Past-paper walk-through

Translational Kinetic Energy ▪ 3.1

eXercise

Questions in this set

- 2026 Q2
- 2025 Q2
- 2024 Q2
- 2022 Q3
- 2015 Q3

Reading the mark scheme

- **B1** a mark that stands on its own – the point is either made or not.
- **M1** a *method* mark: the right approach, even if the number is wrong.
- **A1** an *answer* mark, and it usually needs its M mark first.
- **C1** a working mark on the way to the answer.
- // separates answers the examiner accepts equally.
- **ecf** = error carried forward: a later part is marked on your own earlier answer.
- **owtte** = "or words to that effect" – the wording need not match.

Question 2

2026 ▪ Q2

Two small disks, R and S, are on a straight, horizontal track.
At time $t = 0$, Disk R of mass m_0 is located at position $x = 0$. Disk R is initially moving with speed v_0 in the $+x$-direction. Disk S of mass $3m_0$ is initially at rest, as shown in the top view in Figure 1. Frictional forces are negligible.
At $t = t_1$, the disks collide. Immediately after the collision, Disk R moves with speed $\frac{1}{2}v_0$ in the $-x$-direction.
[Figure 1 (Top View): A horizontal dashed track with two disks. On the left, a smaller shaded disk labeled m_0 ("Disk R") has an arrow above it labeled v_0 pointing right (in the $+x$-direction, with a $+x$ axis arrow shown above). On the right, a larger open disk labeled $3m_0$ ("Disk S") is labeled $v = 0$ above it. Note: Figure not drawn to scale.]

Question 2

(a) The momentum-vector diagram in Figure 2 represents the momentums of Disk R and Disk S before the collision.
[Figure 2: Two rows, each with a horizontal dashed number-line-style axis (light vertical tick marks along it) crossing a vertical axis at a central dot. Top row labeled "Disk R": a solid arrow starts at the central dot and points right, labeled with the heading "Momentum Before Collision" above both rows. Bottom row labeled "Disk S": just a dot with no arrow, labeled "$p = 0$" above it.]
Draw arrows on Figure 3 to represent the momentum vectors of Disk R and Disk S after the collision.

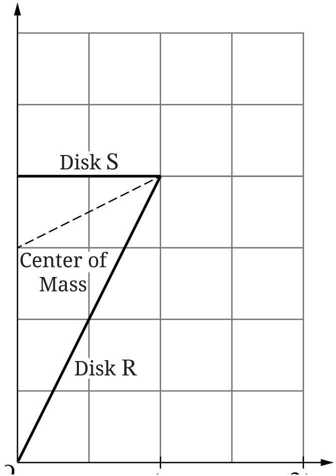
- Each arrow must start on, and point away from, each dot.
- If the momentum of either disk is zero, write "$p = 0$" next to the dot.

Question 2

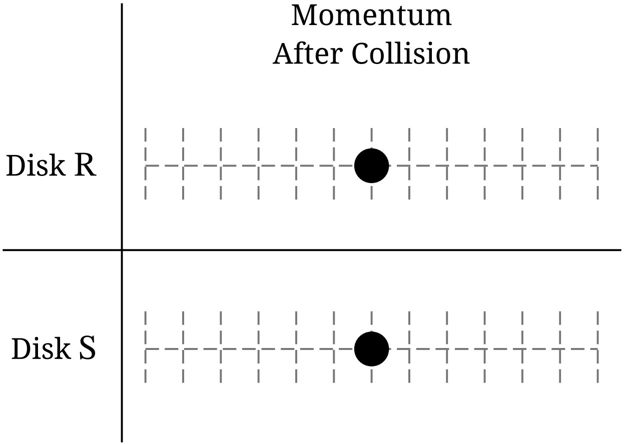
- Draw the length of each arrow to represent the magnitude of each momentum, consistent with the scale used in Figure 2.

[Figure 3: Same style as Figure 2 but blank — two rows each with a horizontal dashed axis and a central dot, headed "Momentum After Collision", one row labeled "Disk R" and one row labeled "Disk S", for the student to draw arrows on.]

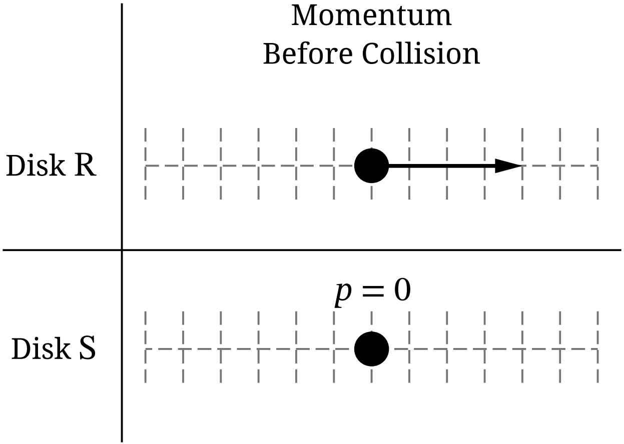
Question 2



Question 2



Question 2



Question 2

2026 ▪ Q2

Two small disks, R and S, are on a straight, horizontal track.
At time $t = 0$, Disk R of mass m_0 is located at position $x = 0$. Disk R is initially moving with speed v_0 in the $+x$-direction. Disk S of mass $3m_0$ is initially at rest, as shown in the top view in Figure 1. Frictional forces are negligible.

At $t = t_1$, the disks collide. Immediately after the collision, Disk R moves with speed $\frac{1}{2}v_0$ in the $-x$-direction.

[Figure 1 (Top View): A horizontal dashed track with two disks. On the left, a smaller shaded disk labeled m_0 ("Disk R") has an arrow above it labeled v_0 pointing right (in the $+x$-direction, with a $+x$ axis arrow shown above). On the right, a larger open disk labeled $3m_0$ ("Disk S") is labeled $v = 0$ above it. Note: Figure not drawn to scale.]

