Past-paper walk-through

Motion in Two or Three Dimensions ▪ 1.5

eXercise

Questions in this set

- 2026 Q2
- 2021 Set 2 Q3
- 2019 Set 1 Q2
- 2017 Q3
- 2015 Q2
- 2014 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

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).]

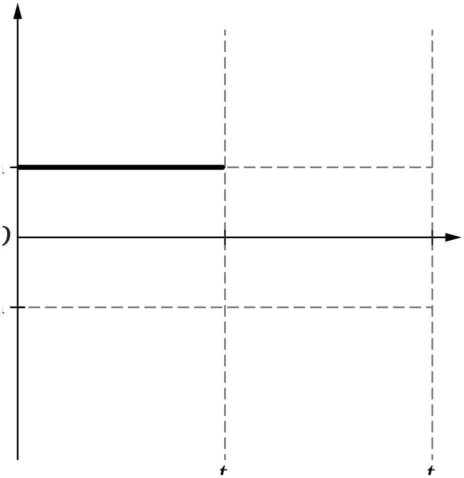
Question 2

[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).]

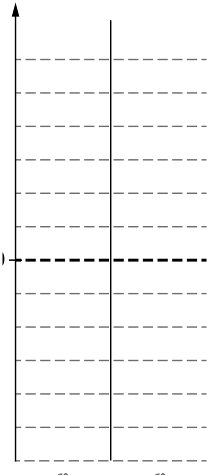
On Figure 3, **draw** shaded bars to represent p_x and p_y of Pieces Q and R at $t = t_1$.

- 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.

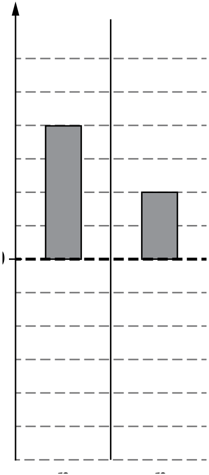
Question 2



Question 2



Question 2



Question 2

2026 ▪ Q2

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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

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Question 2

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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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(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 3

2021 Set 2 ▪ Q3

[Figure: A block of mass m sits on top of a vertical spring (spring constant k) which is compressed a distance Δx from its natural length, at the bottom of a vertical track. The track curves upward and to the right in a smooth arc, reaching a highest point labelled A at height $3R$ above the block's release point, where the track has constant radius of curvature R (shown with a radius arrow labelled R from a center point to point A). The track continues curving over the top and down to point B, at the same height $3R$, where the track becomes horizontal (radius R again, shown with a radius arrow labelled R from a center point to B) and the block exits horizontally moving to the right and slightly upward along a dashed projectile trajectory, landing a horizontal distance D from the end of the track (measured from directly below B). A note states "Figure not drawn to scale."]

Question 3

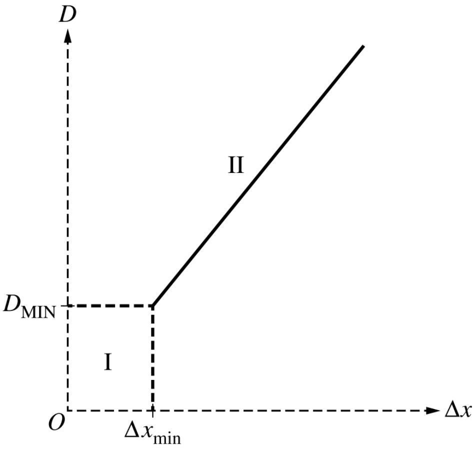
A block of mass m is placed on top of an ideal spring of spring constant k. The block is pushed against the spring, compressing the spring a distance Δx. The block is released from rest, leaves the spring at the position shown in the figure, travels upward, and enters a track with a constant radius of curvature R that has negligible friction. The block enters the track at point A, maintains contact with the track, and exits horizontally at point B, a distance $3R$ above the point the block was released. The block then falls to the ground and lands a horizontal distance D from the end of the track. Express all algebraic answers in terms of m, k, Δx, R, and physical constants, as appropriate. The size of the block is much smaller than the radius of curvature of the track.

(a) On the dot below, which represents the block, draw and label the forces (not components) that act on the block while still in contact with the track at point B.

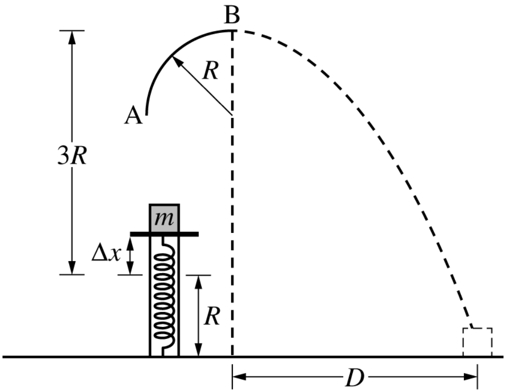
Question 3

Each force must be represented by a distinct arrow starting on, and pointing away from, the dot.
[A single black dot is shown, representing the block at point B, with blank space around it for the student to draw force arrows.]
Justify your choice of vectors.

Question 3



Question 3



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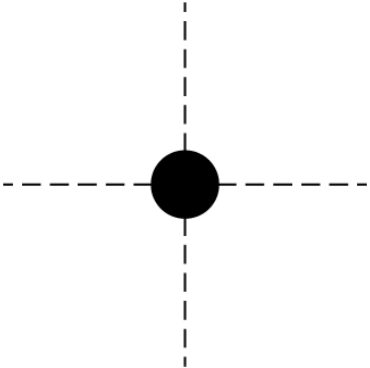
Question 3



Question 3

2021 Set 2 ▪ Q3

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Question 3

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(b)(i) Derive an expression for the speed v of the block at point B.

(b)(ii) Derive an expression for the magnitude of the net force F on the block at point B.

Question 3

2021 Set 2 ▪ Q3

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(c) Derive an expression for the minimum value of Δx_{min} required in order for the block to maintain contact with the track through point B.

The procedure is repeated several times with the distance $\Delta x > \Delta x_{\mathrm{min}}$.

Question 3

2021 Set 2 ▪ Q3

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Question 3

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(d) Calculate the distance D that the block travels.

