a wall. The cart is initially held at rest, as shown in Figure 1. When the cart is released, the system consisting of the cart and spring oscillates between the positions $x = +L$ and $x = -L$. Figure 2 shows the kinetic energy of the cart-spring system as a function of the system's potential energy. Frictional forces are negligible. [Figure 1: A cart attached to a spring coiled between a wall on the left and the cart on the right, resting on a horizontal surface. Positions marked below: $x = -L$ (at the wall end), $x = 0$ (middle), $x = +L$ (at the cart's rest position shown).]
[Figure 2: Graph of kinetic energy K (J) on the vertical axis, from 0 to 6, versus potential energy U (J) on the horizontal axis, from 0 to 6. A straight diagonal line runs from approximately $(0, 4)$ down to $(4, 0)$, i.e., the line has x-intercept and y-intercept both equal in value.]

Question 1

(a) On the graph of kinetic energy K versus potential energy U shown in Figure 2, the values for the x-intercept and y-intercept are the same. Briefly explain why this is true, using physics principles.

Question 1

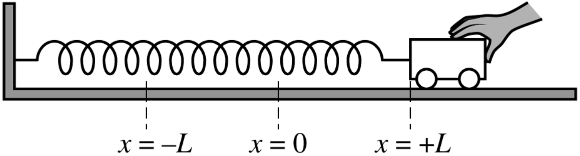


Figure 1

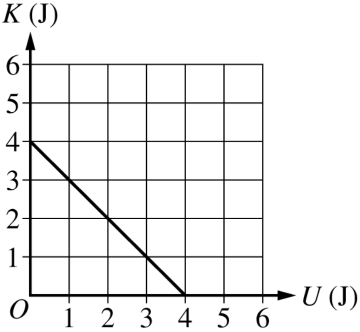


Figure 2

Question 1

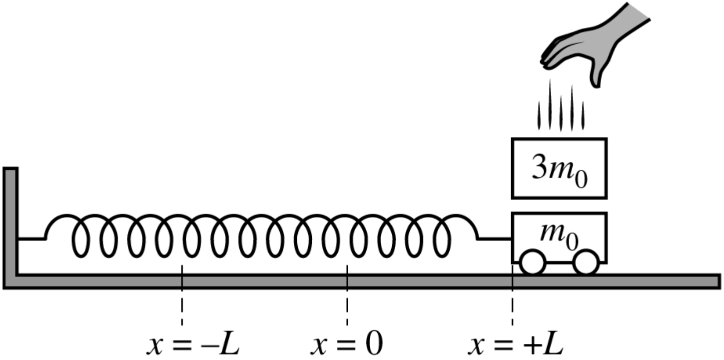


Figure 3

Question 1

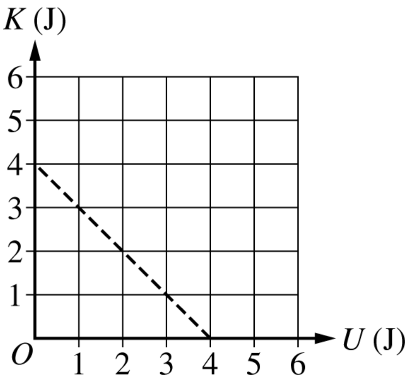


Figure 4

Question 1

2023 ▪ Q1

A cart on a horizontal surface is attached to a spring. The other end of the spring is attached to a wall. The cart is initially held at rest, as shown in Figure 1. When the cart is released, the system consisting of the cart and spring oscillates between the positions $x = +L$ and $x = -L$. Figure 2 shows the kinetic energy of the cart-spring system as a function of the system's potential energy. Frictional forces are negligible.

[Figure 1: A cart attached to a spring coiled between a wall on the left and the cart on the right, resting on a horizontal surface. Positions marked below: $x = -L$ (at the wall end), $x = 0$ (middle), $x = +L$ (at the cart's rest position shown).]

[Figure 2: Graph of kinetic energy K (J) on the vertical axis, from 0 to 6, versus potential energy U (J) on the horizontal axis, from 0 to 6. A straight diagonal line runs from approximately $(0, 4)$ down to $(4, 0)$, i.e., the line has x-intercept and y-intercept both equal in value.]

