Past-paper walk-through

Kinetic and Static Friction ▪ 2.7

eXercise

Questions in this set

- 2026 Q1
- 2026 Q3
- 2025 Q2
- 2025 Q3
- 2025 Q4
- 2023 Set 1 Q3
- 2022 Set 1 Q1
- 2022 Set 2 Q1
- 2021 Set 2 Q1
- 2019 Set 2 Q1

Questions in this set

- 2018 Q3
- 2017 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 1

2026 ▪ Q1

A box of mass M slides to the right on a horizontal surface. A small cube, also of mass M, is inside the box. The cube is against the right wall of the box and above the bottom of the box, as shown in Figure 1. The coefficients of static and kinetic friction between the cube and the wall of the box are μ_s and μ_k, respectively, where $\mu_s > \mu_k$. [Figure 1: Side view diagram. A box labeled "Box, M" slides to the right (shown by motion lines and arrows on the left). Inside the box, a small shaded cube labeled "Cube" and "M" rests against the inside of the right wall of the box, above the bottom of the box, labeled with μ_s, μ_k at the contact surface. An arrow labeled $\vec{F}_R$ points left, into the box, from the right side, representing the resistive force on the box.]
The speed of the box is decreasing as a result of a resistive force that is exerted on the box. The resistive force $\vec{F}_R$ is modeled by $\vec{F}_R = -b\vec{v}$, where b is a positive constant

Question 1

and $\vec{v}$ is the velocity of the box. Friction between the box and horizontal surface is negligible.

Consider the motion of the box and cube for the following times.

- At time $t = 0$, the box-cube system slides to the right with speed v_0. - For $0 \leq t < t_{\text{crit}}$, the cube remains in contact with the wall of the box at a constant height above the bottom of the box. - At $t = t_{\text{crit}}$, the cube begins to slide downward along the wall of the box.

(a)(i) The magnitude of the normal force exerted on the cube by the wall of the box is F_N.

Determine an expression for the magnitude of the acceleration of the cube. Express your answer in terms of M, F_N, and physical constants, as appropriate.

(a)(ii) Derive an expression for F_N as a function of t from $t = 0$ until immediately before the cube reaches the bottom of the box. Express your answer in terms of M, b,

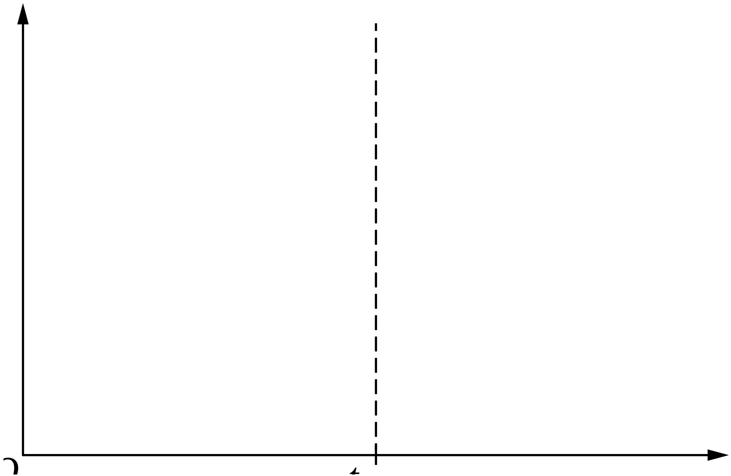
Question 1

v_0, t, and physical constants, as appropriate. Begin your derivation with a fundamental physics principle or an equation from the reference information.

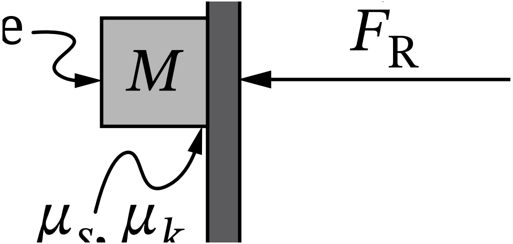
(a)(iii) On the axes shown in Figure 2, **sketch** a graph of the magnitude F_f of the frictional force exerted on the cube by the wall of the box as a function of t from $t = 0$ until immediately before the cube reaches the bottom of the box.

[Figure 2: A blank graph with vertical axis labeled F_f and horizontal axis labeled t, origin labeled O. A vertical dashed line on the horizontal axis is labeled t_{crit}.]

Question 1



Question 1



Question 1

Question 1

2026 ▪ Q1

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The speed of the box is decreasing as a result of a resistive force that is exerted on the box. The resistive force $\vec{F}_R$ is modeled by $\vec{F}_R = -b\vec{v}$, where b is a positive constant and $\vec{v}$ is the velocity of the box. Friction between the box and horizontal surface is negligible.
Consider the motion of the box and cube for the following times.

Question 1

- At time $t = 0$, the box-cube system slides to the right with speed v_0. - For $0 \leq t < t_{\text{crit}}$, the cube remains in contact with the wall of the box at a constant height above the bottom of the box. - At $t = t_{\text{crit}}$, the cube begins to slide downward along the wall of the box.

(b) **Derive** an expression for t_{crit} in terms of M, b, μ_s, v_0, and physical constants, as appropriate. Begin your derivation with a fundamental physics principle or an equation from the reference information.

Question 3

2026 ▪ Q3

The following information applies to parts A and B.

A horizontal spring of known spring constant k is attached to a wall. A block of known mass m is placed on a horizontal surface next to but not attached to the spring. The spring is at its relaxed length when the block is at position $x = 0$, as shown in Figure 1. There is friction between the block and the surface only for positions $x > 0$.

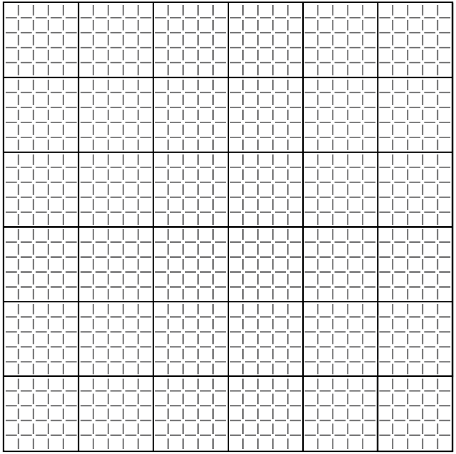
[Figure 1: A horizontal diagram with a $+x$ axis arrow pointing right at the top. A spring with spring constant k is attached to a wall on the left and connects to a block labeled m. To the right of the block (for $x > 0$), the surface is marked with a squiggly friction symbol and labeled μ_k. Below the block is the label $x = 0$.]

A student is asked to experimentally determine the coefficient of kinetic friction μ_k between the block and the surface using a graph. The student is permitted to use only measurements from a meterstick.

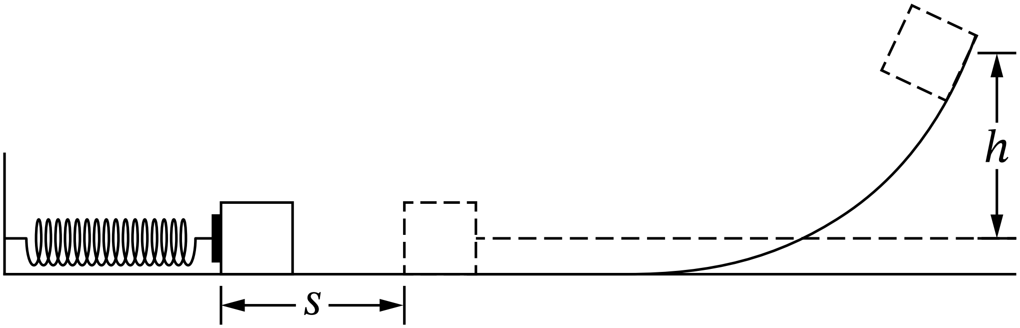
Question 3

(a)(i) Indicate quantities that could be measured by the student that would allow them to determine μ_k using a graph.
(a)(ii) Briefly **describe** a method to reduce experimental uncertainty for the measured quantities.