Question 3

2021 Set 2 ▪ Q3

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(e)(i) The graph below shows the best-fit line drawn by the students through their data of D as a function of Δx.

[Graph: vertical axis D, horizontal axis Δx. A dashed horizontal line marks D_{MIN} on the D-axis, and a dashed vertical line marks $\Delta x_{\min}$ on the Δx-axis, meeting at the start of the data trend. Region "I" is labelled in the lower-left area (below/left of the dashed lines, near the origin O, where there is no plotted line). Region "II" is labelled

Question 3

along a straight line that starts at the point $(\Delta x_{\min}, D_{\mathsf{MIN}})$ and rises linearly up and to the right.]
Explain why there are no data for section I of the graph.
(e)(ii) Explain the reason for the shape and minimum value of section II on the graph.

Solution 3

(a) Mark scheme

- At point B, draw two forces on the dot: weight F_g pointing straight down (1 pt), and the normal force from the track F_N pointing toward the center of the circular path / perpendicular to the track surface (1 pt), with a justification consistent with the diagram (1 pt). Example: 'The force F_g represents the weight of the block and always points downward. The force F_N represents the force the track exerts on the block to keep it moving in a circular path and points perpendicular to the surface of the track.' Acceptable gravity labels: F_G, F_g, F_{grav}, W, mg, Mg, etc. (not G or g alone); acceptable normal-force labels: F_n, F_N, N, 'normal force'. Note: if extraneous forces are drawn, a maximum of 2 of the 3 points can be earned.

Solution 3

(b)(i) Mark scheme

- Use conservation of energy for the system, block starting at rest: $U_1 + K_1 = U_2 + K_2$, i.e. $U_1 + 0 = U_2 + K_2$ (1 pt). Relate the elastic PE at maximum spring compression to the gravitational PE at point B: $U_{s1} + 0 = U_{g2} + K_2$, so $K_2 = U_{s1} - U_{g2}$ (1 pt). Substitute: $\dfrac{1}{2}mv_B^2 = \dfrac{1}{2}k(\Delta x)^2 - mgh_2$, where $h_2 = 3R$ is the height of point B; so $v_B^2 = \dfrac{k}{m}(\Delta x)^2 - 2g(3R)$, giving $v_B = \sqrt{\dfrac{k}{m}(\Delta x)^2 - 6gR}$ (1 pt). Final answer: $v_B = \sqrt{\dfrac{k}{m}(\Delta x)^2 - 6gR}$.

Solution 3

(b)(ii) Mark scheme

- Relate the centripetal (net) force at point B to the speed found in part (b)(i): $F_C = \frac{mv^2}{r} = \frac{mv_B^2}{R}$ (1 pt). Substitute v_B from (b)(i) for an answer consistent with that result: $F_C = \frac{m}{R}\left(\sqrt{\frac{k}{m}(\Delta x)^2 - 6gR}\right)^2 = \frac{k(\Delta x)^2}{R} - 6mg$ (1 pt). Final answer: $F_C = \frac{k(\Delta x)^2}{R} - 6mg$.

Solution 3

(c) Mark scheme

- At the minimum compression, the block barely maintains contact with the track at point B, so the normal force is zero and the net force equals gravity alone: relate the net-force expression from (a)/(b)(ii) to this condition (1 pt): $\dfrac{k(\Delta x)^2}{R} - 6mg = mg$. Substitute and solve (1 pt): $\dfrac{k(\Delta x)^2}{R} = 7mg \implies \Delta x = \sqrt{\dfrac{7mgR}{k}}$. Final answer: $\Delta x_{\min} = \sqrt{\dfrac{7mgR}{k}}$.

Solution 3

(d) Mark scheme

- Relate the height of fall ($4R$, from point B down to the ground) to the time of fall using projectile motion: $y = y_0 + v_{0y}t + \frac{1}{2}a_y t^2$; with a fall height of $4R$: $t = \sqrt{\frac{2(4R)}{g}} = \sqrt{\frac{8R}{g}}$ (1 pt). Substitute into $D = v_x t$ using the (constant) horizontal velocity from part (b)(i): $D = v_x t = \sqrt{\frac{k}{m}(\Delta x)^2 - 6gR} \cdot \sqrt{\frac{8R}{g}}$ (1 pt, must be consistent with the expression for v_B from (b)(i)). Final answer: $D = \sqrt{\frac{k}{m}(\Delta x)^2 - 6gR} \cdot \sqrt{\frac{8R}{g}}$.

Solution 3

(e)(i)

Mark scheme

- Provide a correct justification for the general shape of the D-vs-Δx graph, i.e. why no data/motion occurs for compressions below the minimum (Region I). Example reasoning: 'The block needs a minimum speed to make it through point B on the track; thus, the flat/empty segment (Region I) represents compressions of the spring for which the block does not make it to point B.' (1 pt for a correct justification.)

Solution 3

(e)(ii) Mark scheme

- Explain both the shape and the minimum value of Region II: (1 pt) as the maximum compression Δx increases beyond $\Delta x_{\min}$, the distance D increases — consistent with part (d), D grows with $\sqrt{\frac{k}{m}(\Delta x)^2 - 6gR}$, so beyond the threshold the graph rises monotonically with Δx; (1 pt) the minimum value (onset of Region II, at $\Delta x_{\min}$) occurs because that is exactly the minimum spring compression that gives the block the minimum speed needed to maintain contact with the track through point B (from part (c)).

Question 2

2019 Set 1 ▪ Q2

[Figure above the question: A pendulum setup. Block 1 (labeled "Block 1") is attached via a "String" of length L to a pivot, shown horizontal at the top with the string making angle θ_{MAX} with the vertical at its highest point after swinging (dashed arc). Block 2 sits at the edge of a table of height $2L$, at the top of a support structure. The horizontal distance from the base of the table to the landing point on the floor is $4L$ (dashed box shown on the floor at that distance). Labels: "Mass of Block 1 $= 3M$", "Mass of Block 2 $= M$". Note: Figure not drawn to scale.]