Question 1

(b) [Continuation of Question 1.] When the cart is at $+L$ and momentarily at rest, a block is dropped onto the cart, as shown in Figure 3. The block sticks to the cart, and the block-cart-spring system continues to oscillate between $-L$ and $+L$. The masses of the cart and the block are m_0 and $3m_0$, respectively.
[Figure 3: Same spring-and-wall setup as Figure 1, but now a block labeled $3m_0$ falls (shown with motion marks) onto a cart labeled m_0 sitting atop the cart at position $x = +L$. Positions marked: $x = -L$, $x = 0$, $x = +L$.]
The frequency of oscillation before the block is dropped onto the cart is f_1. The frequency of oscillation after the block is dropped onto the cart is f_2. Calculate the numerical value of the ratio $\dfrac{f_2}{f_1}$.

Question 1

2023 ▪ Q1

A cart on a horizontal surface is attached to a spring. The other end of the spring is attached to a wall. The cart is initially held at rest, as shown in Figure 1. When the cart is released, the system consisting of the cart and spring oscillates between the positions $x = +L$ and $x = -L$. Figure 2 shows the kinetic energy of the cart-spring system as a function of the system's potential energy. Frictional forces are negligible.

[Figure 1: A cart attached to a spring coiled between a wall on the left and the cart on the right, resting on a horizontal surface. Positions marked below: $x = -L$ (at the wall end), $x = 0$ (middle), $x = +L$ (at the cart's rest position shown).]

[Figure 2: Graph of kinetic energy K (J) on the vertical axis, from 0 to 6, versus potential energy U (J) on the horizontal axis, from 0 to 6. A straight diagonal line runs from approximately $(0, 4)$ down to $(4, 0)$, i.e., the line has x-intercept and y-intercept both equal in value.]

Question 1

(c)(i) [Continuation of Question 1.] The dashed line in Figure 4 shows the kinetic energy K versus potential energy U of the block-cart-spring system after the block is dropped onto the cart. This graph is identical to the graph shown in Figure 2 for the cart-spring system before the block is dropped onto the cart.
[Figure 4: Graph of kinetic energy K (J), vertical axis 0 to 6, versus potential energy U (J), horizontal axis 0 to 6. A dashed diagonal line runs from approximately $(0, 4)$ down to $(4, 0)$ — identical to the solid line in Figure 2.]
i. Briefly explain why the two graphs must be the same, using physics principles.
(c)(ii) ii. After the block is dropped onto the cart, consider a system that consists only of the cart and the spring. On Figure 4, sketch a solid line that shows the kinetic energy of the system that consists of the cart and the spring but not the block after the block is dropped onto the cart.

Solution 1

(a)

Mark scheme

- Maximum kinetic energy equals maximum potential energy (both 4 J) because energy is conserved in the cart-spring system: the graph's x-intercept (max U, $K = 0$) and y-intercept (max K, $U = 0$) both represent the same total mechanical energy. Full credit for simply stating 'conservation of energy.'

Solution 1

(b) Mark scheme

- Set up the ratio of frequencies (or periods): $T = 2\pi\sqrt{m/k}$, $f = \frac{1}{2\pi}\sqrt{k/m}$, so $\frac{f_2}{f_1} = \sqrt{\frac{m_1}{m_2}}$ (1 point for using the frequency/period equation in a valid ratio — any equivalent orientation of f_1/f_2, T_1/T_2, etc. is accepted). Substitute the total mass after the block sticks, $4m_0$ (since $m_0 + 3m_0 = 4m_0$), for m_2: $\frac{f_2}{f_1} = \sqrt{\frac{m_0}{4m_0}} = \frac{1}{2}$ (1 point for correctly substituting the total mass $4m_0$ into the ratio). Final answer: the new frequency is half the old frequency, $f_2/f_1 = 1/2$ (equivalently $T_1/T_2 = 1/2$).

Solution 1

(c)(i)

Mark scheme

- Accept any one valid explanation: (1) no (net external) work is done on the system, so its total mechanical energy is unchanged; (2) the maximum spring potential energy does not depend on the mass of the system, so it is unchanged when the block is added; (3) the force exerted on the system (by the wall/spring at the point of interest) is perpendicular to the direction of motion. Example: 'The maximum potential energy of the system does not depend upon the mass of the system, therefore there will be no change when the block is added.'

