Past-paper walk-through

Forces and Free-Body Diagrams ▪ 2.2

eXercise

Questions in this set

- 2024 Q1
- 2024 Q3
- 2022 Q1
- 2019 Q2
- 2018 Q1
- 2017 Q2
- 2016 Q1
- 2015 Q1
- 2015 Q4

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

2024 ▪ Q1

[Figure showing a track: Point A is at the top of a curved ramp at height $6R$ above the horizontal, with a block of mass M shown as a small square on the ramp near A. The ramp curves down to the horizontal level. On the horizontal section there is a small circular loop (Point B at its highest point, radius R) and further along, at the far right, a larger circular loop (Point C at its highest point, radius R) that sits on a raised platform of height $2R$ above the horizontal ground level.]

A block of mass M is released from rest at Point A, a height $6R$ above the horizontal. After being released, the block slides down a track, as shown. When released from Point A, the block does not lose contact with the track at any point. Points B and C are located at the highest points of their respective circular loops, both of radius R. All frictional forces are negligible.

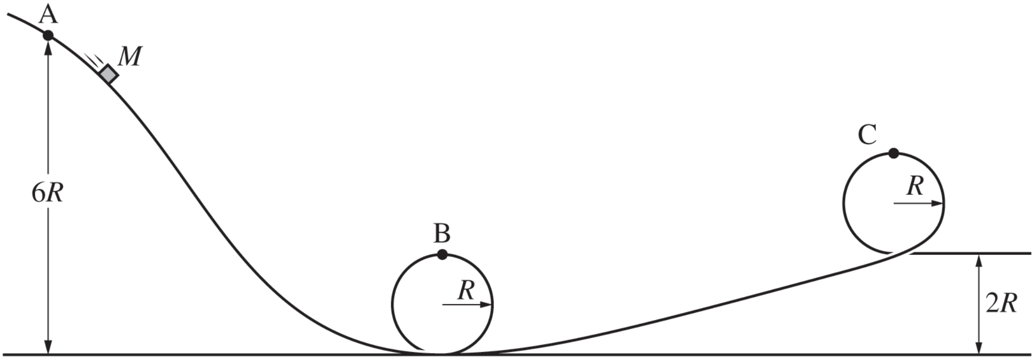
Question 1

(a) [Two energy bar chart diagrams, each with a vertical "Energy" axis (no numerical scale, gridlines shown as horizontal dashed lines) and two columns labeled U_g and K on the horizontal axis.]
Diagram A shows an energy bar chart that represents the gravitational potential energy U_g of the block-Earth system and the kinetic energy K of the block at Point A, when the block is released from rest at height $6R$. In Diagram A, the U_g column is shaded up to a height representing the full scale (six gridline units above zero), and the K column has zero height (block released from rest).
Diagram B has the same axes ("Energy" vertical axis with the same gridline scale, columns labeled U_g and K) but is unshaded, to be completed by the student.
(a) **Draw** shaded regions in Diagram B that represent the gravitational potential energy U_g and kinetic energy K of the block-Earth system when the block is located at Point B, a height $2R$ above the horizontal.

Question 1

- Shaded regions 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 relative height of each shaded region should reflect the magnitude of the respective energy consistent with the scale shown in Diagram A.

Question 1



Question 1

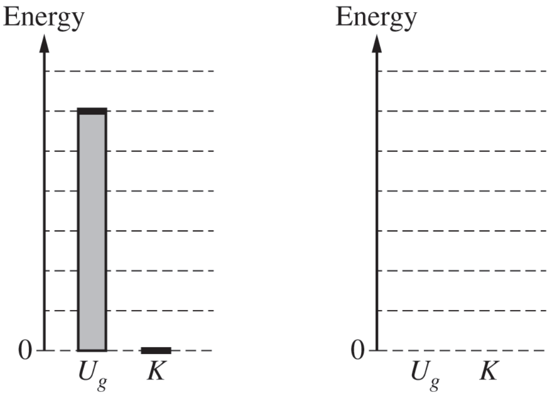


Diagram A

Diagram B

Question 1

2024 ▪ Q1

[Figure showing a track: Point A is at the top of a curved ramp at height $6R$ above the horizontal, with a block of mass M shown as a small square on the ramp near A. The ramp curves down to the horizontal level. On the horizontal section there is a small circular loop (Point B at its highest point, radius R) and further along, at the far right, a larger circular loop (Point C at its highest point, radius R) that sits on a raised platform of height $2R$ above the horizontal ground level.]

A block of mass M is released from rest at Point A, a height $6R$ above the horizontal. After being released, the block slides down a track, as shown. When released from Point A, the block does not lose contact with the track at any point. Points B and C are located at the highest points of their respective circular loops, both of radius R. All frictional forces are negligible.

(b) Starting with conservation of energy, **derive** an expression for the speed of the block at Point B. Express your answer in terms of R and physical constants, as

Question 1

appropriate. Begin your derivation by writing a fundamental physics principle or an equation from the reference book.

Question 1

2024 ▪ Q1

[Figure showing a track: Point A is at the top of a curved ramp at height $6R$ above the horizontal, with a block of mass M shown as a small square on the ramp near A. The ramp curves down to the horizontal level. On the horizontal section there is a small circular loop (Point B at its highest point, radius R) and further along, at the far right, a larger circular loop (Point C at its highest point, radius R) that sits on a raised platform of height $2R$ above the horizontal ground level.]

A block of mass M is released from rest at Point A, a height $6R$ above the horizontal. After being released, the block slides down a track, as shown. When released from Point A, the block does not lose contact with the track at any point. Points B and C are located at the highest points of their respective circular loops, both of radius R. All frictional forces are negligible.

(c)(i) [A single dot representing the block, drawn on the page, with blank space around it for the student to draw force vectors.]

Question 1

On the following dot that represents the block, **draw** and **label** the forces (not components) that are exerted on the block at the instant the block slides through Point C. Each force must be represented by a distinct arrow starting on, and pointing away from, the dot.

(c)(ii) A student claims that $4R$ is the minimum height of Point A, such that the block can slide through Point C without losing contact with the track after the block is released from rest. Briefly **explain** why this claim is incorrect.

Solution 1

(a)

Mark scheme

- Diagram A (given, at Point A, height $6R$): the U_g bar fills the whole scale (6 units) and $K = 0$ since the block starts at rest. By conservation of mechanical energy the total energy stays 6 units everywhere on the track. At Point B (height $2R$), U_g is proportional to height, so $U_g = 2$ units, and the rest converts to kinetic energy: $K = 6 - 2 = 4$ units. Full credit (2 points): draw the two bars in Diagram B so their total heights sum to 6 units (1 point — may be earned even if only one bar is drawn), AND draw the U_g bar with height exactly 2 units (1 point).