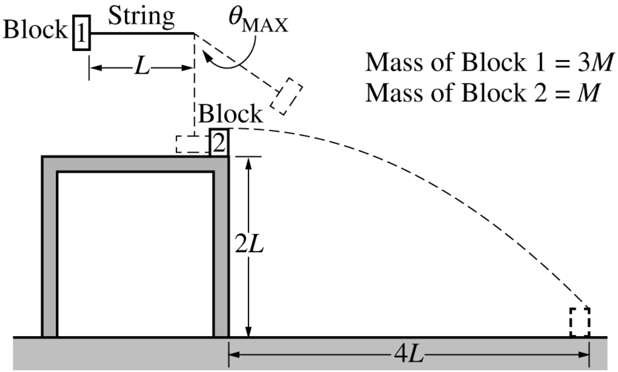
A pendulum of length L consists of block 1 of mass $3M$ attached to the end of a string. Block 1 is released from rest with the string horizontal, as shown above. At the bottom of its swing, block 1 collides with block 2 of mass M, which is initially at rest at the edge of a table of height $2L$. Block 1 never touches the table. As a result of the collision, block 2 is launched horizontally from the table, landing on the floor a

Question 2

distance $4L$ from the base of the table. After the collision, block 1 continues forward and swings up. At its highest point, the string makes an angle θ_{MAX} to the vertical. Air resistance and friction are negligible. Express all algebraic answers in terms of M, L, and physical constants, as appropriate.

(a) Determine the speed of block 1 at the bottom of its swing just before it makes contact with block 2.

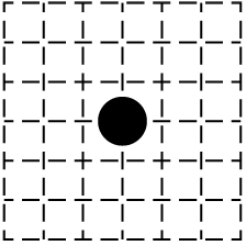
Question 2



Mass of Block 1 = $3M$
Mass of Block 2 = M

Note: Figure not drawn to scale.

Question 2



Question 2

2019 Set 1 ▪ Q2

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Question 2

the collision, block 1 continues forward and swings up. At its highest point, the string makes an angle θ_{MAX} to the vertical. Air resistance and friction are negligible. Express all algebraic answers in terms of M, L, and physical constants, as appropriate.

(b) On the dot below, which represents block 1, draw and label the forces (not components) that act on block 1 just before it makes contact with block 2. Each force must be represented by a distinct arrow starting on, and pointing away from, the dot. Forces with greater magnitude should be represented by longer vectors.

[A dot on a dashed grid, representing block 1, for the student to draw force vectors on.]

Question 2

2019 Set 1 ▪ Q2

[Figure above the question: A pendulum setup. Block 1 (labeled "Block 1") is attached via a "String" of length L to a pivot, shown horizontal at the top with the string making angle θ_{MAX} with the vertical at its highest point after swinging (dashed arc). Block 2 sits at the edge of a table of height $2L$, at the top of a support structure. The horizontal distance from the base of the table to the landing point on the floor is $4L$ (dashed box shown on the floor at that distance). Labels: "Mass of Block 1 = $3M$", "Mass of Block 2 = M". Note: Figure not drawn to scale.]

A pendulum of length L consists of block 1 of mass $3M$ attached to the end of a string. Block 1 is released from rest with the string horizontal, as shown above. At the bottom of its swing, block 1 collides with block 2 of mass M, which is initially at rest at the edge of a table of height $2L$. Block 1 never touches the table. As a result of the collision, block 2 is launched horizontally from the table, landing on the floor a distance $4L$ from the base of the table. After

Question 2

the collision, block 1 continues forward and swings up. At its highest point, the string makes an angle θ_{MAX} to the vertical. Air resistance and friction are negligible. Express all algebraic answers in terms of M, L, and physical constants, as appropriate.

(c) Derive an expression for the tension F_T in the string when the string is vertical just before block 1 makes contact with block 2. If you need to draw anything other than what you have shown in part (b) to assist in your solution, use the space below. Do NOT add anything to the figure in part (b).

For parts (d)–(g), the value for the length of the pendulum is $L = 75$ cm.

Question 2

2019 Set 1 ▪ Q2

[Figure above the question: A pendulum setup. Block 1 (labeled "Block 1") is attached via a "String" of length L to a pivot, shown horizontal at the top with the string making angle θ_{MAX} with the vertical at its highest point after swinging (dashed arc). Block 2 sits at the edge of a table of height $2L$, at the top of a support structure. The horizontal distance from the base of the table to the landing point on the floor is $4L$ (dashed box shown on the floor at that distance). Labels: "Mass of Block 1 = $3M$", "Mass of Block 2 = M". Note: Figure not drawn to scale.]

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Question 2

the collision, block 1 continues forward and swings up. At its highest point, the string makes an angle θ_{MAX} to the vertical. Air resistance and friction are negligible. Express all algebraic answers in terms of M, L, and physical constants, as appropriate.

(d) Calculate the time between the instant block 2 leaves the table and the instant it first contacts the floor.

Question 2

2019 Set 1 ▪ Q2

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Question 2

the collision, block 1 continues forward and swings up. At its highest point, the string makes an angle θ_{MAX} to the vertical. Air resistance and friction are negligible. Express all algebraic answers in terms of M, L, and physical constants, as appropriate.

(e) Calculate the speed of block 2 as it leaves the table.

Question 2

2019 Set 1 ▪ Q2

[Figure above the question: A pendulum setup. Block 1 (labeled "Block 1") is attached via a "String" of length L to a pivot, shown horizontal at the top with the string making angle θ_{MAX} with the vertical at its highest point after swinging (dashed arc). Block 2 sits at the edge of a table of height $2L$, at the top of a support structure. The horizontal distance from the base of the table to the landing point on the floor is $4L$ (dashed box shown on the floor at that distance). Labels: "Mass of Block 1 = $3M$", "Mass of Block 2 = M". Note: Figure not drawn to scale.]

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Question 2

the collision, block 1 continues forward and swings up. At its highest point, the string makes an angle θ_{MAX} to the vertical. Air resistance and friction are negligible. Express all algebraic answers in terms of M, L, and physical constants, as appropriate.

(f) Calculate the speed of block 1 just after it collides with block 2.