Question 3



Question 3



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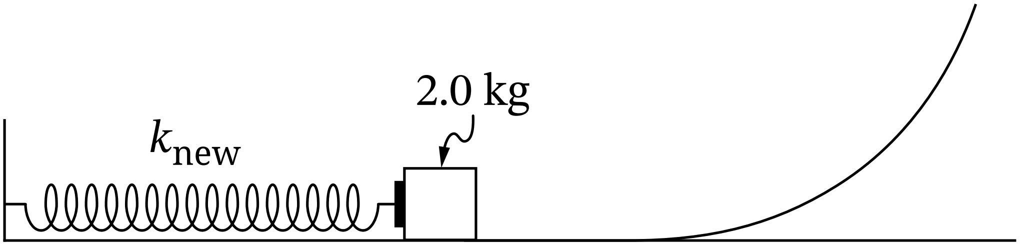

Question 3

2026 ▪ Q3

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A student is asked to experimentally determine the coefficient of kinetic friction μ_k between the block and the surface using a graph. The student is permitted to use only measurements from a meterstick.

Question 3

(b)(i) Indicate what quantities the student could graph on the horizontal and vertical axes to create a graph that can be used to determine μ_k.
(b)(ii) Briefly **describe** the relationship between μ_k and a feature of the graph from part B (i). Your answer may include an equation that relates μ_k and the chosen feature of the graph.

Question 3

2026 ▪ Q3

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[Figure 1: A horizontal diagram with a $+x$ axis arrow pointing right at the top. A spring with spring constant k is attached to a wall on the left and connects to a block labeled m. To the right of the block (for $x > 0$), the surface is marked with a squiggly friction symbol and labeled μ_k. Below the block is the label $x = 0$.]

A student is asked to experimentally determine the coefficient of kinetic friction μ_k between the block and the surface using a graph. The student is permitted to use only measurements from a meterstick.

(c)(i)(n)(t)(r)(o) The following information applies to parts C and D.

Question 3

In a different experiment, the student is asked to determine the spring constant k_{new} of a new spring that is attached to a wall. A block of mass 2.0 kg is placed next to the spring on a surface where frictional forces are negligible. The surface is horizontal near the spring and slopes upward into a ramp to the right of the initial position of the block, as shown in Figure 2.
[Figure 2: A diagram showing a spring labeled k_{new} attached to a wall on the left, connected to a block labeled "2.0 kg" with an arrow "f" curving above it. The horizontal surface to the right of the block slopes upward into a curved ramp rising to the upper right.]
The student pushes the block, compressing the spring a distance s, as shown in Figure 3. The block is released from rest.
[Figure 3: A diagram showing the spring compressed, attached to the wall on the left and to the block, with a distance s marked by a double-arrow between the wall-side

Question 3

spring end and the block's initial (uncompressed) dashed outline position. To the right, a dashed outline of the block is shown partway up the curved ramp at height h above the horizontal surface level, with h marked by a vertical double-arrow.]

The student uses a meterstick to measure the maximum height h of the block on the ramp. The experiment is repeated several times with different compression distances s. The student's measurements of s and h are shown in Table 1.

Table 1

s (m)	h (m)
0.020	0.02
0.040	0.04
0.060	0.13
0.080	0.18
0.100	0.33

(c)(i) **Label** the axes of the grid provided with measured or calculated quantities. Include units, as appropriate. The graphed quantities should yield a linear graph that can be used to determine k_{new}.

(c)(ii) On the grid provided, create a graph of the quantities indicated in part C (i).

Question 3

- Clearly **label** the vertical and horizontal axes with numerical scales.
- **Plot** the corresponding data points on the grid.
- Table 2 is provided in your booklet for scratch work and will not be scored.

[Figure: Two blank labeled-axis lines reading "Quantity (units, if appropriate)" each with two blank underlines for axis labels, flanking a blank square grid for plotting, printed twice (before and after the grid) for the vertical and horizontal axes.]

(c)(iii) Draw a best-fit line for the data graphed in part C (ii).

Question 3

2026 ▪ Q3

The following information applies to parts A and B.

A horizontal spring of known spring constant k is attached to a wall. A block of known mass m is placed on a horizontal surface next to but not attached to the spring. The spring is at its relaxed length when the block is at position $x = 0$, as shown in Figure 1. There is friction between the block and the surface only for positions $x > 0$.

[Figure 1: A horizontal diagram with a $+x$ axis arrow pointing right at the top. A spring with spring constant k is attached to a wall on the left and connects to a block labeled m. To the right of the block (for $x > 0$), the surface is marked with a squiggly friction symbol and labeled μ_k. Below the block is the label $x = 0$.]

A student is asked to experimentally determine the coefficient of kinetic friction μ_k between the block and the surface using a graph. The student is permitted to use only measurements from a meterstick.

Question 3

(d) Using the best-fit line that you drew in part C (iii), **calculate** an experimental value for k_{new}.

Question 2

2025 ▪ Q2

In Scenario 1, a system composed of two springs, A and B, and a block of mass m is at rest on a horizontal surface. Friction between the block and the surface is negligible. Each spring is attached to a fixed wall and the block, as shown in Figure 1. Spring A has a spring constant k and Spring B has a spring constant $2k$. Each spring is at its relaxed length when the block is at position $x = 0$, as shown.
[Figure 1: Spring A (spring constant k) attached to a wall on the left, connected to a block; Spring B (spring constant $2k$) attached to the block on the right, connected to a wall on the right. The block's position is marked $x = 0$.]
The block is moved to $x = x_1$ and held at rest, as shown in Figure 2.
[Figure 2: Same spring-block system as Figure 1, now with the block displaced to the right to position $x = x_1$ (Spring A stretched, Spring B compressed). A coordinate axis

Question 2

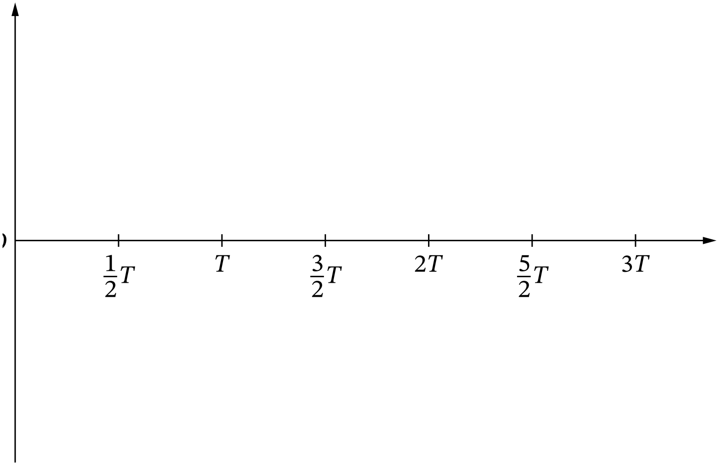
is shown at top right with $+y$ (up) and $+x$ (right) directions labeled. The positions $x = 0$ and $x = x_1$ are marked on the horizontal surface.]

(a) An energy bar chart can be used to represent the elastic potential energy U_A of Spring A, the elastic potential energy U_B of Spring B, and the kinetic energy K_{block} of the block. On the energy bar chart in Figure 3, **draw** shaded bars to represent the energy of the system for when the block is at $x = x_1$.