Solution 1

(b)

Mark scheme

- Derive v_B from conservation of energy: $E_i = E_f \Rightarrow U_{gA} = U_{gB} + K_B \Rightarrow mgy_A = mgy_B + \frac{1}{2}mv^2$. Substituting $y_A = 6R$, $y_B = 2R$: $Mg(6R) = Mg(2R) + \frac{1}{2}Mv^2 \Rightarrow g(6R) = g(2R) + \frac{1}{2}v^2 \Rightarrow \frac{1}{2}v^2 = 4gR \Rightarrow v = \sqrt{8gR}$. Points: a multi-step derivation that begins with conservation of energy (1 point); AND one of — the correct final answer $v = \sqrt{8gR}$, or the correct substitution of the initial/final heights ($6R$, $2R$, consistent with part (a)) (1 point).

Solution 1

(c)(i)

Mark scheme

- At Point C (top of the vertical loop) draw two arrows starting on the dot, both pointing straight down (toward the center of the loop): one labeled as the gravitational force (F_g, F_G, W, mg, Mg, "grav force", etc. — not G or g alone) and one labeled as the normal force (F_N, F_n, N, "normal force", or "track force"). Arrows of any nonzero magnitude earn credit. Points: downward arrow labeled gravitational force (1 point); downward arrow labeled normal force (1 point).

Solution 1

(c)(ii) Mark scheme

- The claim that $4R$ is the minimum height is incorrect: if the block were released from height $4R$, then by energy conservation the block would have speed equal to zero at Point C — and if the speed at the top of the loop is zero, the block cannot maintain contact with the track there (it needs nonzero speed so gravity plus the normal force can supply the centripetal force). So $4R$ is too low, not the true minimum. Full credit (1 point) for indicating any of: the block must be moving at the top of the loop to remain in contact; zero speed at Point C means the block loses contact; the block doesn't have enough kinetic energy/momentum and will lose contact.

Question 3

2024 ▪ Q3

[Figure 1: A vertical wall is shown on the left. Two points are marked on the wall: Point 1 near the top, and Point 2 lower down (above the hinge). A horizontal beam extends from a hinge at the base of the wall to the right, with length L labeled along its underside. A string connects from Point 1 on the wall diagonally down to the right end of the beam, making angle θ_1 with the beam at the point where the string meets the beam.]

The left end of a uniform beam of mass M and length L is attached to a wall by a hinge, as shown in Figure 1. One end of a string with negligible mass is attached to the right end of the beam. The other end of the string is attached to the wall above the hinge at Point 1. The beam remains horizontal. The hinge exerts a force on the beam of magnitude F_H, and the angle between the beam and the string is $\theta = \theta_1$.

Question 3

(a) [A rectangle representing the beam, drawn horizontally, blank for the student to draw and label force vectors.]
The following rectangle represents the beam in Figure 1. On the rectangle, **draw** and **label** the forces (not components) exerted on the beam. Draw each force as a distinct arrow starting on, and pointing away from, the point at which the force is exerted.

Question 3

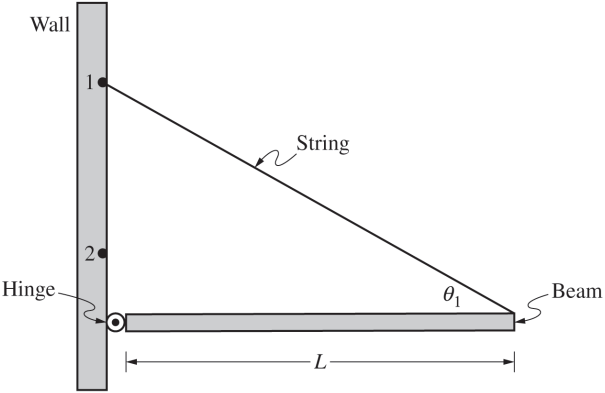


Figure 1

Question 3

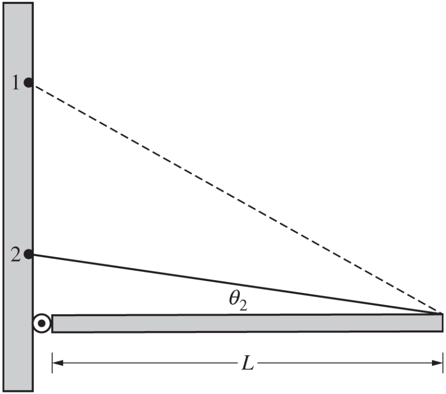
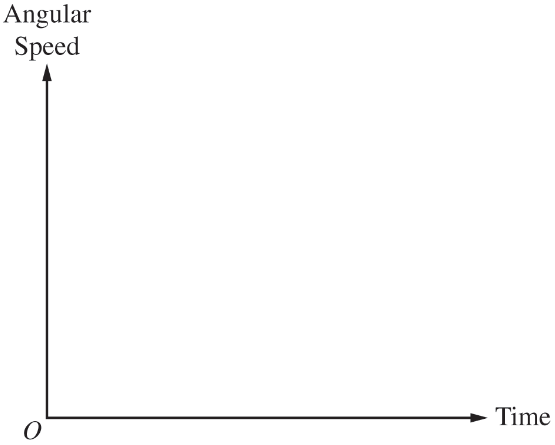


Figure 2

Question 3



Question 3

2024 ▪ Q3

[Figure 1: A vertical wall is shown on the left. Two points are marked on the wall: Point 1 near the top, and Point 2 lower down (above the hinge). A horizontal beam extends from a hinge at the base of the wall to the right, with length L labeled along its underside. A string connects from Point 1 on the wall diagonally down to the right end of the beam, making angle θ_1 with the beam at the point where the string meets the beam.]

The left end of a uniform beam of mass M and length L is attached to a wall by a hinge, as shown in Figure 1. One end of a string with negligible mass is attached to the right end of the beam. The other end of the string is attached to the wall above the hinge at Point 1. The beam remains horizontal. The hinge exerts a force on the beam of magnitude F_H, and the angle between the beam and the string is $\theta = \theta_1$.

(b) [Figure 2: The same wall, hinge, and beam of length L as in Figure 1, but now the string (solid line) connects from Point 2 on the wall (lower than Point 1) to the right

Question 3

end of the beam, making angle θ_2 with the beam. A dashed line is also shown from Point 1 to the right end of the beam, representing the string's position from Figure 1.]
(b) The string is then attached lower on the wall, at Point 2, and the beam remains horizontal, as shown in Figure 2. The angle between the beam and the string is $\theta = \theta_2$. The dashed line represents the string shown in Figure 1.
The magnitude of the tension in the string shown in Figure 1 is F_{T1}. The magnitude of the tension in the string shown in Figure 2 is F_{T2}. **Indicate** which of the following correctly compares F_{T2} with F_{T1}.
$F_{T2} > F_{T1}$ $F_{T2} < F_{T1}$ $F_{T2} = F_{T1}$
Briefly **justify** your answer, using qualitative reasoning beyond referencing equations.