Question 2

2019 Set 1 ▪ Q2

[Figure above the question: A pendulum setup. Block 1 (labeled "Block 1") is attached via a "String" of length L to a pivot, shown horizontal at the top with the string making angle θ_{MAX} with the vertical at its highest point after swinging (dashed arc). Block 2 sits at the edge of a table of height $2L$, at the top of a support structure. The horizontal distance from the base of the table to the landing point on the floor is $4L$ (dashed box shown on the floor at that distance). Labels: "Mass of Block 1 = $3M$", "Mass of Block 2 = M". Note: Figure not drawn to scale.]

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Question 2

the collision, block 1 continues forward and swings up. At its highest point, the string makes an angle θ_{MAX} to the vertical. Air resistance and friction are negligible. Express all algebraic answers in terms of M, L, and physical constants, as appropriate.

(g) Calculate the angle θ_{MAX} that the string makes with the vertical, as shown in the original figure, when block 1 is at its highest point after the collision.

Solution 2

(a)

Mark scheme

- Energy conservation for block 1's swing:
  $U_{g1} = K_2 \Rightarrow mgh = \frac{1}{2}mv^2 \Rightarrow gL = \frac{1}{2}v^2 \Rightarrow v = \sqrt{2gL}$. Full credit even if no work is shown.

Solution 2

(b)

Mark scheme

- Draw two vectors from the dot: the weight F_W pointing straight down, and the string tension F_T pointing straight up, with the tension arrow drawn noticeably LONGER than the weight arrow (net force must be upward/centripetal). 1 pt for correctly drawing and labeling both the weight and the tension; 1 pt for drawing the tension longer than the weight. Only a maximum of 1 point can be earned if any extraneous vectors are included.

Solution 2

(c)

Mark scheme

- Use Newton's second law along the string direction, tension minus weight equals centripetal force (1 pt):
  $F_T = mg + ma_c = mg + \frac{mv^2}{r} = 3Mg + \frac{(3M)(\sqrt{2gL})^2}{L}$. Correct final answer (1 pt): $F_T = 9Mg$.

Solution 2

(d) Mark scheme

- Use a correct kinematic equation for the vertical fall from table height $2L$ (1 pt): $\Delta y = v_i t + \frac{1}{2}at^2 = \frac{1}{2}at^2 \Rightarrow t = \sqrt{\frac{2\Delta y}{a}} = \sqrt{\frac{2(2L)}{g}} = \sqrt{\frac{4(0.75\text{ m})}{9.8\text{ m/s}^2}}$. Correct final answer (1 pt): $t = 0.55$ s.

Solution 2

(e)

Mark scheme

- Use a correct kinematic equation for the horizontal (projectile) motion (1 pt): $\Delta x = vt \Rightarrow v = \frac{\Delta x}{t} = \frac{4L}{t}$. Substitute the time from part (d) (1 pt): $v = \frac{(4)(0.75\ \mathrm{m})}{0.55\ \mathrm{s}} = 5.45\ \mathrm{m/s}$.

Solution 2

(f) Mark scheme

- Use conservation of momentum for the collision (1 pt): $p_i = p_f \Rightarrow m_1 v_{1i} + m_2 v_{2i} = m_1 v_{1f} + m_2 v_{2f}$. Correctly substitute the masses (1 pt): $(3M)v_{1i} + 0 = (3M)v_{1f} + (M)v_{2f}$. Substitute the speeds found in parts (a) and (e) (1 pt): $v_{1f} = \dfrac{(3M)v_{1i} - (M)v_{2f}}{3M} = \dfrac{(3M)\sqrt{2gL} - (M)v_{2f}}{3M}$, giving $v_{1f} = \dfrac{3\sqrt{2(9.8)(0.75)} - (1)(5.45)}{3} = 2.02$ m/s (or $v_{1f} = 2.06$ m/s using $g = 10$ m/s^2).

Solution 2

(g) Mark scheme

- Use conservation of energy for block 1's rise after the collision (1 pt): $K_1 = U_{g2} \Rightarrow \frac{1}{2}mv^2 = mgh$. Correctly substitute $h = L(1-\cos\theta)$ (1 pt): $\frac{1}{2}mv^2 = mgL(1-\cos\theta) \Rightarrow \dfrac{v^2}{2gL} = 1-\cos\theta$. Substitute the speed found in part (f) (1 pt): $\theta = \cos^{-1}\left(1-\dfrac{v^2}{2gL}\right) = \cos^{-1}\left(1-\dfrac{(2.02)^2}{2(9.8)(0.75)}\right) = 43.5^\circ$ (or $\theta = 44.1^\circ$ using $g = 10\ \text{m/s}^2$).

Question 3

2017 ▪ Q3

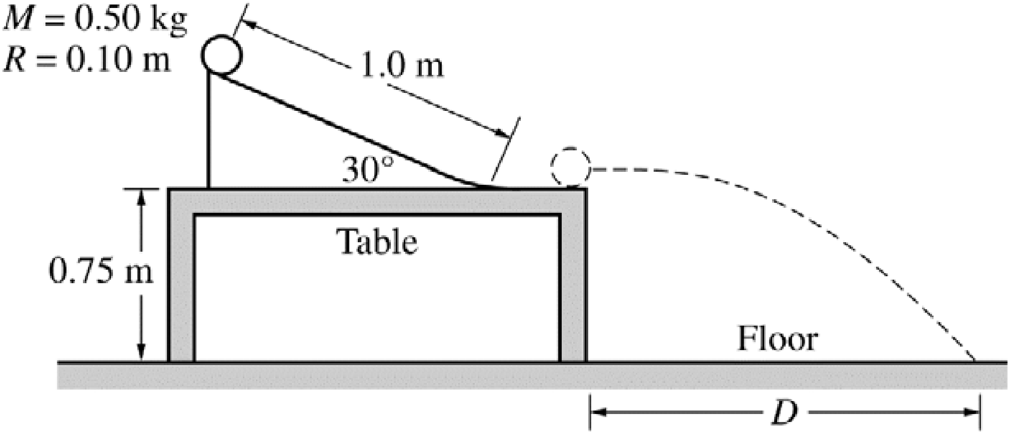
[Figure: A uniform solid cylinder of mass $M = 0.50$ kg and radius $R = 0.10$ m sits at the top of a 1.0 m long inclined plane making a $30°$ angle with the horizontal. The incline descends onto a table of height 0.75 m. The cylinder rolls down the incline, across the table, and launches horizontally off the edge of the table, following a projectile path (shown dashed) to land on the floor a horizontal distance D from the edge of the table. A coiled spring/bumper is shown mounted at the far right on the floor.]