(b) Starting with conservation of linear momentum, **derive** an expression for the kinetic energy of Disk S immediately after the collision. Express your final answer in

Question 2

terms of m_0, v_0, and physical constants, as appropriate. Begin your derivation by writing the fundamental physics principle or an equation from the reference information.

Question 2

2026 ▪ Q2

Two small disks, R and S, are on a straight, horizontal track.

At time $t = 0$, Disk R of mass m_0 is located at position $x = 0$. Disk R is initially moving with speed v_0 in the $+x$-direction. Disk S of mass $3m_0$ is initially at rest, as shown in the top view in Figure 1. Frictional forces are negligible.

At $t = t_1$, the disks collide. Immediately after the collision, Disk R moves with speed $\frac{1}{2}v_0$ in the $-x$-direction.

[Figure 1 (Top View): A horizontal dashed track with two disks. On the left, a smaller shaded disk labeled m_0 ("Disk R") has an arrow above it labeled v_0 pointing right (in the $+x$-direction, with a $+x$ axis arrow shown above). On the right, a larger open disk labeled $3m_0$ ("Disk S") is labeled $v = 0$ above it. Note: Figure not drawn to scale.]

(c) The graph shown in Figure 4 represents the positions x as functions of time t from $t = 0$ until $t = t_1$ for each of the following:

Question 2

- Disk R
- Disk S
- The center of mass of the two-disk system

On the graph shown in Figure 4, **draw** three lines that represent the positions x of Disk R, Disk S, and the center of mass of the two-disk system as functions of t from $t = t_1$ to $t = 2t_1$. Distinctly **label** each line.

[Figure 4: A position (x, vertical axis) vs. time (t, horizontal axis) grid. From $t = 0$ to $t = t_1$, three straight lines rise from the origin O: the steepest line (largest slope) is labeled "Disk S", a shallower line is labeled "Center of Mass" (shown as a dashed line), and the shallowest line is labeled "Disk R". The horizontal axis is marked with tick values t_1 and $2t_1$ (blank beyond t_1 for the student to continue the lines).]

Question 2

2026 ▪ Q2

Two small disks, R and S, are on a straight, horizontal track.
At time $t = 0$, Disk R of mass m_0 is located at position $x = 0$. Disk R is initially moving with speed v_0 in the $+x$-direction. Disk S of mass $3m_0$ is initially at rest, as shown in the top view in Figure 1. Frictional forces are negligible.

At $t = t_1$, the disks collide. Immediately after the collision, Disk R moves with speed $\frac{1}{2}v_0$ in the $-x$-direction.

[Figure 1 (Top View): A horizontal dashed track with two disks. On the left, a smaller shaded disk labeled m_0 ("Disk R") has an arrow above it labeled v_0 pointing right (in the $+x$-direction, with a $+x$ axis arrow shown above). On the right, a larger open disk labeled $3m_0$ ("Disk S") is labeled $v = 0$ above it. Note: Figure not drawn to scale.]

(d) During the collision, the magnitudes of the changes in momentum of Disk R and Disk S are $|\Delta p_R|$ and $|\Delta p_S|$, respectively.

Question 2

Indicate whether $|\Delta p_R|$ is greater than, less than, or equal to $|\Delta p_S|$ by writing one of the following.
- $|\Delta p_R| > |\Delta p_S|$ - $|\Delta p_R| < |\Delta p_S|$ - $|\Delta p_R| = |\Delta p_S|$
Briefly **justify** your response by referencing a fundamental physics principle.

Question 2

2025 ▪ Q2

A block of mass M is released from rest at position $x = 0$ near the top of a ramp. The ramp makes an angle of θ with the horizontal. The block slides down the ramp with negligible friction. At $x = 8D$ the block makes contact with an uncompressed spring with spring constant k. The spring is then compressed and the block momentarily comes to rest at $x = 12D$. Figure 1 shows the instants when the block is at $x = 0$, $x = 6D$, and $x = 10D$, respectively.

[Figure 1: Three diagrams of a ramp inclined at angle θ to the horizontal, with a spring of constant k fixed at the bottom of the ramp. The $+x$ direction points down the incline. Left diagram: block at $x = 0$ at the top of the ramp, with marks at $8D$ (where the spring begins, uncompressed) and $12D$ (spring fully compressed position) shown along the incline. Middle diagram: block shown partway down the ramp at

Question 2

$x = 6D$, moving toward the spring (motion lines shown). Right diagram: block shown further down, in contact with/compressing the spring, at $x = 10D$.]

(a) Figure 4 shows an energy bar chart that represents the kinetic energy K of the block, the gravitational potential energy U_g of the block-spring-Earth system, and the spring potential energy U_s of the block-spring-Earth system at the instant that the block is at $x = 10D$. The gravitational potential energy U_g of the block-spring-Earth system is defined to be zero when the block momentarily comes to rest at $x = 12D$. **Draw** shaded bars that represent K, U_g, and U_s to complete the energy bar charts in Figure 2 and Figure 3 for when the block is released from rest at $x = 0$ and for when the block is at $x = 6D$, respectively.

- Shaded bars should start at the dashed line that represents zero energy. - Represent any energy that is equal to zero with a distinct line on the zero-energy line. - The

Question 2

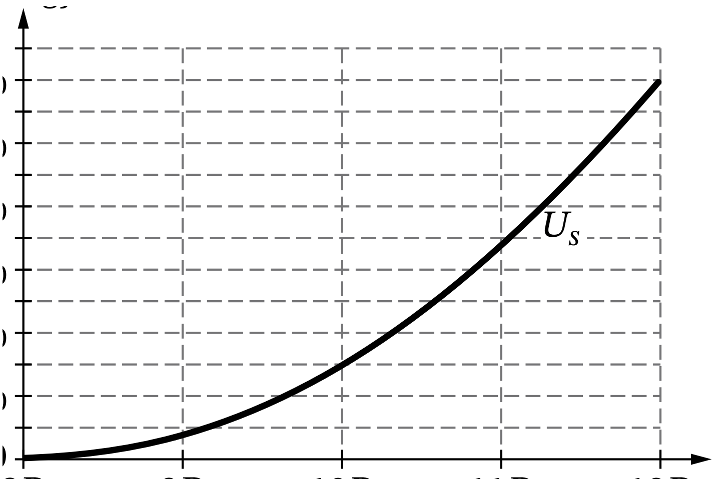
relative heights of each shaded bar should reflect the magnitude of the respective energy consistent with the scale used in Figure 4.