Question 3

2024 ▪ Q3

[Figure 1: A vertical wall is shown on the left. Two points are marked on the wall: Point 1 near the top, and Point 2 lower down (above the hinge). A horizontal beam extends from a hinge at the base of the wall to the right, with length L labeled along its underside. A string connects from Point 1 on the wall diagonally down to the right end of the beam, making angle θ_1 with the beam at the point where the string meets the beam.]

The left end of a uniform beam of mass M and length L is attached to a wall by a hinge, as shown in Figure 1. One end of a string with negligible mass is attached to the right end of the beam. The other end of the string is attached to the wall above the hinge at Point 1. The beam remains horizontal. The hinge exerts a force on the beam of magnitude F_H, and the angle between the beam and the string is $\theta = \theta_1$.

(c) (c) Starting with Newton's second law in rotational form, **derive** an expression for the magnitude of the tension in the string. Express your answer in terms of M, θ,

Question 3

and physical constants, as appropriate. Begin your derivation by writing a fundamental physics principle or an equation from the reference book.

Question 3

2024 ▪ Q3

[Figure 1: A vertical wall is shown on the left. Two points are marked on the wall: Point 1 near the top, and Point 2 lower down (above the hinge). A horizontal beam extends from a hinge at the base of the wall to the right, with length L labeled along its underside. A string connects from Point 1 on the wall diagonally down to the right end of the beam, making angle θ_1 with the beam at the point where the string meets the beam.]

The left end of a uniform beam of mass M and length L is attached to a wall by a hinge, as shown in Figure 1. One end of a string with negligible mass is attached to the right end of the beam. The other end of the string is attached to the wall above the hinge at Point 1. The beam remains horizontal. The hinge exerts a force on the beam of magnitude F_H, and the angle between the beam and the string is $\theta = \theta_1$.

(d) (d) Is your derived equation in part (c) consistent with your justification in part (b)? **Explain** your reasoning.

Question 3

2024 ▪ Q3

[Figure 1: A vertical wall is shown on the left. Two points are marked on the wall: Point 1 near the top, and Point 2 lower down (above the hinge). A horizontal beam extends from a hinge at the base of the wall to the right, with length L labeled along its underside. A string connects from Point 1 on the wall diagonally down to the right end of the beam, making angle θ_1 with the beam at the point where the string meets the beam.]

The left end of a uniform beam of mass M and length L is attached to a wall by a hinge, as shown in Figure 1. One end of a string with negligible mass is attached to the right end of the beam. The other end of the string is attached to the wall above the hinge at Point 1. The beam remains horizontal. The hinge exerts a force on the beam of magnitude F_H, and the angle between the beam and the string is $\theta = \theta_1$.

(e) [A blank set of axes with vertical axis labeled "Angular Speed" and horizontal axis labeled "Time", origin labeled O.]

Question 3

(e) The string is cut, and the beam begins to rotate about the hinge with negligible friction. On the following axes, **sketch** the angular speed of the beam as a function of time for the time interval while the beam falls but before the beam becomes vertical.

Solution 3

(a) Mark scheme

- Draw three force vectors on the beam, each starting on and pointing away from where the force acts, representing a system in equilibrium: the gravitational force ($F_g/F_G/W/mg/Mg/$"grav force" — not G or g alone) drawn downward from the center of the beam; the tension force ($F_T/F_s/F_{\text{string}}/$"tension force") drawn upward and to the left from the right end of the beam (along the string toward the wall); and the hinge/wall (normal) force ($F_N/F_n/$N/"normal force"/"wall force") drawn upward and to the right from the left end (hinge). The three vectors must show the beam in equilibrium (net force zero). Points: downward gravitational force at the beam's center (1 point); tension force at the right end

Solution 3

directed up and to the left (1 point); a diagram with all three force vectors consistent with equilibrium (1 point).

Solution 3

(b) Mark scheme

- Select $F_{T2} > F_{T1}$ (the tension is larger when the string attaches lower, at Point 2, making a smaller angle with the beam). Justification: for the beam to remain horizontal and in equilibrium, the torque exerted by the string about the hinge must stay the same regardless of attachment point. As the angle θ between the string and beam decreases, the perpendicular (torque-producing) component of the tension for a given tension magnitude decreases, so a larger tension is needed to supply the same torque — equivalently, the vertical component of the tension must still balance the same weight of the bar, and a smaller angle means more tension is needed to achieve the same vertical component. Points: selecting $F_{T2} > F_{T1}$ with an attempt at a relevant justification (1 point); a justification

Solution 3

that relates either the vertical component of tension to the beam's weight, or the force needed to produce the same torque to the string's angle (1 point).

Solution 3

(c) Mark scheme

- Derive F_T from Newton's second law in rotational form: $\Sigma\tau = I\alpha$ (with $\alpha = 0$ since the beam is in equilibrium), so $\tau_{\text{gravity}} + \tau_{\text{string}} = 0$. Taking torques about the hinge: $(F_g)\frac{L}{2}\sin 90° - F_T(L)\sin\theta = 0 \Rightarrow Mg\frac{L}{2} = (F_T \sin\theta)L \Rightarrow F_T = \dfrac{Mg}{2\sin\theta}$. Points: a multi-step derivation beginning with $\Sigma\tau = I\alpha$ or $\Sigma\tau = 0$ (1 point); indicating that the net torque is zero OR the net force is zero (1 point); indicating one of — the torque from the string is $(F_T \sin\theta)L$, the torque from the beam's weight is $Mg\frac{L}{2}$, or the correct final answer $F_T = \dfrac{Mg}{2\sin\theta}$ (1 point).

Solution 3

(d) Mark scheme

- The derived equation $F_T = \dfrac{Mg}{2\sin\theta}$ is consistent with the part (b) reasoning: tension is inversely proportional to $\sin\theta$, and for $\theta < 90^\circ$, $\sin\theta$ decreases as θ decreases, so the required tension is greater for smaller angles — matching the claim that $F_{T2} > F_{T1}$ when the string is attached lower (smaller angle). Points: an attempt to use the functional dependence of the part (c) equation to relate to the part (b) reasoning, even if not fully correct (1 point); an explanation that correctly relates the two (1 point).