Solution 1

(c)(ii) Mark scheme

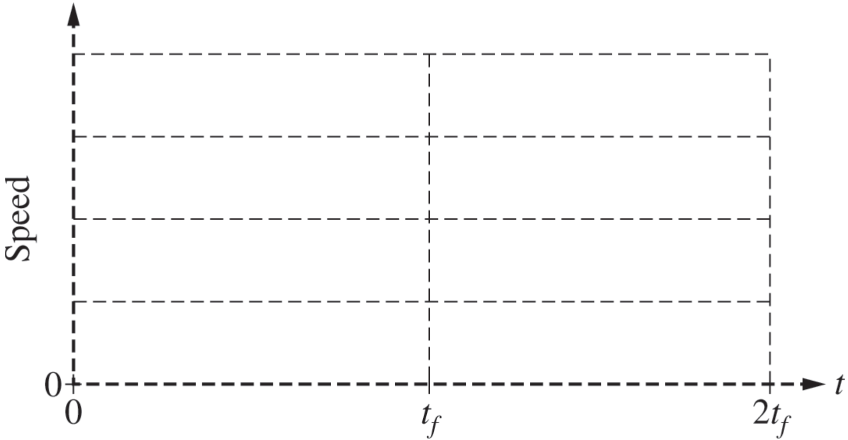
- Sketch a single solid straight line on the K vs U graph from $(U, K) = (0, 1)$ to $(4, 0)$. Three points: (1) the line's horizontal (U) intercept is the same as the original dashed graph's, at $U = 4$ J (max spring PE is unchanged — it doesn't depend on mass); (2) the line's vertical (K) intercept is less than the original graph's vertical intercept (max KE decreases, since the perfectly inelastic collision between the block and cart dissipates some kinetic energy); (3) the vertical intercept is the exact, correct value of 1 J (total mechanical energy after the collision, found from conservation of momentum in the collision then energy conservation in the subsequent oscillation).

Question 3

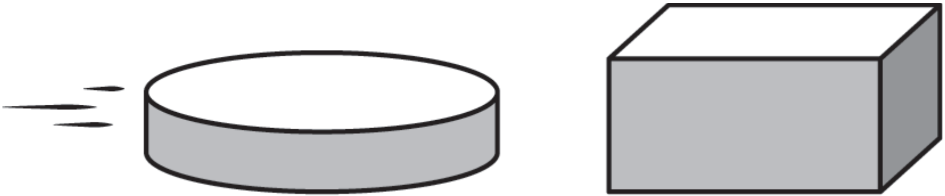
2021 ▪ Q3

(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



Disk Block

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

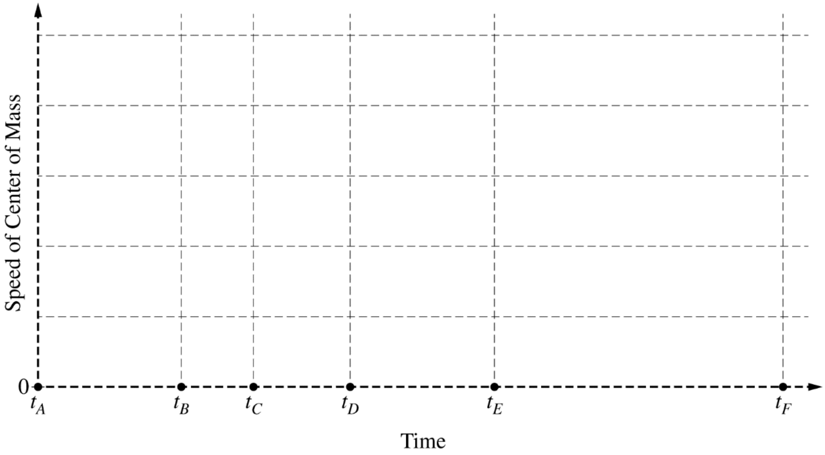
Identical blocks 1 and 2 are placed on a horizontal surface at points A and E, respectively, as shown. The surface is frictionless except for the region between points C and D, where the surface is rough. Beginning at time t_A, block 1 is pushed with a constant horizontal force from point A to point 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.]

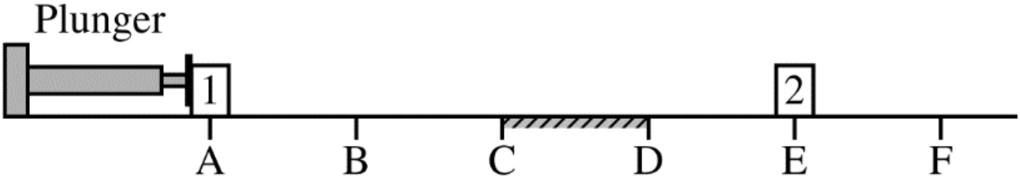
Question 1

(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.]