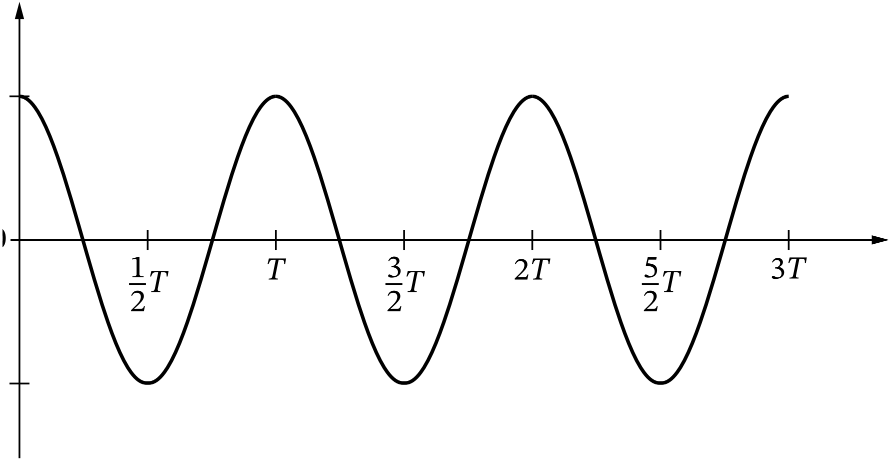
- The height of the shaded bars should be proportional to the relative values of U_A, U_B, and K_{block}. - Any energy that is equal to zero should be represented by a distinct line on the zero-energy line.

[Figure 3: A blank bar-chart grid titled "Energy" (vertical axis) with three labeled columns: U_A, U_B, K_{block}, and a horizontal "0" line partway up the grid, with gridlines above and below for plotting bar heights.]

Question 2



Question 2



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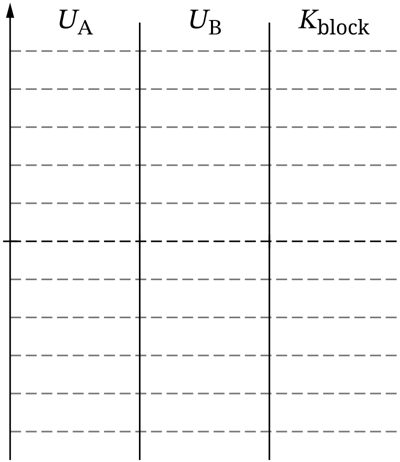

Question 2

2025 ▪ Q2

In Scenario 1, a system composed of two springs, A and B, and a block of mass m is at rest on a horizontal surface. Friction between the block and the surface is negligible. Each spring is attached to a fixed wall and the block, as shown in Figure 1. Spring A has a spring constant k and Spring B has a spring constant $2k$. Each spring is at its relaxed length when the block is at position $x = 0$, as shown.

[Figure 1: Spring A (spring constant k) attached to a wall on the left, connected to a block; Spring B (spring constant $2k$) attached to the block on the right, connected to a wall on the right. The block's position is marked $x = 0$.]

The block is moved to $x = x_1$ and held at rest, as shown in Figure 2.

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Question 2

(b) The block is released from rest at $x = x_1$ and begins to oscillate. **Derive** an expression for the speed v of the block as the block passes through $x = \frac{1}{2}x_1$. Express your answer in terms of m, k, x_1, and physical constants, as appropriate. Begin your derivation by writing a fundamental physics principle or an equation from the reference information.

Question 2

2025 ▪ Q2

In Scenario 1, a system composed of two springs, A and B, and a block of mass m is at rest on a horizontal surface. Friction between the block and the surface is negligible. Each spring is attached to a fixed wall and the block, as shown in Figure 1. Spring A has a spring constant k and Spring B has a spring constant $2k$. Each spring is at its relaxed length when the block is at position $x = 0$, as shown.

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The block is moved to $x = x_1$ and held at rest, as shown in Figure 2.

[Figure 2: Same spring-block system as Figure 1, now with the block displaced to the right to position $x = x_1$ (Spring A stretched, Spring B compressed). A coordinate axis is shown at top right with $+y$ (up) and $+x$ (right) directions labeled. The positions $x = 0$ and $x = x_1$ are marked on the horizontal surface.]

Question 2

(c)(i) In Scenario 1, the block oscillates with period T. The position x of the block in Scenario 1 as a function of time t is shown in Figure 4.
[Figure 4: Graph titled "Scenario 1" of position x vs. time t. Vertical axis x with values $+x_1$ marked above 0 and $-x_1$ marked below 0; horizontal axis t with gridmarks at $\frac{1}{2}T$, T, $\frac{3}{2}T$, $2T$, $\frac{5}{2}T$, $3T$. The curve is a cosine-like oscillation: starts at $+x_1$ at $t = 0$, crosses zero at $\frac{1}{2}T$ going down to $-x_1$ at around $\frac{1}{2}T$ to T, back up through zero, reaching $+x_1$ again at T, and repeating this pattern periodically through $3T$.]
In Scenario 2, the block-springs system is placed on a new surface. There is friction between the block and the new surface. The block is again moved to the same position $x = x_1$ and released from rest. The block completes multiple oscillations with the same period as in Scenario 1 before coming to rest.
On the axes shown in Figure 5, **sketch** a graph of the kinetic energy K of the block as a function of t for Scenario 2.

Question 2

[Figure 5: Blank axes titled "Scenario 2" with vertical axis K and horizontal axis t with gridmarks at $\frac{1}{2}T$, T, $\frac{3}{2}T$, $2T$, $\frac{5}{2}T$, $3T$, origin labeled O.]

Question 2

2025 ▪ Q2

In Scenario 1, a system composed of two springs, A and B, and a block of mass m is at rest on a horizontal surface. Friction between the block and the surface is negligible. Each spring is attached to a fixed wall and the block, as shown in Figure 1. Spring A has a spring constant k and Spring B has a spring constant $2k$. Each spring is at its relaxed length when the block is at position $x = 0$, as shown.

[Figure 1: Spring A (spring constant k) attached to a wall on the left, connected to a block; Spring B (spring constant $2k$) attached to the block on the right, connected to a wall on the right. The block's position is marked $x = 0$.]

The block is moved to $x = x_1$ and held at rest, as shown in Figure 2.

[Figure 2: Same spring-block system as Figure 1, now with the block displaced to the right to position $x = x_1$ (Spring A stretched, Spring B compressed). A coordinate axis is shown at top right with $+y$ (up) and $+x$ (right) directions labeled. The positions $x = 0$ and $x = x_1$ are marked on the horizontal surface.]

Question 2

(d) In Scenario 3, the block is replaced with a new block of larger mass. The coefficient of kinetic friction between the new block and the surface in Scenario 3 is the same as the coefficient of kinetic friction between the original block and the surface in Scenario 2.

The new block is moved to position $x = x_1$ and released from rest. The kinetic energy of the new block is plotted as a function of time.

Describe how one feature of the graph of K as a function of t in Scenario 3 would differ from the graph you drew in Figure 5 for Scenario 2.

Briefly **justify** your answer.

Solution 2

(a) Mark scheme

- Energy bar chart at $x = x_1$ (Figure 3), where the block is momentarily at rest (released from rest at x_1, so all mechanical energy is stored in the two springs): the K_{block} bar has zero height [Point A1]. Both U_A and U_B bars are drawn with positive height, since elastic PE stored in a spring is never negative [Point A2]. Spring B has spring constant $2k$ (twice Spring A's k) and both springs share displacement x_1: $U_A = \frac{1}{2}kx_1^2$ and $U_B = \frac{1}{2}(2k)x_1^2 = 2U_A$, so the U_B bar is drawn exactly twice the height of the U_A bar (this point is awarded on the height ratio regardless of which sign/direction the bars are drawn in) [Point A3].