Solution 3

(e)

Mark scheme

- Sketch the angular speed of the beam vs. time (from the moment the string is cut until the beam becomes vertical) as a curve that starts at the origin, is monotonically increasing throughout the interval, and is concave down (the rate of increase in angular speed decreases over time, since the gravitational torque about the hinge shrinks as the beam rotates toward vertical). Points: drawing a graph that is monotonically increasing (1 point); drawing a concave-down curve (1 point).

Question 1

2022 ▪ Q1

Two blocks are connected by a string that passes over a pulley, as shown above. Block 1 is on a horizontal surface and is attached to a spring that is at its unstretched length. Frictional forces are negligible in the pulley's axle and between the block and the surface. Block 2 is released from rest and moves downward before momentarily coming to rest.

k_0 is the spring constant of the spring.

M_1 is the mass of block 1.

M_2 is the mass of block 2.

Δy is the distance block 2 moves before momentarily coming to rest.

[Figure: A horizontal tabletop with a spring of constant k_0 attached to a wall on the left, connected to Block 1 (M_1) resting on the table. A string runs from Block 1

Question 1

horizontally to a pulley at the right edge of the table, then down to a hanging Block 2 (M_2), which is shown displaced a distance Δy downward from its initial position.]

(a)(i) Block 2 starts from rest and speeds up, then it slows down and momentarily comes to rest at a position below its initial position. In terms of only the forces directly exerted on block 2, explain why block 2 initially speeds up and explain why it slows down to a momentary stop.

(a)(ii) Derive an expression for the distance Δy that block 2 travels before momentarily coming to rest. Express your answer in terms of k_0, M_1, M_2, and physical constants, as appropriate.

Question 1

Diagram A: Negligible Friction

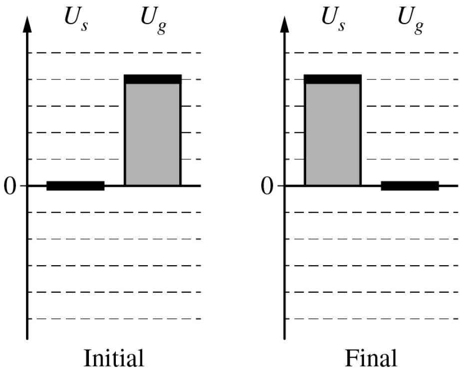
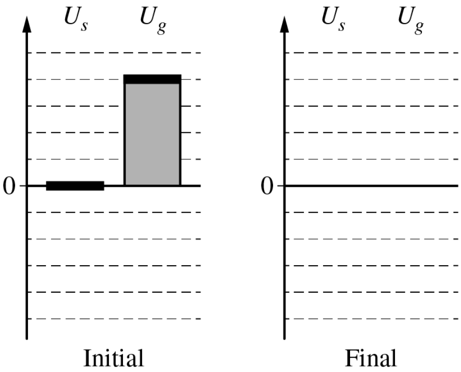
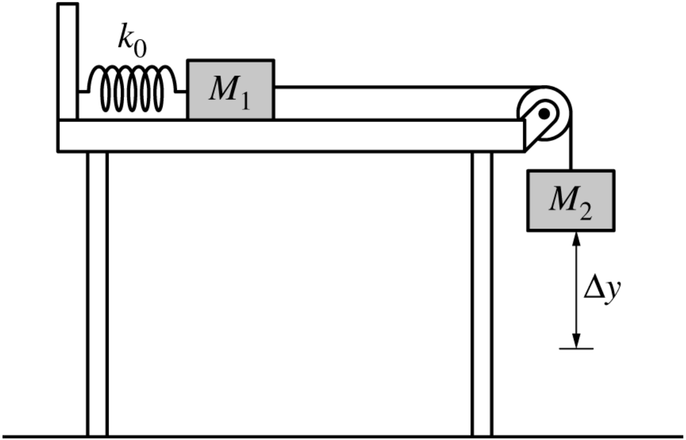


Diagram B: Nonnegligible Friction



Question 1



Question 1

2022 ▪ Q1

Two blocks are connected by a string that passes over a pulley, as shown above. Block 1 is on a horizontal surface and is attached to a spring that is at its unstretched length. Frictional forces are negligible in the pulley's axle and between the block and the surface. Block 2 is released from rest and moves downward before momentarily coming to rest.

k_0 is the spring constant of the spring.

M_1 is the mass of block 1.

M_2 is the mass of block 2.

Δy is the distance block 2 moves before momentarily coming to rest.

[Figure: A horizontal tabletop with a spring of constant k_0 attached to a wall on the left, connected to Block 1 (M_1) resting on the table. A string runs from Block 1 horizontally to a pulley at the right edge of the table, then down to a hanging Block 2 (M_2), which is shown displaced a distance Δy downward from its initial position.]

Question 1

(b) Indicate whether the total mechanical energy of the blocks-spring-Earth system changes as block 2 moves downward.

____ Changes ____ Does not change

Briefly explain your reasoning.

Question 1

2022 ▪ Q1

Two blocks are connected by a string that passes over a pulley, as shown above. Block 1 is on a horizontal surface and is attached to a spring that is at its unstretched length. Frictional forces are negligible in the pulley's axle and between the block and the surface. Block 2 is released from rest and moves downward before momentarily coming to rest.

k_0 is the spring constant of the spring.

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Question 1

(c) Consider the system that includes the spring, Earth, both blocks, and the string, but not the surface. Let the initial state be when the blocks are at rest just before they start moving, and let the final state be when the blocks first come momentarily to rest. Diagram A below is a bar chart that represents the energies in the scenario where there is negligible friction between block 1 and the surface.

The shaded-in bars in the energy bar charts represent the potential energy of the spring and the gravitational potential energy of the blocks-Earth system, U_s and U_g, respectively, in the initial and final states. Positive energy values are above the zero-point line ("0") and negative energy values are below the zero-point line.

[Diagram A: Negligible Friction — two bar charts labeled "Initial" and "Final", each with two bars U_s and U_g, on a vertical axis with a zero-point line "0". Initial: U_s bar is a thin sliver just above 0 (near zero), U_g bar is tall, extending well above 0. Final: U_s

Question 1

bar extends above 0 to a moderate height, U_g bar is a thin sliver just below 0 (near zero, slightly negative).]
[Diagram B: Nonnegligible Friction — two bar charts labeled "Initial" and "Final", each with two bars U_s and U_g. Initial state already provided: U_s bar is a thin sliver just above 0, U_g bar is tall extending well above 0 (same as Diagram A's initial state). Final state is blank/empty, to be completed by the student.]
Complete diagram B (at right above) for the scenario in which friction is nonnegligible. The energies for the initial state are already provided. Shade in the energies in the final state using the same scale as in diagram A.

- Shaded regions should start at the solid line representing the zero-point line.
- Represent any energy that is equal to zero with a distinct line on the zero-point line.