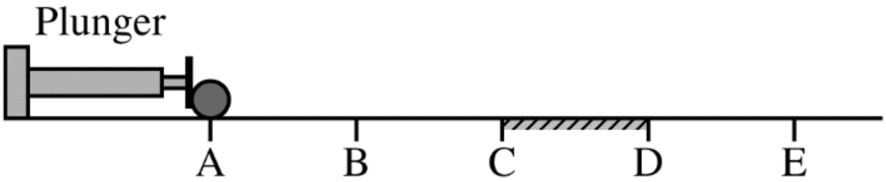
Question 1



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 1

2015 ▪ Q1

[Figure: Two blocks connected by a string over two pulleys mounted on a frame above a table. Block 1 (mass m_1) hangs on the left side, Block 2 (mass m_2) hangs on the right side. Note: Figure not drawn to scale.]

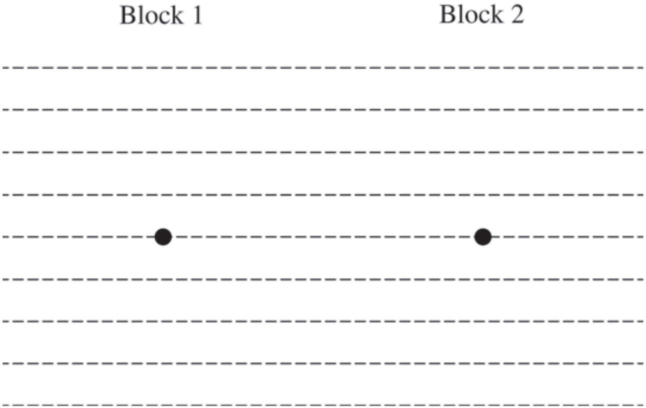
Two blocks are connected by a string of negligible mass that passes over massless pulleys that turn with negligible friction, as shown in the figure above. The mass m_2 of block 2 is greater than the mass m_1 of block 1. The blocks are released from rest.

(a) The dots below represent the two blocks. Draw free-body diagrams showing and labeling the forces (not components) exerted on each block. Draw the relative lengths of all vectors to reflect the relative magnitudes of all the forces.

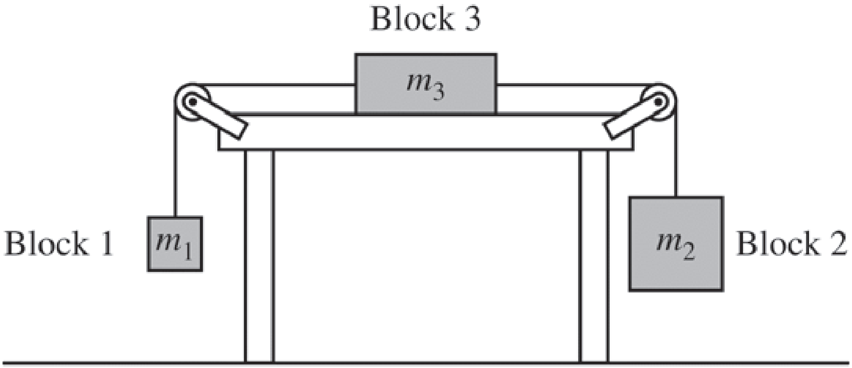
[Two blank labeled diagrams, each showing a single dot on a set of horizontal dashed reference lines, for the student to draw force vectors on: one labeled "Block 1", one labeled "Block 2".]

Question 1

(not components) exerted on each block. Draw the relative lengths of all vectors to
magnitudes of all the forces.

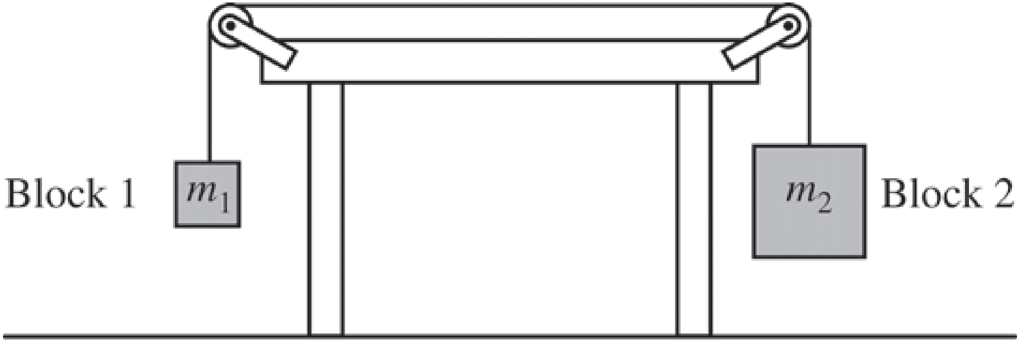


Question 1



Note: Figure not drawn to scale.