[Figure 2: Bar chart titled "$x = 0$", vertical axis "Energy" gridded in increments of $2E_0$ from 0 to $14E_0$, with three empty bar slots labeled K, U_g, U_s on the horizontal axis — bars to be drawn by the student.]

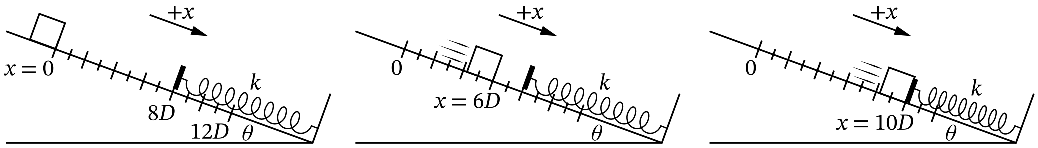
[Figure 3: Bar chart titled "$x = 6D$", vertical axis "Energy" gridded in increments of $2E_0$ from 0 to $14E_0$, with three empty bar slots labeled K, U_g, U_s on the horizontal axis — bars to be drawn by the student.]

[Figure 4: Bar chart titled "$x = 10D$", vertical axis "Energy" gridded in increments of $2E_0$ from 0 to $14E_0$. Three shaded bars are shown: $K \approx 7E_0$, $U_g \approx 1.5E_0$, $U_s \approx 3E_0$.]

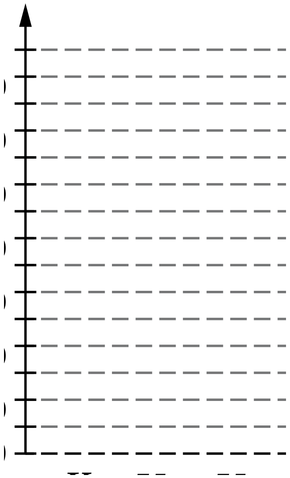
Question 2



Question 2



Question 2



Question 2

2025 ▪ Q2

A block of mass M is released from rest at position $x = 0$ near the top of a ramp. The ramp makes an angle of θ with the horizontal. The block slides down the ramp with negligible friction. At $x = 8D$ the block makes contact with an uncompressed spring with spring constant k. The spring is then compressed and the block momentarily comes to rest at $x = 12D$. Figure 1 shows the instants when the block is at $x = 0$, $x = 6D$, and $x = 10D$, respectively.

[Figure 1: Three diagrams of a ramp inclined at angle θ to the horizontal, with a spring of constant k fixed at the bottom of the ramp. The $+x$ direction points down the incline. Left diagram: block at $x = 0$ at the top of the ramp, with marks at $8D$ (where the spring begins, uncompressed) and $12D$ (spring fully compressed position) shown along the incline. Middle diagram: block shown partway down the ramp at $x = 6D$, moving toward the spring (motion lines shown). Right diagram: block shown further down, in contact with/compressing the spring, at $x = 10D$.]

Question 2

(b) Figure 5 shows the block at $x = 0$ when the block is released from rest and the block at $x = 12D$ when the block momentarily comes to rest against the compressed spring.

Figure 5

[Figure 5: Two diagrams of the same ramp at angle θ with spring constant k at the bottom. Left: block at $x = 0$ at the top, $+x$ direction down the incline, mark at $12D$ shown along the incline. Right: block at $x = 12D$, resting against the fully compressed spring at the bottom of the incline.]

Starting with conservation of energy, **derive** an equation for the spring constant k. Express your answer in terms of M, θ, D, 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

A block of mass M is released from rest at position $x = 0$ near the top of a ramp. The ramp makes an angle of θ with the horizontal. The block slides down the ramp with negligible friction. At $x = 8D$ the block makes contact with an uncompressed spring with spring constant k. The spring is then compressed and the block momentarily comes to rest at $x = 12D$. Figure 1 shows the instants when the block is at $x = 0$, $x = 6D$, and $x = 10D$, respectively.

[Figure 1: Three diagrams of a ramp inclined at angle θ to the horizontal, with a spring of constant k fixed at the bottom of the ramp. The $+x$ direction points down the incline. Left diagram: block at $x = 0$ at the top of the ramp, with marks at $8D$ (where the spring begins, uncompressed) and $12D$ (spring fully compressed position) shown along the incline. Middle diagram: block shown partway down the ramp at $x = 6D$, moving toward the spring (motion lines shown). Right diagram: block shown further down, in contact with/compressing the spring, at $x = 10D$.]

Question 2

(c)(i) Figure 6 shows a graph of the energy of the system as a function of the position of the block from $x = 8D$ to $x = 12D$. The spring potential energy U_s of the block-spring-Earth system is shown on the graph.
On the axes shown in Figure 6, **sketch** and **label** a line or curve that represents the total mechanical energy E for the block-spring-Earth system as a function of the position of the block from $x = 8D$ to $x = 12D$.
Figure 6
[Figure 6: Graph with vertical axis "Energy" gridded in increments of $2E_0$ from 0 to $12E_0$, horizontal axis "Position" marked $8D, 9D, 10D, 11D, 12D$. A curve labeled U_s is plotted starting at $(8D, 0)$ and increasing with upward curvature (quadratic-like shape) to reach $(12D, 12E_0)$. The student must add curves for E and U_g on the same axes.]

Question 2

(c)(ii) Sketch and **label** a line or curve that represents the gravitational potential energy U_g for the block-spring-Earth system as a function of the position of the block from $x = 8D$ to $x = 12D$.