Solution 1

(a)(i) Mark scheme

- Block 2 speeds up while the gravitational force (weight, W) exerted on it is greater than the tension (T) in the string (net force and acceleration point downward, in the direction of motion). As Block 2 falls, the spring (connected to Block 1) stretches further, increasing the tension until T becomes greater than W; the net force and acceleration then point upward (opposite the velocity), decelerating Block 2 until it momentarily stops. Scoring: 1 point for relating the net force to acceleration/change in velocity; 1 point for a correct description of the relative magnitudes of T and W during the motion (both T>W initially and T<W later) – the spring force must be connected to the string tension, not treated as acting directly on Block 2.

Solution 1

(a)(ii)

Mark scheme

- Conservation of energy for the blocks-spring-Earth system (K$_i = K_f = 0) : U_{g,i} + M_2 g\Delta y = U_{g,f} + \frac{1}{2}k_0\Delta y^2, i.e. M_2 g\Delta y = \frac{1}{2}k_0\Delta y^2, so M_2 g = \frac{1}{2}k_0\Delta y, giving \Delta y = \frac{2M_2 g}{k_0}. Scoring : 1 point for a correct energy - conservation equation including both a gravitational PE term and a spring PE term; 1 point for the corr$
  $2M_2 g/k_0 depending only on M_2, k_0, and g.$

Solution 1

(b)

Mark scheme

- Does not change. There are no external forces doing work on the system and no energy is dissipated by friction, so the total mechanical energy of the blocks-spring-Earth system stays the same (energy only transforms between gravitational PE, spring PE, and KE). Scoring: 1 point for selecting "Does not change" with a correct explanation.

Solution 1

(c)

Mark scheme

- With non-negligible friction between Block 1 and the surface, mechanical energy is lost to friction as the blocks move, so at the final state (Block 2 momentarily at rest, $K_f=0$) the total spring PE (U_s) plus gravitational PE (U_g) must be less than the initial total of 4 units. The final bar chart must show both $U_s>0$ and $U_g>0$ (both bars positive), with $U_s+U_g < 4$ units. Scoring: 1 point for a final bar chart where both U_s and U_g are positive; 1 point for a final bar chart where the sum of U_s and U_g is less than four units.

Question 2

2019 ▪ Q2

[Diagram: A horizontal tabletop with Block A resting on top of it near the right edge. A pulley is mounted at the right edge of the tabletop. A light string runs from Block A horizontally to the pulley, then vertically down over the pulley to Block B, which hangs below the tabletop's edge.]

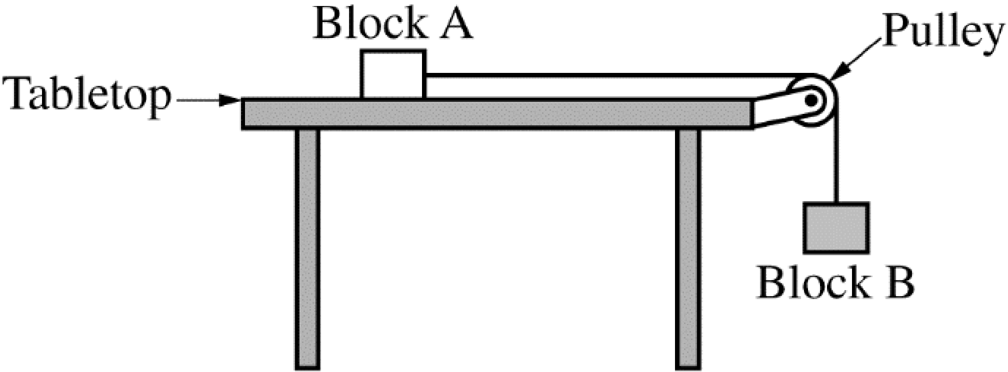
This problem explores how the relative masses of two blocks affect the acceleration of the blocks. Block A, of mass m_A, rests on a horizontal tabletop. There is negligible friction between block A and the tabletop. Block B, of mass m_B, hangs from a light string that runs over a pulley and attaches to block A, as shown above. The pulley has negligible mass and spins with negligible friction about its axle. The blocks are released from rest.

(a)(i) Suppose the mass of block A is much greater than the mass of block B. Estimate the magnitude of the acceleration of the blocks after release.

Question 2

Briefly explain your reasoning without deriving or using equations.
(a)(ii) Now suppose the mass of block A is much less than the mass of block B. Estimate the magnitude of the acceleration of the blocks after release.
Briefly explain your reasoning without deriving or using equations.

Question 2



Question 2

Question 2

2019 ▪ Q2

[Diagram: A horizontal tabletop with Block A resting on top of it near the right edge. A pulley is mounted at the right edge of the tabletop. A light string runs from Block A horizontally to the pulley, then vertically down over the pulley to Block B, which hangs below the tabletop's edge.]

This problem explores how the relative masses of two blocks affect the acceleration of the blocks. Block A, of mass m_A, rests on a horizontal tabletop. There is negligible friction between block A and the tabletop. Block B, of mass m_B, hangs from a light string that runs over a pulley and attaches to block A, as shown above. The pulley has negligible mass and spins with negligible friction about its axle. The blocks are released from rest.

(b) Now suppose neither block's mass is much greater than the other, but that they are not necessarily equal. The dots below represent block A and block B, as indicated by the labels. On each dot, draw and label the forces (not components) exerted on

Question 2

that block after release. Represent each force by a distinct arrow starting on, and pointing away from, the dot.
[Diagram: Two separate large dots side by side on the page, one labeled “Block A” below it and the other labeled “Block B” below it, for the student to draw force vectors on.]

Question 2

2019 ▪ Q2

[Diagram: A horizontal tabletop with Block A resting on top of it near the right edge. A pulley is mounted at the right edge of the tabletop. A light string runs from Block A horizontally to the pulley, then vertically down over the pulley to Block B, which hangs below the tabletop's edge.]

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(c) Derive an equation for the acceleration of the blocks after release in terms of m_A, m_B, and physical constants, as appropriate. If you need to draw anything other than

Question 2

what you have shown in part (b) to assist in your solution, use the space below. Do NOT add anything to the figure in part (b).

Question 2

2019 ▪ Q2

[Diagram: A horizontal tabletop with Block A resting on top of it near the right edge. A pulley is mounted at the right edge of the tabletop. A light string runs from Block A horizontally to the pulley, then vertically down over the pulley to Block B, which hangs below the tabletop's edge.]

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(d) Consider the scenario from part (a)(ii), where the mass of block A is much less than the mass of block B. Does your equation for the acceleration of the blocks from part (c) agree with your reasoning in part (a)(ii)?