Solution 2

(b) Mark scheme

- Derive v at $x = \frac{1}{2}x_1$ using energy conservation (an equivalent SHM method is also accepted) [Point B1: multistep derivation that includes energy conservation or simple harmonic motion]. The system behaves as a single effective spring combining both springs acting on the block together, $k_{eff} = k + 2k = 3k$ [Point B2: relates the presence of both springs to the system's behavior]. Initial state at $x = x_1$: $E_{tot,0} = U_A(x_1) + U_B(x_1) + K_{block}(x_1) = \frac{1}{2}kx_1^2 + \frac{1}{2}(2k)x_1^2 + 0 = \frac{3}{2}kx_1^2$. Final state at $x = \frac{1}{2}x_1$ [Point B3: relates positions $x = x_1$ and $x = \frac{1}{2}x_1$ to the oscillation of the block]: $E_{tot,f} = \frac{1}{2}k\left(\frac{1}{2}x_1\right)^2 + \frac{1}{2}(2k)\left(\frac{1}{2}x_1\right)^2 + K_{block,\frac{1}{2}x_1} = \frac{3}{8}kx_1^2 + K_{block,\frac{1}{2}x_1}$. Setting $E_{tot,0} = E_{tot,f}$:

Solution 2

$\frac{3}{2}kx_1^2 = \frac{3}{8}kx_1^2 + K_{block,\frac{1}{2}x_1} \Rightarrow K_{block,\frac{1}{2}x_1} = \frac{9}{8}kx_1^2 \Rightarrow \frac{1}{2}mv^2 = \frac{9}{8}kx_1^2 \Rightarrow v = \frac{3}{2}x_1\sqrt{\frac{k}{m}}$ [Point B4: correct final expression for v in terms of m, k, x1]. (Equivalent SHM route: $\omega = \sqrt{3k/m}$, $x(t) = x_1 \cos \omega t$, solve $\cos \omega t = \frac{1}{2} \Rightarrow \omega t = \pi/3$, then $v = x_1\omega \sin(\pi/3) = \frac{3}{2}x_1\sqrt{k/m}$ – same result.)

Solution 2

(c)(i) Mark scheme

- Sketch K (kinetic energy of the block) vs. t for Scenario 2 (the block oscillating on the two-spring system WITH friction/damping), on axes marked at $\frac{1}{2}T$, T, $\frac{3}{2}T, 2T, \frac{5}{2}T, 3T$ (Figure 5), where T is the period from the frictionless Scenario 1. The block is released from rest at x_1, so $K = 0$ at $t = 0$, and the curve must start at zero and remain ≥ 0 for all t (kinetic energy cannot be negative) [Point C1]. Because the block passes through $x = 0$ (where K is maximum) twice per full oscillation period T and momentarily has $K = 0$ at each turning point (also twice per period T), the sketched curve should be periodic with zeros spaced $\frac{1}{2}T$ apart – i.e. humps peaking near $\frac{1}{4}T, \frac{3}{4}T, \frac{5}{4}T, \ldots$ and touching zero at $0, \frac{1}{2}T$, T, $\frac{3}{2}T, 2T, \ldots$ [Point C2]. Because friction dissipates

Solution 2

mechanical energy each cycle, the successive peak heights of K must decrease over time, i.e. the curve is a periodic wave of decreasing amplitude [Point C3].

Solution 2

(d) Mark scheme

- Scenario 3: the block is replaced with a new, LARGER-mass block (same coefficient of kinetic friction as Scenario 2). Compare the K vs. t graph of Scenario 3 to that of Scenario 2 (part C) and describe ONE feature that would differ, with a correct justification. Acceptable answers (state ONE, with matching reasoning): (1) 'The period increases' – because the period of the oscillator is $T = 2\pi\sqrt{m/k_{eff}}$, and increasing the mass m (with k_{eff} unchanged) increases T [Point D1 + Point D2]. (2) 'The rate at which the graph approaches zero amplitude increases' – because a larger mass under the same coefficient of friction experiences a larger friction force, so the block loses mechanical energy at a greater rate. (3) 'The maximum value of K over each period is less than the

Solution 2

graph drawn [in part C]' – a valid alternative feature with matching reasoning (more energy lost to friction per cycle). Award Point D1 for indicating any ONE of these three features, and Point D2 for a justification that correctly supports the specific feature chosen.

Question 3

2025 ▪ Q3

A box is connected to one end of a rigid rod. Both the box and the rod have negligible mass. The other end of the rod is connected to a pivot. The box is open on one side, and a block is placed inside the box.

The center of mass of the block is displaced a vertical distance h, as shown in Figure 1. The block-box system is then released from rest and swings downward. There is negligible friction about the pivot. When the system is at the lowest point of its swing, the rod collides with a rigid stopper, as shown in Figure 2. The box comes to rest, and the block is launched horizontally out of the box. The block moves across a horizontal surface toward a motion sensor that measures the speed of the block. All frictional forces are negligible.

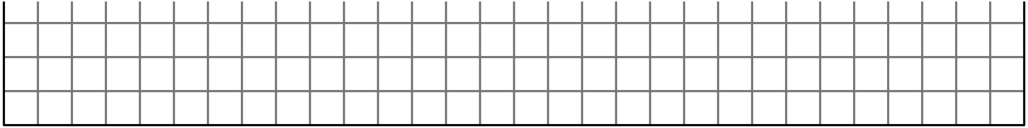
[Figure 1: A pivot at top connected by a rod to a box (containing a block) displaced to the left and up, with the center of mass of the block shown a vertical distance h above

Question 3

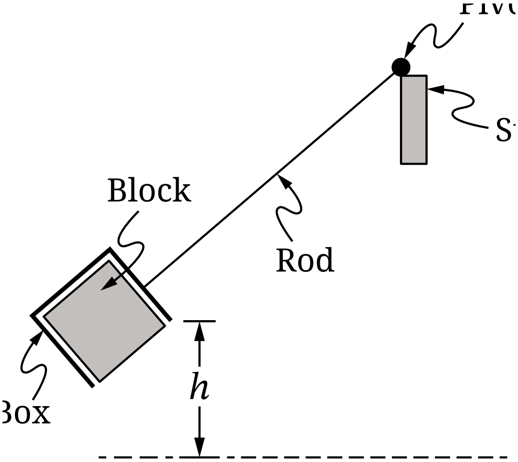
the box's lowest-point position (dashed horizontal line). A stopper is shown attached near the pivot.]
[Figure 2: The rod now hangs vertically straight down from the pivot, with the box (and block) at its lowest point, aligned with the dashed horizontal line.]
(a) Students are asked to experimentally determine the acceleration due to gravity g using a linear graph. To determine g, the students are permitted to use measurements from only a meterstick and the motion sensor.
Describe an experimental procedure using the described setup to collect data that would allow the students to determine an experimental value of g using a linear graph. Include any steps necessary to reduce experimental uncertainty.

Question 3

Question 3



Question 3



Question 3

h (m)	x_{max} (m)
0.30	0.76
0.45	1.10
0.60	1.40
0.75	1.90
0.90	2.30

Question 3

2025 ▪ Q3

A box is connected to one end of a rigid rod. Both the box and the rod have negligible mass. The other end of the rod is connected to a pivot. The box is open on one side, and a block is placed inside the box.

The center of mass of the block is displaced a vertical distance h, as shown in Figure 1. The block-box system is then released from rest and swings downward. There is negligible friction about the pivot. When the system is at the lowest point of its swing, the rod collides with a rigid stopper, as shown in Figure 2. The box comes to rest, and the block is launched horizontally out of the box. The block moves across a horizontal surface toward a motion sensor that measures the speed of the block. All frictional forces are negligible.