A uniform solid cylinder of mass $M = 0.50$ kg and radius $R = 0.10$ m is released from rest, rolls without slipping down a 1.0 m long inclined plane, and is launched horizontally from a horizontal table of height 0.75 m. The inclined plane makes an angle of $30°$ with the horizontal. The cylinder lands on the floor a distance D away from the edge of the table, as shown in the figure above. There is a smooth transition

Question 3

from the inclined plane to the horizontal table, and the motion occurs with no frictional energy losses. The rotational inertia of a cylinder around its center is $MR^2/2$.
(a) Calculate the total kinetic energy of the cylinder as it reaches the horizontal table.

Question 3



Question 3

2017 ▪ Q3

[Figure: A uniform solid cylinder of mass $M = 0.50$ kg and radius $R = 0.10$ m sits at the top of a 1.0 m long inclined plane making a $30°$ angle with the horizontal. The incline descends onto a table of height 0.75 m. The cylinder rolls down the incline, across the table, and launches horizontally off the edge of the table, following a projectile path (shown dashed) to land on the floor a horizontal distance D from the edge of the table. A coiled spring/bumper is shown mounted at the far right on the floor.]

A uniform solid cylinder of mass $M = 0.50$ kg and radius $R = 0.10$ m is released from rest, rolls without slipping down a 1.0 m long inclined plane, and is launched horizontally from a horizontal table of height 0.75 m. The inclined plane makes an angle of $30°$ with the horizontal. The cylinder lands on the floor a distance D away from the edge of the table, as shown in the figure above. There is a smooth transition from the inclined plane to the

Question 3

horizontal table, and the motion occurs with no frictional energy losses. The rotational inertia of a cylinder around its center is $MR^2/2$.

(b) Calculate the angular velocity of the cylinder around its axis at the moment it reaches the floor.

Question 3

2017 ▪ Q3

[Figure: A uniform solid cylinder of mass $M = 0.50$ kg and radius $R = 0.10$ m sits at the top of a 1.0 m long inclined plane making a $30°$ angle with the horizontal. The incline descends onto a table of height 0.75 m. The cylinder rolls down the incline, across the table, and launches horizontally off the edge of the table, following a projectile path (shown dashed) to land on the floor a horizontal distance D from the edge of the table. A coiled spring/bumper is shown mounted at the far right on the floor.]

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Question 3

horizontal table, and the motion occurs with no frictional energy losses. The rotational inertia of a cylinder around its center is $MR^2/2$.

(c) Calculate the ratio of the rotational kinetic energy to the total kinetic energy for the cylinder at the moment it reaches the floor.

Question 3

2017 ▪ Q3

[Figure: A uniform solid cylinder of mass $M = 0.50$ kg and radius $R = 0.10$ m sits at the top of a 1.0 m long inclined plane making a $30°$ angle with the horizontal. The incline descends onto a table of height 0.75 m. The cylinder rolls down the incline, across the table, and launches horizontally off the edge of the table, following a projectile path (shown dashed) to land on the floor a horizontal distance D from the edge of the table. A coiled spring/bumper is shown mounted at the far right on the floor.]

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Question 3

horizontal table, and the motion occurs with no frictional energy losses. The rotational inertia of a cylinder around its center is $MR^2/2$.

(d) Calculate the horizontal distance D.

A sphere of the same mass and radius is now rolled down the same inclined plane. The rotational inertia of a sphere around its center is $\frac{2}{5}MR^2$.

Question 3

2017 ▪ Q3

[Figure: A uniform solid cylinder of mass $M = 0.50$ kg and radius $R = 0.10$ m sits at the top of a 1.0 m long inclined plane making a $30°$ angle with the horizontal. The incline descends onto a table of height 0.75 m. The cylinder rolls down the incline, across the table, and launches horizontally off the edge of the table, following a projectile path (shown dashed) to land on the floor a horizontal distance D from the edge of the table. A coiled spring/bumper is shown mounted at the far right on the floor.]

A uniform solid cylinder of mass $M = 0.50$ kg and radius $R = 0.10$ m is released from rest, rolls without slipping down a 1.0 m long inclined plane, and is launched horizontally from a horizontal table of height 0.75 m. The inclined plane makes an angle of $30°$ with the horizontal. The cylinder lands on the floor a distance D away from the edge of the table, as shown in the figure above. There is a smooth transition from the inclined plane to the

Question 3

horizontal table, and the motion occurs with no frictional energy losses. The rotational inertia of a cylinder around its center is $MR^2/2$.

(e)(i) Is the total kinetic energy of the sphere at the moment it reaches the floor greater than, less than, or equal to the total kinetic energy of the cylinder at the moment it reaches the floor?

_____ Greater than _____ Less than _____ Equal to

Justify your answer.

(e)(ii) Is the rotational kinetic energy of the sphere at the moment it reaches the floor greater than, less than, or equal to the rotational kinetic energy of the cylinder at the moment it reaches the floor?

_____ Greater than _____ Less than _____ Equal to

Justify your answer.

Question 3

(e)(iii) Is the horizontal distance the sphere travels from the table to where it hits the floor greater than, less than, or equal to the horizontal distance the cylinder travels from the table to where it hits the floor?

_____ Greater than _____ Less than _____ Equal to

Justify your answer.

Solution 3

(a)

Mark scheme

- Using conservation of energy from the top of the incline to the bottom (table level): $U_{g,top} = K_{table}$, i.e. $mgh = K_{table}$, where $h = L\sin\theta = (1.0\ \mathrm{m})\sin 30^\circ = 0.50\ \mathrm{m}$. So $K_{table} = mgh = (0.50\ \mathrm{kg})(9.8\ \mathrm{m/s^2})(1.0\ \mathrm{m})(\sin 30^\circ) = 2.45\ \mathrm{J}$ (or $2.5\ \mathrm{J}$ using $g = 10\ \mathrm{m/s^2}$). 1 point for correctly applying conservation of energy, 1 point for the correct numeric answer with units.