Question 2

_____ Yes _____ No

Briefly explain your reasoning by addressing why, according to your equation, the acceleration becomes (or approaches) a certain value when m_A is much less than m_B.

Question 2

2019 ▪ Q2

[Diagram: A horizontal tabletop with Block A resting on top of it near the right edge. A pulley is mounted at the right edge of the tabletop. A light string runs from Block A horizontally to the pulley, then vertically down over the pulley to Block B, which hangs below the tabletop's edge.]

This problem explores how the relative masses of two blocks affect the acceleration of the blocks. Block A, of mass m_A, rests on a horizontal tabletop. There is negligible friction between block A and the tabletop. Block B, of mass m_B, hangs from a light string that runs over a pulley and attaches to block A, as shown above. The pulley has negligible mass and spins with negligible friction about its axle. The blocks are released from rest.

(e) While the blocks are accelerating, the tension in the vertical portion of the string is T_1. Next, the pulley of negligible mass is replaced with a second pulley whose mass is

Question 2

not negligible. When the blocks are accelerating in this scenario, the tension in the vertical portion of the string is T_2. How do the two tensions compare to each other?
_____ $T_2 > T_1$ _____ $T_2 = T_1$ _____ $T_2 < T_1$
Briefly explain your reasoning.

Solution 2

(a)(i) Mark scheme

- Correct claim: the acceleration is nearly zero / small / negligible / much less than g / '<<g'. Point 1: for a correct qualitative answer with an attempted, consistent justification. Point 2: for correct reasoning. Reasoning: block A has a much greater mass (much greater inertia) than block B, so block A strongly resists acceleration and the light block B cannot meaningfully accelerate it; the acceleration of the connected system is therefore nearly zero. (Example 2-point answers: 'Very small, because block A has a large inertia, it won't speed up much.' / 'Close to zero because block B is so light that it can hardly budge block A.')

Solution 2

(a)(ii)

Mark scheme

- Correct claim: the acceleration is nearly g (acceptable: 'g', '9.8 m/s^2', '10 m/s^2', or just '9.8'/'10'). The single point is earned for a correct answer WITH correct justification. Reasoning: block A has negligible mass compared to block B and negligible friction with the tabletop, so essentially no tension is needed to accelerate block A; block B is therefore nearly in free fall, and the string tension is nearly zero, giving the whole system an acceleration close to g.

Solution 2

(b) Mark scheme

- Free-body diagram, Block A (on the tabletop): three distinct force arrows – normal force N (or F_N) pointing straight UP from the table; gravity F_g (or mg, W, $m_A g$) pointing straight DOWN; tension F_T pointing horizontally toward the pulley (i.e. toward block B's side). Free-body diagram, Block B (hanging): two distinct force arrows – tension F_T pointing straight UP (toward the pulley); gravity F_g (or $m_B g$) pointing straight DOWN. Points: 1 for a correct, correctly labeled normal force on block A only (acceptable labels: N, F_N, 'normal force', F_{table}, 'table force', or any label indicating a normal/table force); 1 for correct, correctly labeled gravitational forces on BOTH diagrams (acceptable: F_g, F_{grav}, W, mg, $m_A g$ – NOT G or g alone – and no extraneous forces on either diagram); 1 for correct,

Solution 2

correctly labeled tension forces on BOTH diagrams (acceptable: 'tension', 'string force', F_T, $F_{tension}$, F_{string}, F_S, T – NOT $m_B g$, F_{m_B}, or 'force from block B'). Forces must be drawn as distinct arrows starting on and pointing away from the dot, not components.

Solution 2

(c) Mark scheme

- Apply Newton's second law separately to each block, then combine. Block B (down positive): $m_B g - T = m_B a$. Block A (horizontal): $T = m_A a$. Since the string is inextensible and the tension magnitude is the same on both blocks, combine to eliminate T: $m_B g - m_A a = m_B a \Rightarrow a = \dfrac{m_B}{m_A + m_B} g$. Alternate whole-system method: treat both blocks + string as one system of total mass $m_A + m_B$ with no net internal force; the only external force along the direction of motion is gravity on block B, so $F_{net} = m_B g = (m_A + m_B)a$, giving the same $a = \dfrac{m_B}{m_A + m_B} g$. Points: 1 for using separate Newton's-second-law equations for each block (or the equivalent whole-system equation containing no internal

Solution 2

forces); 1 for correctly combining the equations with correct notation, using m_A and m_B, correctly indicating that the same tension force acts on both blocks and that they share the same acceleration; 1 for the correct final equation with supporting work: $a = \frac{m_B}{m_A + m_B} g$.

Solution 2

(d) Mark scheme

- Correct answer: 'Yes' – the equation from part (c), $a = \dfrac{m_B}{m_A + m_B} g$, agrees with the reasoning in part (a)(ii). The single point is earned for valid reasoning connecting the two: when $m_A \ll m_B$, the m_A term in the denominator can be neglected, so $(m_A + m_B) \approx m_B$ and $a \approx \dfrac{m_B}{m_B} g = g$, matching the claim in part (a)(ii) that the acceleration approaches g. ('No' is acceptable ONLY if it is consistent with an equation from part (c) that does not actually reduce to g in this limit, or with an inconsistent answer given in (a)(ii).)

Solution 2

(e) Mark scheme

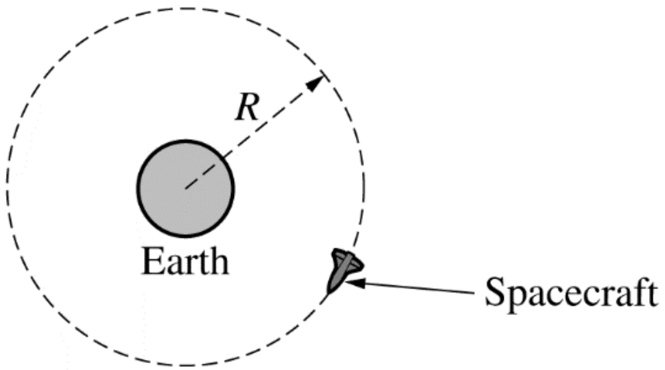
- Correct answer: $T_2 > T_1$ (a maximum of 1 point can be earned if the wrong option is selected). Point 1: for reasoning that the acceleration of both blocks is SMALLER in the second (heavier-pulley) scenario, because the pulley's now-nonzero rotational inertia requires torque/energy to spin it up, leaving less net force available to accelerate the blocks. Point 2: for connecting this, via Newton's second law applied to block B ($\vec{a} = \sum \vec{F}/m$, i.e. $T = m_B g - m_B a$ or $m_B g - T = m_B a$), to conclude that a SMALLER acceleration of block B implies a LARGER tension T_2 (closer in magnitude to the gravitational force on block B than T_1 was).