Question 2

2025 ▪ Q2

A block of mass M is released from rest at position $x = 0$ near the top of a ramp. The ramp makes an angle of θ with the horizontal. The block slides down the ramp with negligible friction. At $x = 8D$ the block makes contact with an uncompressed spring with spring constant k. The spring is then compressed and the block momentarily comes to rest at $x = 12D$. Figure 1 shows the instants when the block is at $x = 0$, $x = 6D$, and $x = 10D$, respectively.

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Question 2

(d) Indicate whether the speed v_{9D} of the block at $x = 9D$ is greater than, less than, or equal to the speed v_{8D} of the block at $x = 8D$.

________ $v_{9D} > v_{8D}$

________ $v_{9D} < v_{8D}$

________ $v_{9D} = v_{8D}$

Justify how your response is consistent with the energy lines or curves you drew in Figure 6 in part C.

Solution 2

(a) Mark scheme

- Complete two energy bar charts, each totaling the constant mechanical energy $12E_0$. Figure 2 (block at $x = 0$, released from rest, not yet touching the spring): draw a single bar for U_g at height $12E_0$; the K and U_s bars are at zero. Figure 3 (block at $x = 6D$, partway down, still not touching the spring): draw bars for K and U_g only (no U_s), each at height $6E_0$. Point A1 for drawing one bar in Figure 2 that shows only U_g (the correct height is not required for this point); Point A2 for including only K and U_g bars in Figure 3 (correct heights not required); Point A3 for the bars in Figures 2 and 3 each totaling $12E_0$.

Solution 2

(b) Mark scheme

- By conservation of energy, the initial gravitational PE converts entirely into spring PE at the point where the block is momentarily at rest against the fully compressed spring: $E_0 = E_f \Rightarrow U_g = U_s \Rightarrow mg\Delta y = \frac{1}{2}k(\Delta x)^2$. Substituting $\Delta y = 12D\sin\theta$ (the height dropped along the incline from $x = 0$ to $x = 12D$) and $\Delta x = 4D$ (the spring compression, from $x = 8D$ to $x = 12D$): $Mg(12D\sin\theta) = \frac{1}{2}k(4D)^2$, which gives $k = \frac{3}{2}\frac{Mg\sin\theta}{D}$. Point B1 for a multistep derivation that includes conservation of energy; B2 for equating U_g to U_s; B3 for substituting $12D\sin\theta$ for Δy OR $4D$ for Δx in the respective energy expression; B4 for a correct expression for k (any algebraic equivalent of $k = \frac{3}{2}\frac{Mg\sin\theta}{D}$). A correct, isolated final expression for k earns B2, B3, and B4.

Solution 2

(c)(i)

Mark scheme

- Sketch a horizontal line at $E = 12E_0$, drawn continuously from $x = 8D$ to $x = 12D$, labeled to indicate it is the total mechanical energy E of the block-spring-Earth system (constant, since no non-conservative forces act). Point C1.

Solution 2

(c)(ii)

Mark scheme

- Sketch a straight, decreasing line (linear, since $U_g = Mg(12D - x)\sin\theta$ is linear in x) from $x = 8D$ to $x = 12D$, labeled to indicate gravitational potential energy U_g, starting at the point $(8D,\ 4E_0)$ and decreasing to $(12D,\ 0)$. Point C2 for a decreasing straight line labeled as gravitational potential energy; Point C3 for starting that line at $(8D, 4E_0)$.

Solution 2

(d) Mark scheme

- $v_{9D} > v_{8D}$. Justification: from the total-energy line ($E = 12E_0$ everywhere) and the U_g line drawn in part C, at $x = 8D$, $U_g = 4E_0$, so $K = 12E_0 - 4E_0 = 8E_0$ (with $U_s \approx 0$ there). At $x = 9D$, U_g has dropped to about $3E_0$ and U_s is still less than E_0, so $K = E - U_g - U_s > 12E_0 - 3E_0 - E_0 = 8E_0$. Since the kinetic energy — and therefore the speed — is greater at $x = 9D$ than at $x = 8D$, $v_{9D} > v_{8D}$. Point D1 for the comparison consistent with the student's part-C graph (whichever position has the smaller $U_g + U_s$ has the larger speed); Point D2 for a justification consistent with that graph that correctly relates speed to U_g, U_s, and either K or total energy E.

Question 2

2024 ▪ Q2

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

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

Question 2

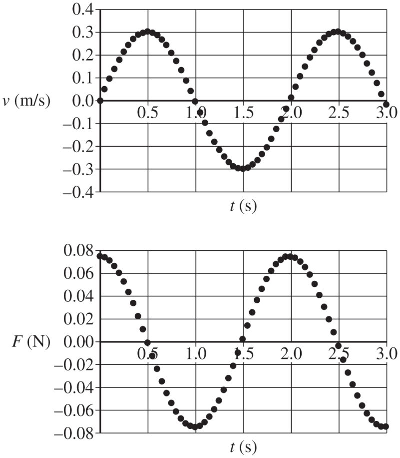
(a) (a) Design an experimental procedure the student could use to determine the spring constant k of the spring.
In the following table, list the quantities that would be measured using only the provided equipment in your experiment. Define a symbol to represent each quantity.
In the space below the table, **describe** the overall procedure. Provide enough detail so that another student could replicate the experiment, including any steps necessary to reduce experimental uncertainty. As needed, use the symbols defined in the table. If needed, you may include a simple diagram with your procedure.