[Figure 1: A pivot at top connected by a rod to a box (containing a block) displaced to the left and up, with the center of mass of the block shown a vertical distance h above the box's lowest-point position (dashed horizontal line). A stopper is shown attached near the pivot.]

Question 3

[Figure 2: The rod now hangs vertically straight down from the pivot, with the box (and block) at its lowest point, aligned with the dashed horizontal line.]

(b) Describe how the data collected in part A could be graphed and how that graph would be analyzed to determine the value of g.

Question 3

2025 ▪ Q3

A box is connected to one end of a rigid rod. Both the box and the rod have negligible mass. The other end of the rod is connected to a pivot. The box is open on one side, and a block is placed inside the box.
The center of mass of the block is displaced a vertical distance h, as shown in Figure 1. The block-box system is then released from rest and swings downward. There is negligible friction about the pivot. When the system is at the lowest point of its swing, the rod collides with a rigid stopper, as shown in Figure 2. The box comes to rest, and the block is launched horizontally out of the box. The block moves across a horizontal surface toward a motion sensor that measures the speed of the block. All frictional forces are negligible.
[Figure 1: A pivot at top connected by a rod to a box (containing a block) displaced to the left and up, with the center of mass of the block shown a vertical distance h above the box's lowest-point position (dashed horizontal line). A stopper is shown attached near the pivot.]

Question 3

[Figure 2: The rod now hangs vertically straight down from the pivot, with the box (and block) at its lowest point, aligned with the dashed horizontal line.]

(c)(i) The experiment is repeated, but the horizontal surface on which the block slides is replaced with a new rough surface, as shown in Figure 3. The coefficient of kinetic friction between the block and the new surface is μ.

[Figure 3: A rod hanging vertically from a pivot with the box/block at its lowest point on a rough (wavy-line) horizontal surface at position $x = 0$; a dashed square outline is shown further right at position $x = x_{\max}$, indicating where the block comes to rest.]

The block-box system is pulled aside so that the center of mass of the block is displaced various vertical distances h and then released from rest. For each vertical distance, students measure the position $x = x_{\max}$ at which the block comes to rest. The students' measurements of h and $x_{\max}$ are shown in Table 1.

Table 1

Question 3

| h (m) | $x_{\max}$ (m) | |—|—| | 0.30 | 0.76 | | 0.45 | 1.10 | | 0.60 | 1.40 | | 0.75 | 1.90 | | 0.90 | 2.30 |
Indicate two quantities, either measured quantities from Table 1 or additional calculated quantities, that could be graphed to produce a straight line that could be used to determine μ.
Vertical axis:
$H^{orizontalaxis}$:

(c)(ii) On the grid provided, create a graph of the quantities indicated in part C (i).

- Use Table 2 to record the measured or calculated quantities that you will plot.
- Clearly **label** the axes, including units as appropriate.
- **Plot** the points you recorded in Table 2.

[A blank graphing grid (square-ruled) is provided for plotting the chosen quantities.]
(c)(iii) Draw a best-fit line to the data graphed in part C (ii).

Question 3

2025 ▪ Q3

A box is connected to one end of a rigid rod. Both the box and the rod have negligible mass. The other end of the rod is connected to a pivot. The box is open on one side, and a block is placed inside the box.
The center of mass of the block is displaced a vertical distance h, as shown in Figure 1. The block-box system is then released from rest and swings downward. There is negligible friction about the pivot. When the system is at the lowest point of its swing, the rod collides with a rigid stopper, as shown in Figure 2. The box comes to rest, and the block is launched horizontally out of the box. The block moves across a horizontal surface toward a motion sensor that measures the speed of the block. All frictional forces are negligible.
[Figure 1: A pivot at top connected by a rod to a box (containing a block) displaced to the left and up, with the center of mass of the block shown a vertical distance h above the box's lowest-point position (dashed horizontal line). A stopper is shown attached near the pivot.]

Question 3

[Figure 2: The rod now hangs vertically straight down from the pivot, with the box (and block) at its lowest point, aligned with the dashed horizontal line.]

(d) Using the best-fit line that you drew in part C (iii), **calculate** an experimental value for μ.

Solution 3

(a) Mark scheme

- Describe an experimental procedure (using only a meterstick and a motion sensor) to collect data allowing determination of g from a linear graph, including a step to reduce experimental uncertainty. Model answer: measure the height h from which the block(-box) system is released (using the meterstick). Measure the resulting speed v of the block as it moves across the horizontal surface (using the motion sensor) [Point A1: procedure includes measuring h and the block's speed]. Repeat the speed measurement for multiple different release heights h (or repeat multiple trials at the same h and average) to reduce experimental/random uncertainty [Point A2: any reasonable uncertainty-reduction method, e.g. repeating trials at one h, or repeating across several values of h].

Solution 3

(b) Mark scheme

- Describe how the data from part A could be graphed/analyzed to determine g. Any of the following linear relationships is acceptable, along with their reciprocals: v^2 vs. $2h$ (slope $= g$); $\frac{1}{2}v^2$ vs. h (slope $= g$); v^2 vs. h (slope $= 2g$); v vs. $\sqrt{h}$ (slope $= \sqrt{2g}$) [Point B1: describes a graph with a linear trend usable to find g; may be earned independently of part A]. Model answer: plot v^2 on the vertical axis and $2h$ on the horizontal axis; the slope of the best-fit line equals g [Point B2: correctly relates the best-fit slope to g, per whichever pairing is chosen – see the graph/analysis table above for the correct slope-to-g relationship for each valid axis choice].

Solution 3

(c)(i)

Mark scheme

- New scenario: the horizontal surface is replaced by a rough surface with kinetic friction coefficient μ; the block (released from height h) slides and comes to rest at $x_{\max}$. Indicate quantities that could be plotted to produce a LINEAR graph usable to determine μ. Model answer: plot h vs. $x_{\max}$ (the reciprocal, $x_{\max}$ vs. h, is equally acceptable) [Point C1: any correct linear pairing of measurable quantities that yields μ from the slope, e.g. h vs. x$_max$].

Solution 3

(c)(ii) Mark scheme

- Graph the quantities identified in part C(i) using the data in Table 2. Label both axes, including units, with a linear scale – e.g. h (m) on the vertical axis and $x_{\max}$ (m) on the horizontal axis, with evenly-spaced gridlines from 0 upward [Point C2: correctly labeled linear-scale axes with units]. Plot each data point from Table 2 as a dot at its $(x_{\max}, h)$ coordinates on the grid, consistent with the axes chosen in part C(i) – the example data trend roughly linearly from about $(0.3\text{ m}, 0.15\text{ m})$ through $(1.4, 0.6)$, $(1.9, 0.75)$, up to about $(2.9\text{ m}, 1.1\text{ m})$ [Point C3: plotted points consistent with the part-C(i) quantities, Table 2's values, or the grid's own labeled axes].

Solution 3

(c)(iii)

Mark scheme

- Draw a best-fit straight line through the data points plotted in part C(ii) – a single straight line that approximates the overall increasing linear trend of the plotted $(x_{\max}, h)$ points (not simply connecting the dots), extending across the range of the data [Point C4: any reasonable line/curve that approximates the trend of the plotted data].