Question 1

2018 ▪ Q1

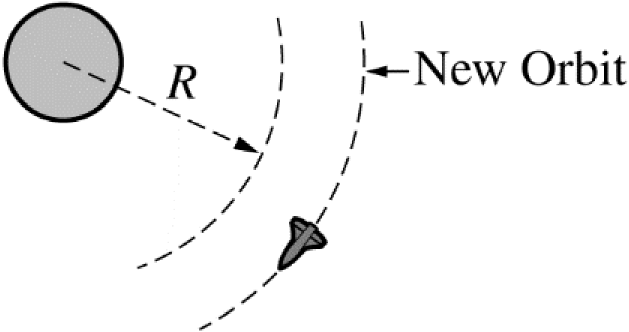
A spacecraft of mass m is in a clockwise circular orbit of radius R around Earth, as shown in the figure above. The mass of Earth is M_E.
[Figure: Earth (a solid grey circle, labeled "Earth") at the center, with a dashed circular orbit of radius R around it; a spacecraft icon sits on the orbit path, labeled "Spacecraft", indicating clockwise motion. Note: Figure not drawn to scale.]
(a) In the figure below, draw and label the forces (not components) that act on the spacecraft. Each force must be represented by a distinct arrow starting on, and pointing away from, the spacecraft.
[Figure: Earth shown at upper left with the spacecraft positioned on a dashed arc representing part of its orbit, provided blank for the student to draw and label force arrows. Note: Figure not drawn to scale.]

Question 1



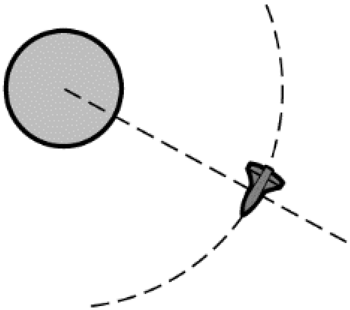
Note: Figure not drawn to scale.

Question 1



Note: Figure not drawn to scale.

Question 1



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Question 1

2018 ▪ Q1

A spacecraft of mass m is in a clockwise circular orbit of radius R around Earth, as shown in the figure above. The mass of Earth is M_E.

[Figure: Earth (a solid grey circle, labeled "Earth") at the center, with a dashed circular orbit of radius R around it; a spacecraft icon sits on the orbit path, labeled "Spacecraft", indicating clockwise motion. Note: Figure not drawn to scale.]

(b)(i) Derive an equation for the orbital period T of the spacecraft in terms of m, M_E, R, and physical constants, as appropriate. If you need to draw anything other than what you have shown in part (a) to assist in your solution, use the space below. Do NOT add anything to the figure in part (a).

(b)(ii) A second spacecraft of mass $2m$ is placed in a circular orbit with the same radius R. Is the orbital period of the second spacecraft greater than, less than, or equal to the orbital period of the first spacecraft?

Question 1

_____ Greater than _____ Less than _____ Equal to

Briefly explain your reasoning.

Question 1

2018 ▪ Q1

A spacecraft of mass m is in a clockwise circular orbit of radius R around Earth, as shown in the figure above. The mass of Earth is M_E.

[Figure: Earth (a solid grey circle, labeled "Earth") at the center, with a dashed circular orbit of radius R around it; a spacecraft icon sits on the orbit path, labeled "Spacecraft", indicating clockwise motion. Note: Figure not drawn to scale.]

(c) The first spacecraft is moved into a new circular orbit that has a radius greater than R, as shown in the figure below.

[Figure: Earth with the original dashed orbit of radius R shown alongside a larger, concentric dashed orbit labeled "New Orbit"; the spacecraft is shown on this larger new orbit. Note: Figure not drawn to scale.]

Is the speed of the spacecraft in the new orbit greater than, less than, or equal to the original speed?

Question 1

_____ Greater than _____ Less than _____ Equal to

Briefly explain your reasoning.

Solution 1

(a)

Mark scheme

- Only one force acts on the orbiting spacecraft: the gravitational force from Earth. Draw a single arrow starting on the spacecraft and pointing directly toward Earth's center, labeled F_g (gravity). No other forces (e.g. a forward 'motion' force) should be drawn. Scoring (2 points, 1 each): (1) an arrow directed toward Earth's center; (2) a correct label on that arrow identifying it as the gravitational force, with the arrow pointing toward Earth's center. Note: a maximum of 1 point can be earned if extraneous (incorrect) forces are also present.

Solution 1

(b)(i) Mark scheme

- Apply Newton's second law, setting the gravitational force equal to the centripetal force: $F_g = ma = \frac{mv^2}{R}$, so $\frac{GmM_E}{R^2} = \frac{mv^2}{R}$. Relate speed to period via the orbit's circumference: $v = \frac{2\pi R}{T}$. Combine and solve for T: $T = \sqrt{\frac{4\pi^2 R^3}{GM_E}}$ (equivalently $T^2 = \frac{4\pi^2 R^3}{GM_E}$, an acceptable final form). Scoring (3 points, 1 each): (1) using (or implying) Newton's second law and equating the centripetal force to the gravitational force, $\frac{GmM_E}{R^2} = \frac{mv^2}{R}$; (2) explicitly or implicitly determining

Solution 1

$v = \dfrac{2\pi R}{T}$; (3) a correct final answer algebraically equivalent to $T = \sqrt{4\pi^2 R^3/(GM_E)}$.

Solution 1

(b)(ii) Mark scheme

- Correct answer: 'Equal to.' The orbital period does not depend on the spacecraft's mass – from part (b)(i), $T = \sqrt{4\pi^2 R^3/(GM_E)}$ contains no dependence on m (mass cancels out of Newton's second law), so doubling the mass to $2m$ leaves the period unchanged for the same orbital radius R. Scoring (1 point): for a correct explanation that the period does not depend on the spacecraft's mass (or depends only on Earth's mass and the orbital radius), OR an explanation consistent with the (possibly incorrect) equation derived in part (b)(i). The explanation must be consistent with whichever box is checked.

Solution 1

(c)

Mark scheme

- Correct answer: 'Less than.' From the derivation in part (b)(i), $v = \sqrt{GM_E/R}$, so orbital speed decreases as the orbital radius R increases; a spacecraft in a larger orbit therefore moves slower than in the original orbit. Scoring (1 point): for a correct explanation of why speed decreases with increasing orbital radius (e.g., citing the part (b)(i) derivation step showing $v \propto 1/\sqrt{R}$). Note: if the wrong option is selected, the explanation is not graded.

Question 2

2017 ▪ Q2

A student wants to determine the coefficient of static friction between a long, flat wood board and a small wood block.