Solution 3

(b) Mark scheme

- Total KE is translational plus rotational: $K = \frac{1}{2}mv^2 + \frac{1}{2}I\omega^2$. For a cylinder, $I = \frac{1}{2}MR^2$ and $v = R\omega$, so $K = \frac{1}{2}M(R\omega)^2 + \frac{1}{2}\left(\frac{1}{2}MR^2\right)\omega^2 = \frac{1}{2}M(R\omega)^2 + \frac{1}{4}M(R\omega)^2 = \frac{3}{4}M(R\omega)^2$. Solving for ω: $\omega = \sqrt{\frac{4K}{3MR^2}} = \sqrt{\frac{4(2.45\ \mathrm{J})}{3(0.50\ \mathrm{kg})(0.10\ \mathrm{m})^2}} = 25.6\ \mathrm{rad/s}$ (or $26.0\ \mathrm{rad/s}$ using $g = 10\ \mathrm{m/s^2}$ and $K = 2.5\ \mathrm{J}$). 1 point for correctly writing K as translational plus

Solution 3

rotational KE, 1 point for correctly substituting $v = R\omega$ and $I = \frac{1}{2}MR^2$, 1 point for the correct numeric answer.

Solution 3

(c) Mark scheme

- No torque acts on the cylinder during its fall off the table (only gravity, through the center of mass), so the rotational KE at the floor equals the rotational KE at the table edge: $K_{rot} = \frac{1}{4}M(R\omega)^2$. The total KE at the floor equals the total KE at the table ($K_{table} = \frac{3}{4}M(R\omega)^2$) plus the additional KE gained by falling the table height $h_{table} = 0.75\ \mathrm{m}$: $K_{tot} = \frac{3}{4}M(R\omega)^2 + Mgh_{table}$. So $\frac{K_{rot}}{K_{tot}} = \frac{(R\omega)^2}{3(R\omega)^2 + 4gh_{table}} = \frac{[(0.10\ \mathrm{m})(25.6\ \mathrm{rad/s})]^2}{3[(0.10)(25.6)]^2 + 4(9.81\ \mathrm{m/s^2})(0.75\ \mathrm{m})} = 0.133$ (or 0.135 using $g = 10\ \mathrm{m/s^2}$). [Equivalent alternate approach given in the scoring

Solution 3

guideline: $K_{rot}/U_{total} = \dfrac{1}{4}(R\omega)^2/[g(h+y)]$, using the total incline-plus-table height drop, gives the same ≈ 0.13.] 1 point for a correct ratio expression, 1 point for the correct substituted numeric answer.

Solution 3

(d) Mark scheme

- Vertical motion (free fall from the table, height $y = 0.75\ \mathrm{m}$): $y = \frac{1}{2}gt^2 \Rightarrow t = \sqrt{\frac{2y}{g}} = \sqrt{\frac{2(0.75\ \mathrm{m})}{9.81\ \mathrm{m/s^2}}} = 0.39\ \mathrm{s}$. Horizontal motion (constant velocity $v = R\omega$, no horizontal force during the fall): $D = (R\omega)t = (0.10\ \mathrm{m})(25.6\ \mathrm{rad/s})(0.39\ \mathrm{s}) = 1.0\ \mathrm{m}$. 1 point for correctly finding the fall time from vertical kinematics, 1 point for correctly using $D = R\omega t$ to get $D = 1.0\ \mathrm{m}$.

Solution 3

(e)(i)

Mark scheme

- Correct answer: Equal to. By conservation of energy, the total KE at the floor equals the total gravitational PE lost, $Mg(h+y)$. Since the sphere has the same mass and falls through the same total height as the cylinder, its total KE at the floor is the same as the cylinder's. 1 point for selecting 'Equal to' with an attempted relevant justification, 1 point for a fully correct justification.

Solution 3

(e)(ii) Mark scheme

- Correct answer: Less than. Because the sphere's rotational inertia is less than the cylinder's, the sphere rotates faster and, since $v = R\omega$ for rolling without slipping, moves with a greater linear speed. Because the mass is the same and the linear speed is greater, the sphere has greater linear (translational) kinetic energy. Since the total kinetic energies of the sphere and cylinder at the floor are equal (part i), the sphere must therefore have LESS rotational kinetic energy than the cylinder. 1 point for selecting 'Less than' with an attempted relevant justification, 1 point for a fully correct justification.

Solution 3

(e)(iii)

Mark scheme

- Correct answer: Greater than. Since the sphere has a greater linear speed than the cylinder as it leaves the table (from part ii), and both fall through the same height in the same time, the sphere travels a greater horizontal distance $D = vt$ before reaching the floor than the cylinder does. 1 point for selecting 'Greater than' with an attempted relevant justification, 1 point for a fully correct justification.

Question 2

2015 ▪ Q2

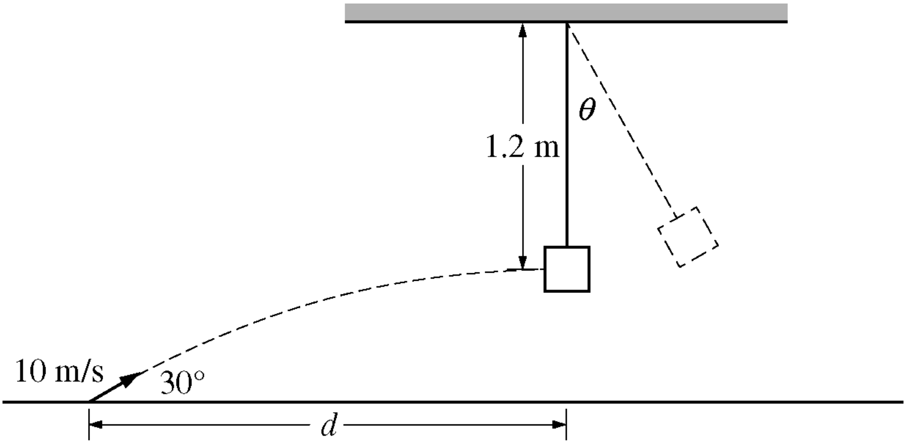
A small dart of mass 0.020 kg is launched at an angle of 30° above the horizontal with an initial speed of 10 m/s. At the moment it reaches the highest point in its path and is moving horizontally, it collides with and sticks to a wooden block of mass 0.10 kg that is suspended at the end of a massless string. The center of mass of the block is 1.2 m below the pivot point of the string. The block and dart then swing up until the string makes an angle θ with the vertical, as shown above. Air resistance is negligible. [Diagram: A ceiling (hatched bar) with a string of length 1.2 m hanging straight down to a small square block. A dashed line at angle θ from the vertical string shows the block's swung-up position (dashed square), with θ marked at the pivot between the vertical string and the dashed string. Below, a dart is launched from the ground at 10 m/s at 30° above the horizontal (arrow labeled "10 m/s" with angle "30°" marked from the horizontal ground line); a dashed curved trajectory arcs up from the launch

Question 2

point to the block, reaching the block moving horizontally at the top of its arc. A horizontal distance d is marked along the ground from the dart's launch point to the point on the floor directly below the block.]