Solution 3

(d) Mark scheme

- Using the best-fit line from part C(iii), calculate an experimental value of μ. Derivation: by conservation of energy, $mgh - F_f x_{\max} = 0$ where $F_f = \mu mg$ (kinetic friction on a horizontal surface, normal force $= mg$), so $mgh = \mu mg\, x_{\max} \Rightarrow h = \mu x_{\max}$. Comparing to $y = mx + b$ with h vs. $x_{\max}$: the slope of the best-fit line equals μ directly [Point D1: correctly relates the best-fit slope to μ]. Reading two well-separated points off the best-fit line, e.g. $(0.70\text{ m}, 0.30\text{ m})$ and $(2.4\text{ m}, 0.95\text{ m})$: slope $= \dfrac{0.95 - 0.30}{2.4 - 0.70} = 0.38$, so $\mu = 0.38$ [Point D2: award for any value of μ within the acceptable range 0.30 to 0.50, since the exact value depends on the student's own graphed data/line].

Question 4

2025 ▪ Q4

A uniform disk and ring, each of mass M and radius R, roll without slipping along a horizontal surface, as shown in Figure 1. The outer edges of the disk and ring are made of the same material. The center of mass of the disk and the center of mass of the ring each initially move with the same constant speed v.

The disk and the ring then smoothly transition to a ramp that is inclined at an angle θ above the horizontal. Both the disk and the ring continue to roll without slipping as they move up the ramp, as shown in Figure 2.

The ring travels a greater distance along the ramp than the disk travels before each momentarily comes to rest.

[Figure 1: A horizontal surface with a Disk (solid gray circle, radius R labeled) on the left and a Ring (gray annulus/hoop) to its right, both moving to the right (motion lines shown behind each) toward a ramp inclined at angle θ.]

Question 4

[Figure 2: The disk and ring shown together partway up the ramp inclined at angle θ, moving up-slope (motion lines behind them), with the ring positioned slightly behind/around the disk.]

(a) While the disk and the ring are rolling on the ramp without slipping, the magnitudes of the static frictional force exerted on the disk and on the ring by the ramp are f_D and f_R, respectively.

Indicate whether f_D is greater than, less than, or equal to f_R by writing one of the following.

- $f_D > f_R$
- $f_D < f_R$
- $f_D = f_R$

Justify your answer using qualitative reasoning beyond referencing equations.

Question 4

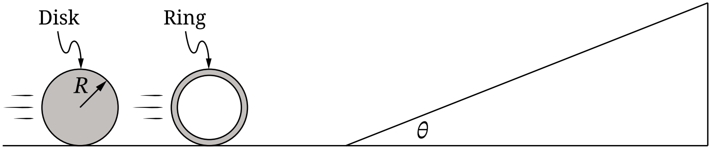
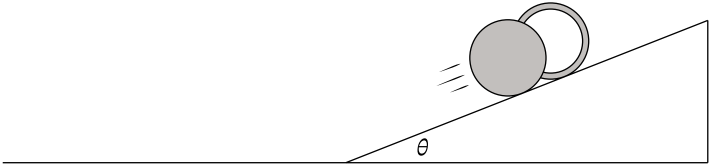


Figure 1



Question 4

2025 ▪ Q4

A uniform disk and ring, each of mass M and radius R, roll without slipping along a horizontal surface, as shown in Figure 1. The outer edges of the disk and ring are made of the same material. The center of mass of the disk and the center of mass of the ring each initially move with the same constant speed v.

The disk and the ring then smoothly transition to a ramp that is inclined at an angle θ above the horizontal. Both the disk and the ring continue to roll without slipping as they move up the ramp, as shown in Figure 2.

The ring travels a greater distance along the ramp than the disk travels before each momentarily comes to rest.

[Figure 1: A horizontal surface with a Disk (solid gray circle, radius R labeled) on the left and a Ring (gray annulus/hoop) to its right, both moving to the right (motion lines shown behind each) toward a ramp inclined at angle θ.]

Question 4

[Figure 2: The disk and ring shown together partway up the ramp inclined at angle θ, moving up-slope (motion lines behind them), with the ring positioned slightly behind/around the disk.]

(b) A cylinder has mass M, radius R, and rotational inertia I about its central axis. The cylinder rolls without slipping up a ramp that is inclined at an angle θ above the horizontal.

Derive an expression for the magnitude of the static frictional force f exerted on the cylinder by the ramp. Express your answer in terms of M, R, I, θ, and physical constants, as appropriate. Begin your derivation by writing a fundamental physics principle or an equation from the reference information.

Question 4

2025 ▪ Q4

A uniform disk and ring, each of mass M and radius R, roll without slipping along a horizontal surface, as shown in Figure 1. The outer edges of the disk and ring are made of the same material. The center of mass of the disk and the center of mass of the ring each initially move with the same constant speed v.

The disk and the ring then smoothly transition to a ramp that is inclined at an angle θ above the horizontal. Both the disk and the ring continue to roll without slipping as they move up the ramp, as shown in Figure 2.

The ring travels a greater distance along the ramp than the disk travels before each momentarily comes to rest.

[Figure 1: A horizontal surface with a Disk (solid gray circle, radius R labeled) on the left and a Ring (gray annulus/hoop) to its right, both moving to the right (motion lines shown behind each) toward a ramp inclined at angle θ.]

Question 4

[Figure 2: The disk and ring shown together partway up the ramp inclined at angle θ, moving up-slope (motion lines behind them), with the ring positioned slightly behind/around the disk.]

(c) In a different scenario, the centers of mass of the original disk and ring each have the same initial speed v as they did in the original scenario. The ramp is replaced by a new ramp on which the disk and the ring initially slip as they roll up the new ramp. **Indicate** whether the magnitude of the kinetic frictional force exerted on the disk by the new ramp is greater than, less than, or equal to the magnitude of the kinetic frictional force exerted on the ring by the new ramp while both are slipping.

Briefly **justify** your answer.

Solution 4

(a) Mark scheme

- Compare the magnitudes of static friction f_D (on the disk) and f_R (on the ring) as both roll without slipping on the ramp (same mass, radius, initial conditions). Answer: $f_D < f_R$ [Point A1]. Justification (model, from the scoring guidelines): the ring has a greater rotational inertia because it has more mass distributed toward the edge, so the ring travels farther and has less acceleration down the ramp; because the ring and disk have the same mass, the gravitational force components on them are the same, so from Newton's second law the ring must have less net force down the ramp and more friction (up the ramp) than the disk. This justification compares the disk's and ring's rotational inertias (the ring's is larger, since its mass sits farther from the axis) [Point A2: a justification

Solution 4

comparing translational kinematics, OR rotational kinematics, OR rotational inertias of the disk and ring – any ONE suffices], and it reasons via Newton's second law in translational form (equal gravity component, so the shape with the smaller net accelerating force down the ramp – the ring – must have the larger friction force) [Point A3: justification using N2L in translational form, OR rotational form, OR conservation of energy – any ONE suffices]. Reasoning must go beyond simply citing equations.

Solution 4

(b) Mark scheme

- Cylinder of mass M, radius R, rotational inertia I about its central axis, rolling without slipping UP a ramp inclined at angle θ. Derive an expression for the magnitude of the static friction force f from the ramp, in terms of M, R, I, θ. Rotational form of Newton's second law about the center of mass (friction f is the only force producing a torque about the axis, torque arm R): $\alpha_{sys} = \frac{\sum \tau}{I_{sys}} \Rightarrow \frac{a}{R} = \frac{fR}{I} \Rightarrow a = \frac{fR^2}{I}$ (uses the rolling-without-slipping constraint $a = R\alpha$) [Point B3: uses $a = r\alpha$ in an attempt to solve the system of equations]. Translational form of Newton's second law along the incline (the cylinder decelerates as it rolls up, so net force points down the incline):

Solution 4

$\vec{a}_{sys} = \dfrac{\sum \vec{F}}{m_{sys}} \Rightarrow f - Mg\sin\theta = -Ma$ – friction (up the incline) and the gravity component (down the incline) enter with opposite signs [Point B2: opposite signs for the gravitational and frictional force terms]. Combining Newton's second law in BOTH translational and rotational forms is the required multistep derivation [Point B1]. Substituting:
$f - Mg\sin\theta = -M\left(\dfrac{fR^2}{I}\right) \Rightarrow f + M\dfrac{fR^2}{I} = Mg\sin\theta \Rightarrow f\left(1 + \dfrac{MR^2}{I}\right) = Mg\sin\theta$,
giving $f = \dfrac{Mg\sin\theta}{1 + \dfrac{MR^2}{I}}$. (A response using conservation of energy instead may earn full credit per the scoring note.)