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

Question 2

Procedure (and diagram, if needed):

Question 2



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

Question 2

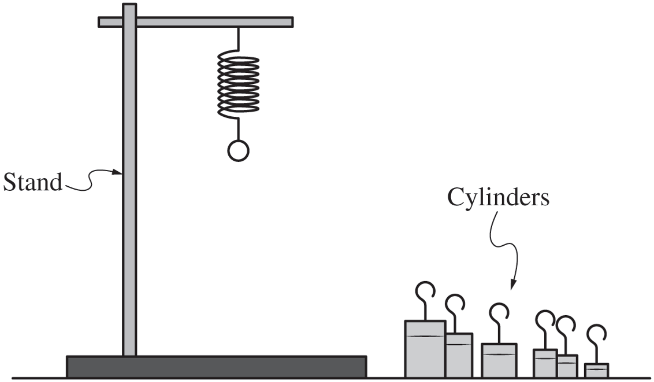


Figure 1

Question 2

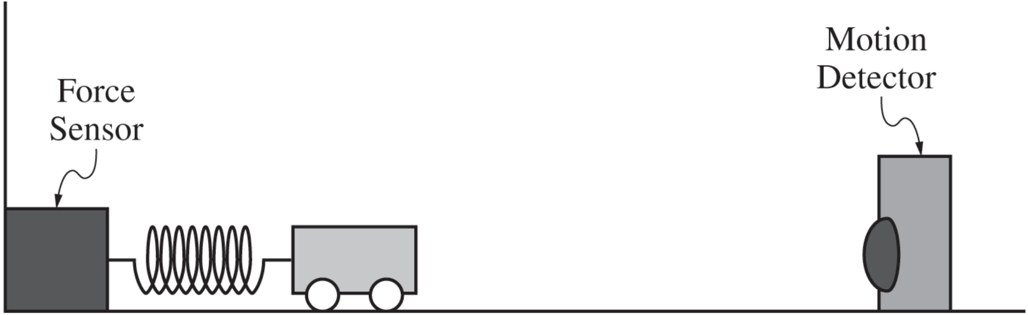


Figure 2

Question 2

2024 ▪ Q2

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

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

(b)(i) (b)

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

Vertical axis: ____________________ Horizontal axis: ____________________

Question 2

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

Question 2

2024 ▪ Q2

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

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

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

Question 2

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

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

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

Question 2

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

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

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

Question 2

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

Solution 2

(a) Mark scheme

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

Solution 2

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

Solution 2

(b)(i) Mark scheme

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

Solution 2

(b)(ii) Mark scheme

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

Solution 2

(c)(i)

Mark scheme

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

Solution 2

(c)(ii)

Mark scheme

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

Solution 2

(c)(iii)

Mark scheme

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

Question 3

2022 ▪ Q3

[Figure: A wheel mounted on a horizontal axle, standing on a support post above a floor. A string is wrapped around the wheel's rim and hangs down to a small hanging block. Labels: "Wheel" (top, pointing to the wheel), "Axle" (pointing to the horizontal axle at the wheel's center), "Hanging Block" (pointing to the small block hanging from the string), "Floor" (the ground below).]

A wheel is mounted on a horizontal axle. A light string is attached to the wheel's rim and wrapped around it several times, and a small block is attached to the free end of the string, as shown in the figure. When the block is released from rest and begins to fall, the wheel begins to rotate with negligible friction.

Question 3

Two students are discussing how different forms of energy change as the block falls. One student says that the kinetic energy of the block increases as it falls. The second student says that this is because gravitational potential energy is converted to kinetic energy. The students decide to test whether the decrease in gravitational potential energy is equal to the increase in the block's kinetic energy from when the block starts moving to immediately before it reaches the floor.

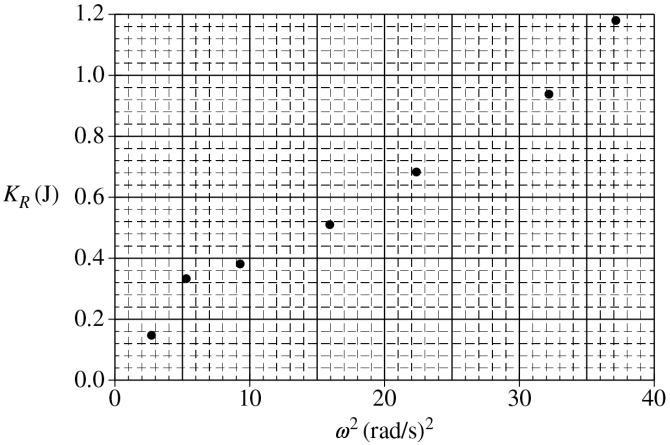
(a) Design an experimental procedure that the students could use to compare the increase in the block's translational kinetic energy with the decrease in the gravitational potential energy of the block-Earth system as the block falls.

Question 3

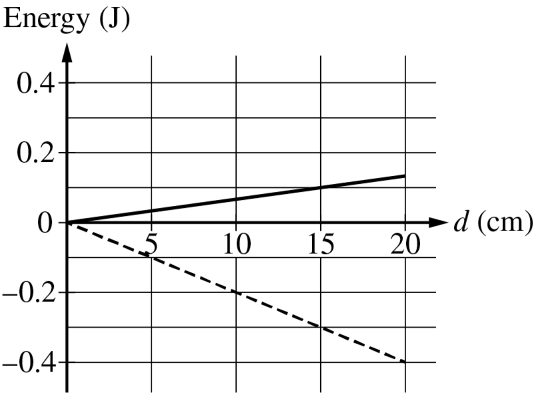
In the table, list the quantities that would be measured in your experiment. Define a symbol to represent each quantity and list the equipment that would be used to measure each quantity. You do not need to fill in every row. If you need additional rows, you may add them in the space just below the table.
In the space to the right of the table, describe the overall procedure. Provide enough detail so that another student could replicate the experiment, including any steps necessary to reduce experimental uncertainty. As needed, use the symbols defined in the table.
If needed, you may include a simple diagram of the setup with your procedure.