(a) Determine the speed of the dart just before it strikes the block.

Question 2



Question 2

2015 ▪ Q2

A small dart of mass 0.020 kg is launched at an angle of 30° above the horizontal with an initial speed of 10 m/s. At the moment it reaches the highest point in its path and is moving horizontally, it collides with and sticks to a wooden block of mass 0.10 kg that is suspended at the end of a massless string. The center of mass of the block is 1.2 m below the pivot point of the string. The block and dart then swing up until the string makes an angle θ with the vertical, as shown above. Air resistance is negligible.

[Diagram: A ceiling (hatched bar) with a string of length 1.2 m hanging straight down to a small square block. A dashed line at angle θ from the vertical string shows the block's swung-up position (dashed square), with θ marked at the pivot between the vertical string and the dashed string. Below, a dart is launched from the ground at 10 m/s at 30° above the horizontal (arrow labeled "10 m/s" with angle "30°" marked from the horizontal ground line); a dashed curved trajectory arcs up from the launch point to the block, reaching the block

Question 2

moving horizontally at the top of its arc. A horizontal distance d is marked along the ground from the dart's launch point to the point on the floor directly below the block.]

(b) Calculate the horizontal distance d between the launching point of the dart and a point on the floor directly below the block.

Question 2

2015 ▪ Q2

A small dart of mass 0.020 kg is launched at an angle of 30° above the horizontal with an initial speed of 10 m/s. At the moment it reaches the highest point in its path and is moving horizontally, it collides with and sticks to a wooden block of mass 0.10 kg that is suspended at the end of a massless string. The center of mass of the block is 1.2 m below the pivot point of the string. The block and dart then swing up until the string makes an angle θ with the vertical, as shown above. Air resistance is negligible.

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Question 2

moving horizontally at the top of its arc. A horizontal distance d is marked along the ground from the dart's launch point to the point on the floor directly below the block.]

(c) Calculate the speed of the block just after the dart strikes.

Question 2

2015 ▪ Q2

A small dart of mass 0.020 kg is launched at an angle of 30° above the horizontal with an initial speed of 10 m/s. At the moment it reaches the highest point in its path and is moving horizontally, it collides with and sticks to a wooden block of mass 0.10 kg that is suspended at the end of a massless string. The center of mass of the block is 1.2 m below the pivot point of the string. The block and dart then swing up until the string makes an angle θ with the vertical, as shown above. Air resistance is negligible.

[Diagram: A ceiling (hatched bar) with a string of length 1.2 m hanging straight down to a small square block. A dashed line at angle θ from the vertical string shows the block's swung-up position (dashed square), with θ marked at the pivot between the vertical string and the dashed string. Below, a dart is launched from the ground at 10 m/s at 30° above the horizontal (arrow labeled "10 m/s" with angle "30°" marked from the horizontal ground line); a dashed curved trajectory arcs up from the launch point to the block, reaching the block

Question 2

moving horizontally at the top of its arc. A horizontal distance d is marked along the ground from the dart's launch point to the point on the floor directly below the block.]

(d) Calculate the angle θ through which the dart and block on the string will rise before coming momentarily to rest.

Question 2

2015 ▪ Q2

A small dart of mass 0.020 kg is launched at an angle of 30° above the horizontal with an initial speed of 10 m/s. At the moment it reaches the highest point in its path and is moving horizontally, it collides with and sticks to a wooden block of mass 0.10 kg that is suspended at the end of a massless string. The center of mass of the block is 1.2 m below the pivot point of the string. The block and dart then swing up until the string makes an angle θ with the vertical, as shown above. Air resistance is negligible.

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Question 2

moving horizontally at the top of its arc. A horizontal distance d is marked along the ground from the dart's launch point to the point on the floor directly below the block.]

(e) The block then continues to swing as a simple pendulum. Calculate the time between when the dart collides with the block and when the block first returns to its original position.

Question 2

2015 ▪ Q2

A small dart of mass 0.020 kg is launched at an angle of 30° above the horizontal with an initial speed of 10 m/s. At the moment it reaches the highest point in its path and is moving horizontally, it collides with and sticks to a wooden block of mass 0.10 kg that is suspended at the end of a massless string. The center of mass of the block is 1.2 m below the pivot point of the string. The block and dart then swing up until the string makes an angle θ with the vertical, as shown above. Air resistance is negligible.

[Diagram: A ceiling (hatched bar) with a string of length 1.2 m hanging straight down to a small square block. A dashed line at angle θ from the vertical string shows the block's swung-up position (dashed square), with θ marked at the pivot between the vertical string and the dashed string. Below, a dart is launched from the ground at 10 m/s at 30° above the horizontal (arrow labeled "10 m/s" with angle "30°" marked from the horizontal ground line); a dashed curved trajectory arcs up from the launch point to the block, reaching the block

Question 2

moving horizontally at the top of its arc. A horizontal distance d is marked along the ground from the dart's launch point to the point on the floor directly below the block.]

(f) In a second experiment, a dart with more mass is launched at the same speed and angle. The dart collides with and sticks to the same wooden block.

(f)(i) Would the angle θ that the dart and block swing to increase, decrease, or stay the same?

$I^{ncrease}{}_{D}{}^{ecrease}{}_{S}{}^{taythesame}$

Justify your answer.