Solution 4

(c) Mark scheme

- New scenario: the disk and the ring (same initial center-of-mass speed v as before) roll up a DIFFERENT ramp on which they initially SLIP while rolling. Compare the magnitude of the kinetic friction force on the disk to that on the ring while both are slipping. Answer: 'Equal to' [Point C1]. Justification (model, from the scoring guidelines): the friction here is kinetic (since the objects are slipping), and kinetic friction depends only on the coefficient of kinetic friction between the surfaces in contact and on the normal force ($f_k = \mu_k N$), not on rotational inertia or shape. Since the disk and ring have the same mass and are on the same ramp, their normal forces are equal, and the coefficient of kinetic friction is the same for both (same pair of surfaces), so the kinetic friction forces on the disk and the ring

Solution 4

are equal in magnitude [Point C2: justification includes that kinetic friction depends only on the surfaces/coefficient of kinetic friction and the normal force].

Question 3

2023 Set 1 ▪ Q3

[Figure 1: A horizontal surface with Point B on the left and Point A near the middle marked by a black dot (the sphere's initial position at rest). A rod is shown above Point A, extending upward and connected at a pivot to a small block/weight at the top, with the rod initially vertical making a $90°$ angle at the pivot. A dashed curved arrow shows the rod swinging down from vertical to horizontal, striking the sphere at Point A. Note: Figure not drawn to scale.]

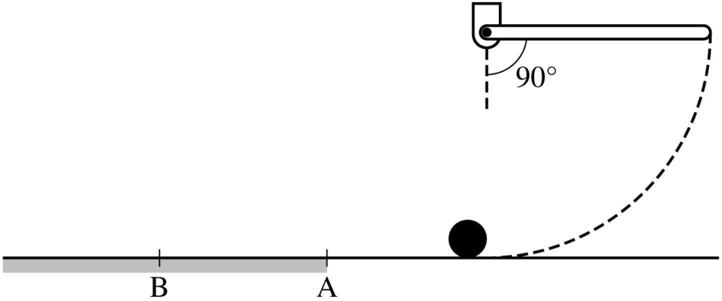
A system consists of a small sphere of mass m and radius R at rest on a horizontal surface and a uniform rod of mass $M = 2m$ and length ℓ attached at one end to a pivot with negligible friction, where $R \ll \ell$. There is negligible friction between the surface and the sphere to the right of Point A and nonnegligible friction to the left of Point A. The rod is held horizontally as shown in Figure 1, then is released from rest. The total

Question 3

rotational inertia of the rod about the pivot is $\frac{1}{3}M\ell^2$ and the rotational inertia of the sphere about its center is $\frac{2}{5}mR^2$. After the rod is released, the rod swings down and strikes the sphere head-on. As a result of this collision, the rod is stopped, and the ball initially slides without rotating to the left across the horizontal surface.

(a) Derive an expression for the angular speed of the rod just before striking the sphere in terms of the length ℓ and physical constants as appropriate.

Question 3



Note: Figure not drawn to scale.

Figure 1

Question 3

2023 Set 1 ▪ Q3

[Figure 1: A horizontal surface with Point B on the left and Point A near the middle marked by a black dot (the sphere's initial position at rest). A rod is shown above Point A, extending upward and connected at a pivot to a small block/weight at the top, with the rod initially vertical making a 90° angle at the pivot. A dashed curved arrow shows the rod swinging down from vertical to horizontal, striking the sphere at Point A. Note: Figure not drawn to scale.]

A system consists of a small sphere of mass m and radius R at rest on a horizontal surface and a uniform rod of mass $M = 2m$ and length ℓ attached at one end to a pivot with negligible friction, where $R \ll \ell$. There is negligible friction between the surface and the sphere to the right of Point A and nonnegligible friction to the left of Point A. The rod is held horizontally as shown in Figure 1, then is released from rest. The total rotational inertia of the rod about the pivot is $\frac{1}{3}M\ell^2$ and the rotational inertia of the sphere about its center is $\frac{2}{5}mR^2$. After the rod is released, the rod swings down and strikes the sphere head-on. As a result of this collision,

Question 3

the rod is stopped, and the ball initially slides without rotating to the left across the horizontal surface.

(b) Derive an expression for the linear speed v_0 of the sphere immediately after colliding with the rod in terms of the length ℓ and physical constants as appropriate. After sliding a short distance, at time $t = 0$ the sphere encounters a region of the horizontal surface with a coefficient of kinetic friction μ, beginning at Point A as indicated in Figure 1. The sphere begins rotating while sliding and eventually begins rolling without sliding at Point B, also as indicated.

Question 3

2023 Set 1 ▪ Q3

[Figure 1: A horizontal surface with Point B on the left and Point A near the middle marked by a black dot (the sphere's initial position at rest). A rod is shown above Point A, extending upward and connected at a pivot to a small block/weight at the top, with the rod initially vertical making a 90° angle at the pivot. A dashed curved arrow shows the rod swinging down from vertical to horizontal, striking the sphere at Point A. Note: Figure not drawn to scale.]

A system consists of a small sphere of mass m and radius R at rest on a horizontal surface and a uniform rod of mass $M = 2m$ and length ℓ attached at one end to a pivot with negligible friction, where $R \ll \ell$. There is negligible friction between the surface and the sphere to the right of Point A and nonnegligible friction to the left of Point A. The rod is held horizontally as shown in Figure 1, then is released from rest. The total rotational inertia of the rod about the pivot is $\frac{1}{3}M\ell^2$ and the rotational inertia of the sphere about its center is $\frac{2}{5}mR^2$. After the rod is released, the rod swings down and strikes the sphere head-on. As a result of this collision,

Question 3

the rod is stopped, and the ball initially slides without rotating to the left across the horizontal surface.

(c) In the following diagram, which represents the sphere while the sphere is traveling between Points A and B, draw and label the forces (not components) that act on the sphere. Each force must be represented by a distinct arrow starting on, and pointing away from, the point of application on the sphere.
[A circle is shown representing the sphere, for the student to draw and label force vectors starting on the circle.]

Question 3

2023 Set 1 ▪ Q3

[Figure 1: A horizontal surface with Point B on the left and Point A near the middle marked by a black dot (the sphere's initial position at rest). A rod is shown above Point A, extending upward and connected at a pivot to a small block/weight at the top, with the rod initially vertical making a $90°$ angle at the pivot. A dashed curved arrow shows the rod swinging down from vertical to horizontal, striking the sphere at Point A. Note: Figure not drawn to scale.]

A system consists of a small sphere of mass m and radius R at rest on a horizontal surface and a uniform rod of mass $M = 2m$ and length ℓ attached at one end to a pivot with negligible friction, where $R \ll \ell$. There is negligible friction between the surface and the sphere to the right of Point A and nonnegligible friction to the left of Point A. The rod is held horizontally as shown in Figure 1, then is released from rest. The total rotational inertia of the rod about the pivot is $\frac{1}{3}M\ell^2$ and the rotational inertia of the sphere about its center is $\frac{2}{5}mR^2$. After the rod is released, the rod swings down and strikes the sphere head-on. As a result of this collision,

Question 3

the rod is stopped, and the ball initially slides without rotating to the left across the horizontal surface.