Quantity to Be Measured	**Symbol for Quantity**	**Equipment for Measurement**	**Procedure (and diagram, if needed)**

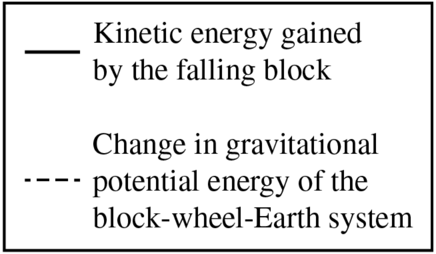
Question 3



Question 3

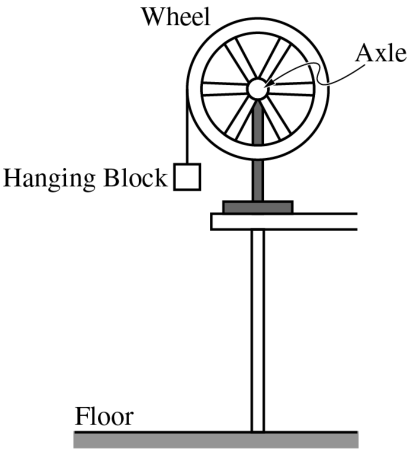


Energy (J)
0.4
0.2
0
–0.2
–0.4
5
10
15
20
d (cm)



Kinetic energy gained by the falling block
Change in gravitational potential energy of the block-wheel-Earth system

Question 3



Question 3

2022 ▪ Q3

[Figure: A wheel mounted on a horizontal axle, standing on a support post above a floor. A string is wrapped around the wheel's rim and hangs down to a small hanging block. Labels: "Wheel" (top, pointing to the wheel), "Axle" (pointing to the horizontal axle at the wheel's center), "Hanging Block" (pointing to the small block hanging from the string), "Floor" (the ground below).]

A wheel is mounted on a horizontal axle. A light string is attached to the wheel's rim and wrapped around it several times, and a small block is attached to the free end of the string, as shown in the figure. When the block is released from rest and begins to fall, the wheel begins to rotate with negligible friction.

Two students are discussing how different forms of energy change as the block falls. One student says that the kinetic energy of the block increases as it falls. The second student says that this is because gravitational potential energy is converted to kinetic energy. The students decide to test whether the decrease in gravitational potential energy is equal to the increase in

Question 3

the block's kinetic energy from when the block starts moving to immediately before it reaches the floor.

(b) Explain how the students could determine the kinetic energy of the block immediately before it reaches the floor using the quantities you indicated in the table in part (a).

Question 3

2022 ▪ Q3

[Figure: A wheel mounted on a horizontal axle, standing on a support post above a floor. A string is wrapped around the wheel's rim and hangs down to a small hanging block. Labels: "Wheel" (top, pointing to the wheel), "Axle" (pointing to the horizontal axle at the wheel's center), "Hanging Block" (pointing to the small block hanging from the string), "Floor" (the ground below).]

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Question 3

the block's kinetic energy from when the block starts moving to immediately before it reaches the floor.

(c) [Graph: "Energy (J)" on the y-axis from -0.4 to 0.4 J (gridlines at $-0.4, -0.2, 0, 0.2, 0.4$), "*d* (cm)" on the x-axis from 0 to 20 cm (gridlines at 5, 10, 15, 20). A solid line labeled "Kinetic energy gained by the falling block" starts near $(0, 0)$ and rises gently to about $(20, 0.15)$. A dashed line labeled "Change in gravitational potential energy of the block-wheel-Earth system" starts near $(0, 0)$ and falls to about $(20, -0.35)$.]

The graph above represents both the change in the gravitational potential energy of the block-wheel-Earth system and the translational kinetic energy gained by the block as functions of the block's falling distance *d*. On the graph, draw a line or curve to represent the rotational kinetic energy of the wheel as a function of the block's falling distance *d*.

Question 3

2022 ▪ Q3

[Figure: A wheel mounted on a horizontal axle, standing on a support post above a floor. A string is wrapped around the wheel's rim and hangs down to a small hanging block. Labels: "Wheel" (top, pointing to the wheel), "Axle" (pointing to the horizontal axle at the wheel's center), "Hanging Block" (pointing to the small block hanging from the string), "Floor" (the ground below).]

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Question 3

the block's kinetic energy from when the block starts moving to immediately before it reaches the floor.

(d)(i) The students also measure the angular velocity ω of the wheel as the block falls and determine the rotational kinetic energy K_R of the wheel. The students then make a graph of K_R as a function of ω^2, as shown.

[Graph: "K_R (J)" on the y-axis from 0.0 to 1.2 J (gridlines at 0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2), "ω^2 (rad/s)^2" on the x-axis from 0 to 40 (gridlines at 0, 10, 20, 30, 40). Data points (approximate): $(5, 0.15)$, $(8, 0.28)$, $(10, 0.35)$, $(17, 0.5)$, $(24, 0.65)$, $(32, 0.95)$, $(35, 1.15)$.]

On the above graph, draw a straight line that best represents the data.

(d)(ii) Using the line you drew for part (d)(i), calculate an experimental value for the rotational inertia of the wheel.

Solution 3

(a) Mark scheme

- Design: measure the mass m_B of the block with a mass balance; hold the block with the string taut and measure the fall distance d (initial height above the floor) with a meterstick; release the block and use a stopwatch to measure the fall time t_B (start at release, stop when the block hits the floor); repeat 3 trials at the same d and repeat for several different values of d to reduce uncertainty (e.g. by averaging). Table: Mass of block m_B – mass balance; Distance block falls d – meterstick; Time for block to fall t_B – stopwatch. Scoring (1 point each): listing relevant equipment matching the measured quantities; listing measurements sufficient to determine the block's kinetic energy; listing measurements sufficient to determine the gravitational PE of the block-Earth system; a plausible procedure

Solution 3

(can be done in a typical school physics lab); attempting to reduce uncertainty (e.g. repeated trials/averaging).

Solution 3

(b)

Mark scheme

- Compute the block's average speed as $d/t_B; sinceitfallsfromrestwithconstantacceleration, thef$ $2d/t_B. ThenthefinalkineticenergyisK = \frac{1}{2}m_B v_F^2 = \frac{1}{2}m_B(2d/t_B)^2.Scoring :$ $1 pointforindicatingthatmassandvelocityareneeded(neednotbethefinalvelocity); 1 pointforavalic$

Solution 3

(c) Mark scheme

- On the Energy vs. d graph, draw a straight line through the origin with positive slope representing the kinetic energy gained by the falling block, and a line representing the change in gravitational PE such that the total energy sum is (approximately) zero at all values of d – the correct line passes through the origin and through (15 cm, 0.2 J), so that KE gained plus the (negative) change in PE sums to zero, showing energy conservation. Scoring: 1 point for drawing a straight line that passes through the origin and has a positive slope; 1 point for drawing a line that yields a total energy sum of zero at all values of d.