Question 1



Note: Figure not drawn to scale.

Question 1

2015 ▪ Q1

[Figure: Two blocks connected by a string over two pulleys mounted on a frame above a table. Block 1 (mass m_1) hangs on the left side, Block 2 (mass m_2) hangs on the right side. Note: Figure not drawn to scale.]

Two blocks are connected by a string of negligible mass that passes over massless pulleys that turn with negligible friction, as shown in the figure above. The mass m_2 of block 2 is greater than the mass m_1 of block 1. The blocks are released from rest.

(b) Derive the magnitude of the acceleration of block 2. Express your answer in terms of m_1, m_2, and g.

Question 1

2015 ▪ Q1

[Figure: Two blocks connected by a string over two pulleys mounted on a frame above a table. Block 1 (mass m_1) hangs on the left side, Block 2 (mass m_2) hangs on the right side. Note: Figure not drawn to scale.]

Two blocks are connected by a string of negligible mass that passes over massless pulleys that turn with negligible friction, as shown in the figure above. The mass m_2 of block 2 is greater than the mass m_1 of block 1. The blocks are released from rest.

(c) Block 3 of mass m_3 is added to the system, as shown below. There is no friction between block 3 and the table.

[Figure: Block 3 (mass m_3) now sits on top of the table, connected by strings over the same two pulleys to Block 1 (mass m_1) hanging on the left and Block 2 (mass m_2) hanging on the right. Note: Figure not drawn to scale.]

Question 1

Indicate whether the magnitude of the acceleration of block 2 is now larger, smaller, or the same as in the original two-block system. Explain how you arrived at your answer.

Solution 1

(a) Mark scheme

- Free-body diagrams for Block 1 and Block 2 (each hanging from a string over a pulley, connected to the other block). Each block has exactly two forces: tension T pointing up, and gravity ($m_1 g$ or $m_2 g$) pointing down. Scoring: 1 point for drawing two vectors starting on the dots that point upward, of equal length, both labeled as the tension force T. 1 point for drawing two vectors starting on the dots that point downward, where the vector for Block 1 (weight $m_1 g$) is shorter than the vector for Block 2 (weight $m_2 g$), both labeled as the gravitational force – consistent with $m_2 > m_1$ so the system accelerates with Block 2 moving down. Deduct 1 point for any extraneous vectors; deduct 1 point if the vector lengths would not allow the system to accelerate in the proper direction.

Solution 1

(b) Mark scheme

- Apply Newton's second law to each block (T = string tension, a = common acceleration magnitude): Block 1 (accelerates upward): $m_1 a = T - m_1 g$. Block 2 (accelerates downward): $m_2 a = m_2 g - T$. Eliminate T: from Block 1, $T = m_1 a + m_1 g$; substituting into Block 2's equation: $m_2 a = m_2 g - m_1 a - m_1 g \Rightarrow (m_2 + m_1)a = (m_2 - m_1)g$. Result: $a = \dfrac{(m_2 - m_1)g}{m_2 + m_1}$. Scoring (3 points): 1 for the correct Newton's-second-law equation for Block 1, 1 for Block 2, 1 for correctly eliminating T to reach an equation solvable for a. Alternate (system) solution earns the same 3 points via: $F_{net} = (m_2 - m_1)g$ (1 pt), $F_{net} = (m_2 + m_1)a$ (1 pt), combine to solve for a (1 pt) – same final answer.

Solution 1

(c) Mark scheme

- Block 3 (mass m_3, frictionless on the table) is inserted into the same string/pulley system between Block 1 and Block 2. The acceleration of Block 2 is now SMALLER than in the original two-block system. Reasoning: the total mass being accelerated increases from $(m_1 + m_2)$ to $(m_1 + m_2 + m_3)$ while the net driving force $(m_2 - m_1)g$ is unchanged, so $a = (m_2 - m_1)g/(m_1 + m_2 + m_3)$ is smaller; equivalently the tension on Block 2 increases (more mass for the string to pull along) which reduces its net accelerating force. Scoring (2 points): 1 point for indicating the mass of the system is larger, 1 point for a clear indication that the tension on Block 2 is greater. (Alternate solution, same 2 points: 1 for indicating the system mass is larger, 1 for indicating the net force exerted on the system

Solution 1

stays the same.) No points are earned for a correct prediction without a reasonable explanation attempt, and no points are earned for an incorrect prediction regardless of explanation.