(d)(i) Derive an expression for each of the following as the sphere is rotating and sliding between points A and B in terms of v_0, μ, R, t, and physical constants as appropriate.

The linear velocity v of the center of mass of the sphere as a function of time t

(d)(ii) The angular velocity ω of the sphere as a function of time t

Question 3

2023 Set 1 ▪ Q3

[Figure 1: A horizontal surface with Point B on the left and Point A near the middle marked by a black dot (the sphere's initial position at rest). A rod is shown above Point A, extending upward and connected at a pivot to a small block/weight at the top, with the rod initially vertical making a $90°$ angle at the pivot. A dashed curved arrow shows the rod swinging down from vertical to horizontal, striking the sphere at Point A. Note: Figure not drawn to scale.]

A system consists of a small sphere of mass m and radius R at rest on a horizontal surface and a uniform rod of mass $M = 2m$ and length ℓ attached at one end to a pivot with negligible friction, where $R \ll \ell$. There is negligible friction between the surface and the sphere to the right of Point A and nonnegligible friction to the left of Point A. The rod is held horizontally as shown in Figure 1, then is released from rest. The total rotational inertia of the rod about the pivot is $\frac{1}{3}M\ell^2$ and the rotational inertia of the sphere about its center is $\frac{2}{5}mR^2$. After the rod is released, the rod swings down and strikes the sphere head-on. As a result of this collision,

Question 3

the rod is stopped, and the ball initially slides without rotating to the left across the horizontal surface.

(e)(i) Derive an expression for the time it takes the sphere to travel from Point A to Point B in terms of v_0, μ, and physical constants as appropriate.

(e)(ii) Derive an expression for the linear velocity of the sphere upon reaching Point B in terms of v_0.

Question 1

2022 Set 1 ▪ Q1

A block of mass m is pulled across a rough horizontal table by a string connected to a motor that is attached to the floor. The string passes over a pulley with negligible friction that is vertically aligned with the left edge of the table as shown. The string and pulley both have negligible mass. The pulley is at height H above the table. The motor exerts a constant force of tension F_T on the string, and the block remains in contact with the table at all times as the block slides across the table from $x = L$ to $x = 0$. The coefficient of kinetic friction between the table and the block is μ_k. Express all algebraic answers in terms of m, H, F_T, x, μ_k, L, and physical constants as appropriate.
[Diagram: A pulley (marked with a dot in a circle) is mounted at the top-left, at height H above a horizontal table. A dashed horizontal line runs from the pulley to the right, and a "+y" axis arrow points up with "+x" pointing right from a small axes

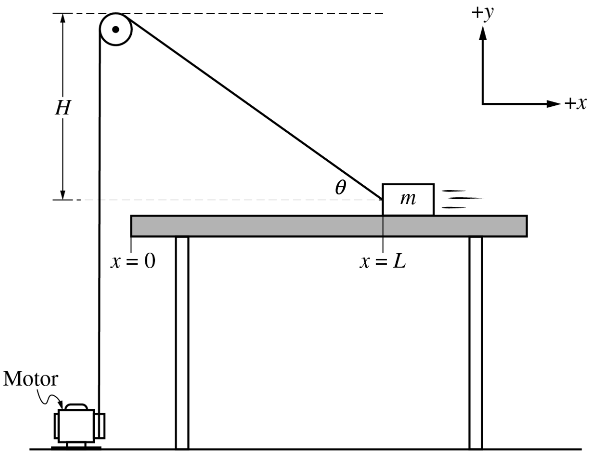
Question 1

marker near the pulley's dashed line. A string runs from the pulley down at an angle θ to a block of mass m resting on the table. The table's left edge is at $x = 0$ and the block starts at $x = L$ (marked on the table surface). Below the table, on the floor, is a motor connected via the string that runs up to the pulley.]

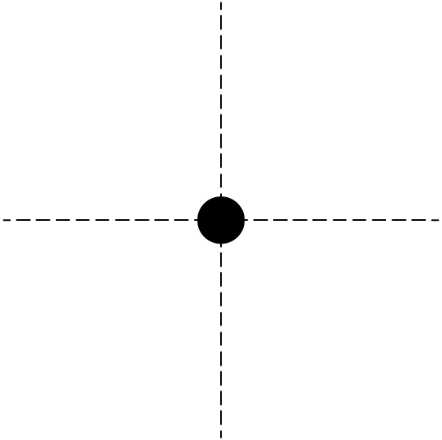
(a) On the dot below that represents the block, draw and label the forces (not components) that act on the block when the block is at $x = L$. Each force must be represented by a distinct arrow starting on, and pointing away from, the dot.

[Diagram: A single dot with a dashed horizontal line through it and a dashed vertical line through it, representing the free body of the block, on which forces should be drawn.]

Question 1



Question 1



Question 1

2022 Set 1 ▪ Q1

A block of mass m is pulled across a rough horizontal table by a string connected to a motor that is attached to the floor. The string passes over a pulley with negligible friction that is vertically aligned with the left edge of the table as shown. The string and pulley both have negligible mass. The pulley is at height H above the table. The motor exerts a constant force of tension F_T on the string, and the block remains in contact with the table at all times as the block slides across the table from $x = L$ to $x = 0$. The coefficient of kinetic friction between the table and the block is μ_k. Express all algebraic answers in terms of m, H, F_T, x, μ_k, L, and physical constants as appropriate.

[Diagram: A pulley (marked with a dot in a circle) is mounted at the top-left, at height H above a horizontal table. A dashed horizontal line runs from the pulley to the right, and a "+y" axis arrow points up with "+x" pointing right from a small axes marker near the pulley's dashed line. A string runs from the pulley down at an angle θ to a block of mass m resting on the table. The table's left edge is at $x = 0$ and the block starts at $x = L$ (marked on the table

Question 1

surface). Below the table, on the floor, is a motor connected via the string that runs up to the pulley.]

(b) Derive an expression for the angle θ that the string makes with the horizontal as a function of x.

Question 1

2022 Set 1 ▪ Q1

A block of mass m is pulled across a rough horizontal table by a string connected to a motor that is attached to the floor. The string passes over a pulley with negligible friction that is vertically aligned with the left edge of the table as shown. The string and pulley both have negligible mass. The pulley is at height H above the table. The motor exerts a constant force of tension F_T on the string, and the block remains in contact with the table at all times as the block slides across the table from $x = L$ to $x = 0$. The coefficient of kinetic friction between the table and the block is μ_k. Express all algebraic answers in terms of m, H, F_T, x, μ_k, L, and physical constants as appropriate.

[Diagram: A pulley (marked with a dot in a circle) is mounted at the top-left, at height H above a horizontal table. A dashed horizontal line runs from the pulley to the right, and a "+y" axis arrow points up with "+x" pointing right from a small axes marker near the pulley's dashed line. A string runs from the pulley down at an angle θ to a block of mass m resting on the table. The table's left edge is at $x = 0$ and the block starts at $x = L$ (marked on the table

Question 1

surface). Below the table, on the floor, is a motor connected via the string that runs up to the pulley.]

(c)(i) Derive an expression for the normal force F_N exerted on the block by the table as a function of the block's position x.

(c)(ii) Derive an expression for the magnitude of the net horizontal force F_{net} exerted on the block as a function of the position x.

Question 1

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(d) Write, but do not solve, an integral expression that could be used to solve for the work W done by the string on the block as the block moves from $x = L$ to $x = 0$.