(f)(ii) Would the period of oscillation after the collision increase, decrease, or stay the same?

_______ Increase _______ Decrease _______ Stay the same

Justify your answer.

Question 3

2014 ▪ Q3

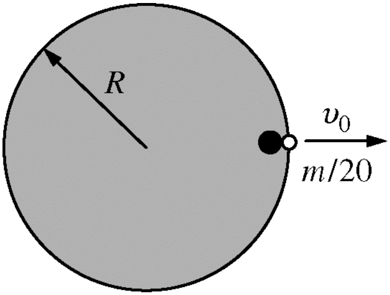
[Figure, Top View: A large filled circle of radius R (labelled with an arrow from center to edge) representing a disk, with a small stone of mass $m/20$ shown just outside the edge of the disk moving away with velocity v_0 (arrow labelled v_0, $m/20$).]
[Figure, Side View: A person holding a stone stands atop a raised platform of height h above the ground, throwing the stone horizontally with initial speed v_0 (arrow labelled v_0); h is marked as the vertical distance from the platform surface to the ground.]
Mech. 3.
A large circular disk of mass m and radius R is initially stationary on a horizontal icy surface. A person of mass $m/2$ stands on the edge of the disk. Without slipping on the disk, the person throws a large stone of mass $m/20$ horizontally at initial speed v_0 from a height h above the ice in a radial direction, as shown in the figures above. The coefficient of friction between the disk and the ice is μ. All velocities are measured

Question 3

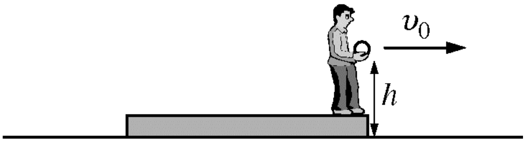
relative to the ground. The time it takes to throw the stone is negligible. Express all algebraic answers in terms of m, R, v_0, h, μ, and fundamental constants, as appropriate.

(a) Derive an expression for the length of time it will take the stone to strike the ice.

Question 3

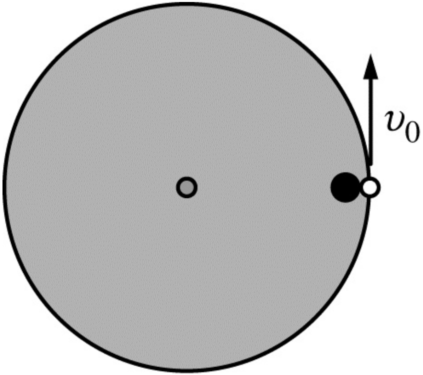


Top View



Side View

Question 3



Top View

Question 3

2014 ▪ Q3

[Figure, Top View: A large filled circle of radius R (labelled with an arrow from center to edge) representing a disk, with a small stone of mass $m/20$ shown just outside the edge of the disk moving away with velocity v_0 (arrow labelled v_0, $m/20$).]
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Question 3

the stone is negligible. Express all algebraic answers in terms of m, R, v_0, h, μ, and fundamental constants, as appropriate.

(b) Assuming that the disk is free to slide on the ice, derive an expression for the speed of the disk and person immediately after the stone is thrown.

Question 3

2014 ▪ Q3

[Figure, Top View: A large filled circle of radius R (labelled with an arrow from center to edge) representing a disk, with a small stone of mass $m/20$ shown just outside the edge of the disk moving away with velocity v_0 (arrow labelled v_0, $m/20$).]
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Question 3

the stone is negligible. Express all algebraic answers in terms of m, R, v_0, h, μ, and fundamental constants, as appropriate.

(c) Derive an expression for the time it will take the disk to stop sliding.

Question 3

2014 ▪ Q3

[Figure, Top View: A large filled circle of radius R (labelled with an arrow from center to edge) representing a disk, with a small stone of mass $m/20$ shown just outside the edge of the disk moving away with velocity v_0 (arrow labelled v_0, $m/20$).]
[Figure, Side View: A person holding a stone stands atop a raised platform of height h above the ground, throwing the stone horizontally with initial speed v_0 (arrow labelled v_0); h is marked as the vertical distance from the platform surface to the ground.]
Mech. 3.

A large circular disk of mass m and radius R is initially stationary on a horizontal icy surface. A person of mass $m/2$ stands on the edge of the disk. Without slipping on the disk, the person throws a large stone of mass $m/20$ horizontally at initial speed v_0 from a height h above the ice in a radial direction, as shown in the figures above. The coefficient of friction between the disk and the ice is μ. All velocities are measured relative to the ground. The time it takes to throw

Question 3

the stone is negligible. Express all algebraic answers in terms of m, R, v_0, h, μ, and fundamental constants, as appropriate.

(d) [Figure, Top View: A large filled circle (disk) with a small open circle marking its center, and a small stone (filled circle) at the edge of the disk moving tangentially with velocity v_0 (arrow labelled v_0 pointing tangent to the circle at the edge point).]

The person now stands on a similar disk of mass m and radius R that has a fixed pole through its center so that it can only rotate on the ice. The person throws the same stone horizontally in a tangential direction at initial speed v_0, as shown in the figure above. The rotational inertia of the disk is $mR^2/2$.

Derive an expression for the angular speed ω of the disk immediately after the stone is thrown.

Question 3

2014 ▪ Q3

[Figure, Top View: A large filled circle of radius R (labelled with an arrow from center to edge) representing a disk, with a small stone of mass $m/20$ shown just outside the edge of the disk moving away with velocity v_0 (arrow labelled v_0, $m/20$).]
[Figure, Side View: A person holding a stone stands atop a raised platform of height h above the ground, throwing the stone horizontally with initial speed v_0 (arrow labelled v_0); h is marked as the vertical distance from the platform surface to the ground.]
Mech. 3.

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Question 3

the stone is negligible. Express all algebraic answers in terms of m, R, v_0, h, μ, and fundamental constants, as appropriate.

(e) The person now stands on the disk at rest $R/2$ from the center of the disk. The person now throws the stone horizontally with a speed v_0 in the same direction as in part (d). Is the angular speed of the disk immediately after throwing the stone from this new position greater than, less than, or equal to the angular speed found in part (d)?

_____ Greater than _____ Less than _____ Equal to

Justify your answer.