Solution 3

(d)(i)

Mark scheme

- On the K$_{R}vs.\omega^{2}graph, drawareasonablebest-fitstraightlinethroughtheplotteddatapoints.Scor$
$1 pointfordrawingareasonablebest - fitline.$

Solution 3

(d)(ii)

Mark scheme

- From the best-fit line, slope $= \dfrac{1.04 - 0.20}{35 - 2.5} = 0.0258$ kg $\cdot$ m$^2 .SinceK_R = \dfrac{1}{2}I\omega^2, theslopeofK_Rvs.\omega^2 equals \dfrac{1}{2}I, soI = 2 \times$ slope $= 0.0517$ kg $\cdot$ m$^2 .Scoring : 1 pointforcorrectlycalculatingavaluefortheslopeusingpointsonthedrawnline(orstatingacalculatc$

Question 3

2015 ▪ Q3

[Figure: A block is held against a spring of negligible mass attached to a wall, on a frictionless surface, at position $x = -D$. Position $x = 0$ marks the end of the frictionless surface and the start of a rough (shaded) track extending to the right. A dashed box near $x = 0$ and another dashed box further right (near $x = 3D$) mark reference positions. The x-axis is labeled with $-D$, 0, and $3D$.]

A block is initially at position $x = 0$ and in contact with an uncompressed spring of negligible mass. The block is pushed back along a frictionless surface from position $x = 0$ to $x = -D$, as shown above, compressing the spring by an amount $\Delta x = D$. The block is then released. At $x = 0$ the block enters a rough part of the track and eventually comes to rest at position $x = 3D$. The coefficient of kinetic friction between the block and the rough track is μ.

Question 3

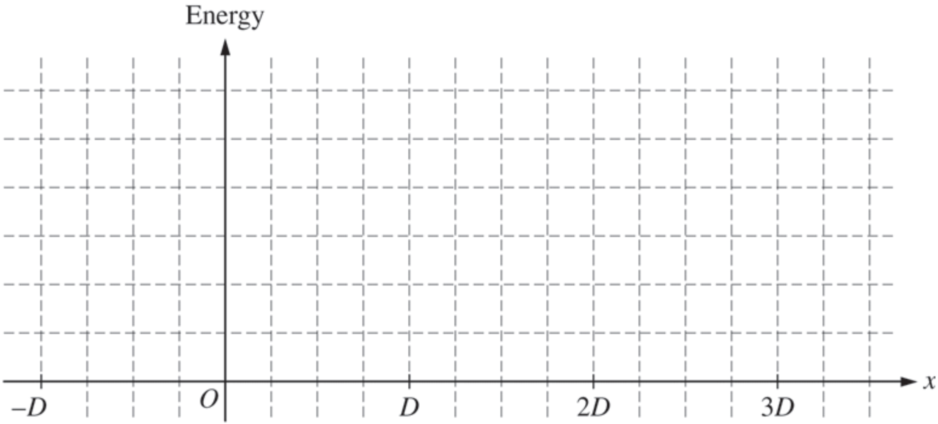
(a) On the axes below, sketch and label graphs of the following two quantities as a function of the position of the block between $x = -D$ and $x = 3D$. You do not need to calculate values for the vertical axis, but the same vertical scale should be used for both quantities.

i. The kinetic energy K of the block

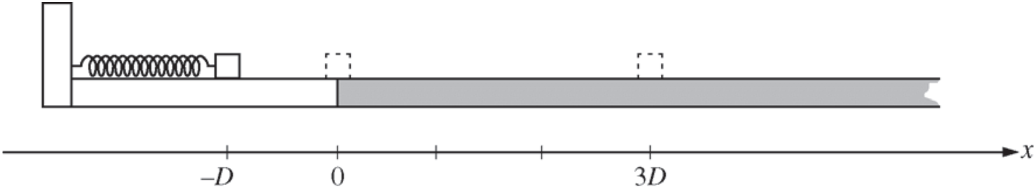
ii. The potential energy U of the block-spring system

[Blank grid: vertical axis labeled "Energy" (unmarked scale), horizontal axis labeled x with gridlines/tick labels at $-D$, O, D, $2D$, $3D$, for the student to sketch the two graphs on.]

Question 3



Question 3



Question 3

2015 ▪ Q3

[Figure: A block is held against a spring of negligible mass attached to a wall, on a frictionless surface, at position $x = -D$. Position $x = 0$ marks the end of the frictionless surface and the start of a rough (shaded) track extending to the right. A dashed box near $x = 0$ and another dashed box further right (near $x = 3D$) mark reference positions. The x-axis is labeled with $-D$, 0, and $3D$.]

A block is initially at position $x = 0$ and in contact with an uncompressed spring of negligible mass. The block is pushed back along a frictionless surface from position $x = 0$ to $x = -D$, as shown above, compressing the spring by an amount $\Delta x = D$. The block is then released. At $x = 0$ the block enters a rough part of the track and eventually comes to rest at position $x = 3D$. The coefficient of kinetic friction between the block and the rough track is μ.

(b)(i) The spring is now compressed twice as much, to $\Delta x = 2D$. A student is asked to predict whether the final position of the block will be twice as far at $x = 6D$. The

Question 3

student reasons that since the spring will be compressed twice as much as before, the block will have more energy when it leaves the spring, so it will slide farther along the track before stopping at position $x = 6D$.

Which aspects of the student's reasoning, if any, are correct? Explain how you arrived at your answer.

(b)(ii) Which aspects of the student's reasoning, if any, are incorrect? Explain how you arrived at your answer.

Question 3

2015 ▪ Q3

[Figure: A block is held against a spring of negligible mass attached to a wall, on a frictionless surface, at position $x = -D$. Position $x = 0$ marks the end of the frictionless surface and the start of a rough (shaded) track extending to the right. A dashed box near $x = 0$ and another dashed box further right (near $x = 3D$) mark reference positions. The x-axis is labeled with $-D$, 0, and $3D$.]

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(c) Use quantitative reasoning, including equations as needed, to develop an expression for the new final position of the block. Express your answer in terms of D.

Question 3

2015 ▪ Q3

[Figure: A block is held against a spring of negligible mass attached to a wall, on a frictionless surface, at position $x = -D$. Position $x = 0$ marks the end of the frictionless surface and the start of a rough (shaded) track extending to the right. A dashed box near $x = 0$ and another dashed box further right (near $x = 3D$) mark reference positions. The x-axis is labeled with $-D$, 0, and $3D$.]

A block is initially at position $x = 0$ and in contact with an uncompressed spring of negligible mass. The block is pushed back along a frictionless surface from position $x = 0$ to $x = -D$, as shown above, compressing the spring by an amount $\Delta x = D$. The block is then released. At $x = 0$ the block enters a rough part of the track and eventually comes to rest at position $x = 3D$. The coefficient of kinetic friction between the block and the rough track is μ.

(d) Explain how any correct aspects of the student's reasoning identified in part (b) are expressed by your mathematical relationships in part (c). Explain how your

Question 3

relationships in part (c) correct any incorrect aspects of the student's reasoning identified in part (b). Refer to the relationships you wrote in part (c), not just the final answer you obtained by manipulating those relationships.

Solution 3

(a) Mark scheme

- Sketch Energy vs. position x from $x = -D$ to $x = 3D$. Region $x \in [-D, 0]$ (block still compressing/leaving the spring): kinetic energy K starts at 0 at $x = -D$ and rises to a maximum at $x = 0$; potential energy U (spring) starts at a maximum at $x = -D$ and falls to 0 at $x = 0$, with $K + U$ constant throughout (energy conservation while on the spring). Region $x \in [0, 3D]$ (block on the rough track, spring no longer in contact): potential energy $U = 0$ for the entire interval; kinetic energy K decreases LINEARLY from its maximum value at $x = 0$ to zero at $x = 3D$ (constant kinetic friction force removes energy linearly with distance). Scoring (4 points, 1 each): (1) either energy curve sketched with a reasonably correct shape from $x = -D$ to $x = 0$, with zero and maximum values at the

Solution 3

correct locations; (2) both curves sketched from $x = -D$ to $x = 0$ with shapes/values such that total energy is constant (even if the individual curve shapes are imperfect); (3) potential energy sketched as zero from $x = 0$ to $x = 3D$; (4) kinetic energy sketched as a linear function decreasing from its maximum at $x = 0$ to zero at $x = 3D$.

Solution 3

(b)(i)

Mark scheme

- The student is CORRECT that the block will have more energy when it leaves the spring: compressing the spring twice as far (to $\Delta x = 2D$) stores spring potential energy $U = \frac{1}{2}k(\Delta x)^2$, which scales with the SQUARE of the compression, so doubling the compression gives $4\times$ the stored (and hence kinetic) energy. 1 point for identifying this aspect of the student's reasoning as correct, with a valid explanation.

Solution 3

(b)(ii)

Mark scheme

- The student is INCORRECT that the block will travel exactly twice as far (predicting $x = 6D$): this conclusion assumes energy scales LINEARLY with compression, but spring potential energy actually scales with the SQUARE of the compression ($U \propto \Delta x^2$), so the relationship between compression and final sliding distance is not simply proportional. 1 point for identifying this aspect as incorrect, with a valid explanation.

Solution 3

(c) Mark scheme

- Quantitative derivation: original spring energy $U_1 = \frac{1}{2}kD^2$; with double compression, $U_2 = \frac{1}{2}k(2D)^2 = 4\left(\frac{1}{2}kD^2\right) = 4U_1$. Original friction work to stop the block over distance $3D$ (from $x = 0$ to $x = 3D$): $W_1 = \mu mg(3D)$; in the new case, work to stop over the new (unknown) sliding distance Δx_2: $W_2 = \mu mg\,\Delta x_2$. By energy conservation $W_1 = U_1$ and $W_2 = U_2 = 4U_1 = 4W_1$, so $\mu mg\,\Delta x_2 = 4(\mu mg(3D)) \Rightarrow \Delta x_2 = 4(3D) = 12D$. The new final position is $x = 12D$ (NOT $6D$ – four times, not twice, the original stopping distance). Scoring (3 points, 1 each): (1) indicating that the final spring energy (mechanical energy of the block as it reaches the rough track) is four times the original spring energy; (2) indicating that the frictional force is unchanged; (3) equating the

Solution 3

initial spring energy to an expression showing the friction-dissipated energy is proportional to sliding distance, and solving for the new distance ($\Delta x_2 = 12D$).

Solution 3

(d) Mark scheme

- The student's correct reasoning that the block has more energy in the second situation is expressed by the part (c) comparison of initial spring energies ($U_2 = 4U_1$). The student's correct reasoning that the block slides farther is expressed by the part (c) equation showing that the friction work needed to stop the block in the second situation is a factor ($4\times$) greater than in the first ($W_2 = 4W_1$). The student's incorrect reasoning – that distance scales LINEARLY with compression (so doubling compression should double the distance to $6D$) – is corrected by the part (c) expression for spring energy, $U = \frac{1}{2}kx^2$, which shows energy (and hence stopping distance) scales with the SQUARE of the compression, giving $4\times$ the distance ($12D$) rather than $2\times$ ($6D$). Scoring (3

Solution 3

points, 1 each): (1) linking the 'more energy' correct reasoning to the part (c) energy comparison; (2) linking the 'slides farther' correct reasoning to the part (c) friction-work equation; (3) showing how the part (c) spring-energy expression corrects the student's incorrect linear-scaling assumption. Must reference the relationships from part (c), not just the final numeric answer.