(a)(i) Describe an experiment for determining the coefficient of static friction between the wood board and the wood block. Assume equipment usually found in a school physics laboratory is available.

Draw a diagram of the experimental setup of the board and block. In your diagram, indicate each quantity that would be measured and draw or state what equipment would be used to measure each quantity.

(a)(ii) Describe the overall procedure to be used, including any steps necessary to reduce experimental uncertainty. Give enough detail so that another student could replicate the experiment.

Question 2

Lab Group Number	Coefficient of Kinetic Friction	Coefficient of Static Friction
1	0.45	0.54
2	0.46	0.52
3	0.42	0.56
4	0.43	0.55
5	0.74	0.23
6	0.44	0.54
Average	0.49	0.49

Question 2

2017 ▪ Q2

A student wants to determine the coefficient of static friction between a long, flat wood board and a small wood block.

(b) Derive an equation for the coefficient of static friction in terms of quantities measured in the procedure from part (a).

A physics class consisting of six lab groups wants to test the hypothesis that the coefficient of static friction between the board and the block equals the coefficient of kinetic friction between the board and the block. Each group determines the coefficients of kinetic and static friction between the board and the block. The groups' results are shown below, with the class averages indicated in the bottom row.

Lab Group Number	Coefficient of Kinetic Friction	Coefficient of Static Friction
1	0.45	0.54
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6	0.44	0.54
Average	0.49	0.49

Question 2

2017 ▪ Q2

A student wants to determine the coefficient of static friction between a long, flat wood board and a small wood block.

(c) Based on these data, what conclusion should the students make about the hypothesis that the coefficients of static and kinetic friction are equal?

______ The static and kinetic coefficients are equal.

______ The static and kinetic coefficients are not equal.

Briefly justify your reasoning.

Question 2

2017 ▪ Q2

A student wants to determine the coefficient of static friction between a long, flat wood board and a small wood block.

(d) A metal disk is glued to the top of the wood block. The mass of the block-disk system is twice the mass of the original block. Does the coefficient of static friction between the bottom of the block and the board increase, decrease, or remain the same when the disk is added to the block?

_____ Increase _____ Decrease _____ Remain the same

Briefly state your reasoning.

Solution 2

(a)(i) Mark scheme

- Set up the wood board as an incline: hinge/rest one end of the board on the table so the other end can be raised, with the wood block placed on the board. Slowly raise the free end (increasing the angle θ between board and table) until the block is on the verge of sliding, and measure that critical angle θ with a protractor. Diagram should show: the board tilted at angle θ above the horizontal table, the block resting on the board, θ marked at the pivot between board and table, and a protractor indicated as the instrument used to measure θ. Points: 1 pt for a diagram of an experimental setup to measure the coefficient of friction that is feasible in a school physics lab; 1 pt for indicating the measurement(s) necessary

Solution 2

for calculating the coefficient of friction (the critical angle θ); 1 pt for indicating the equipment necessary for measuring that quantity (a protractor).

Solution 2

(a)(ii) Mark scheme

- With the block at rest on the board (board initially near horizontal), slowly lift one end of the board, increasing the angle θ, until the block just begins to slide, and record θ at that instant. Repeat this measurement several times, and/or with the block placed at different locations on the board, then average the resulting angles to reduce experimental (random) error. Points: 1 pt for a description consistent with the diagram in part (a)(i), in enough detail that another student could replicate the experiment; 1 pt for a description that is a conceptually valid method to find quantities allowing calculation of the friction coefficient; 1 pt for including a valid method for reducing experimental uncertainty (e.g., repeating trials at different board locations and averaging).

Solution 2

(b) Mark scheme

- At the critical angle θ (block on the verge of sliding) the block is in equilibrium. Newton's second law perpendicular to the board's surface: $N - mg\cos\theta = 0 \Rightarrow N = mg\cos\theta$. Newton's second law parallel to the board's surface: $mg\sin\theta - f_{s,max} = 0 \Rightarrow f_{s,max} = mg\sin\theta$. Since $f_{s,max} = \mu_s N$, dividing gives $\mu_s = \dfrac{f_{s,max}}{N} = \dfrac{mg\sin\theta}{mg\cos\theta} = \tan\theta$. Final answer: $\mu_s = \tan\theta$, where θ is the critical sliding angle measured in part (a). Points: 1 pt for using Newton's second law (or zero-net-force reasoning) parallel to the board's surface, explicitly or implicitly; 1 pt for using Newton's second law (or zero-net-force reasoning) perpendicular to the board's surface, explicitly or implicitly (replacing the normal

Solution 2

force with *mg* alone is only valid/implicit for a horizontal surface; a tilted surface must show the $\cos\theta$ term); 1 pt for a correctly derived expression $\mu_s = \tan\theta$ in terms of quantities from part (a). Full credit requires all variables to be defined in the diagram/procedure of part (a).

Solution 2

(c) Mark scheme

- Correct answer: the static and kinetic coefficients are NOT equal (reasoning only earns credit if this option is selected). Group 5's data is an outlier compared to the other five lab groups' results (its measured coefficients deviate substantially from the pattern of the rest of the class). Once Group 5 is identified as an outlier and excluded (or simply noted), the remaining groups' data show $\mu_s \neq \mu_k$ (or the coefficients differ from group to group rather than clustering at a common equal value), supporting the conclusion that static and kinetic friction coefficients are not equal. Points: 1 pt for identifying Group 5's results as an outlier, or indicating the presence of an outlier; 1 pt for a conclusion that the coefficients are not the

Solution 2

same, justified either by removing the outlier or by noting the coefficients are different for each group.

Solution 2

(d) Mark scheme

- Correct answer: Remain the same. The coefficient of static friction is a property of the two surfaces in contact (the block's bottom surface and the board's surface), not of the normal force or the masses of the objects pressing them together. Gluing the metal disk to the block doubles the mass (and hence the normal force between block and board), but since $\mu_s = f_{s,max}/N$ is a ratio that depends only on the nature/roughness of the two contacting surfaces, μ_s remains unchanged even though the normal force and the maximum static friction force both double. Points: 1 pt for a valid argument that the coefficient of static friction is a property of the two surfaces, consistent with the selected answer ("Remain the same," justified via μ_s's independence from mass/normal force, is

Solution 2

the credited reasoning; e.g. referring to the equation from part (b) showing $\mu_s = \tan\theta$ does not depend on mass).

Question 1

2016 ▪ Q1

A wooden wheel of mass M, consisting of a rim with spokes, rolls down a ramp that makes an angle θ with the horizontal, as shown above. The ramp exerts a force of static friction on the wheel so that the wheel rolls without slipping.
[Figure at top of page: A wheel of mass M sits at the top of an inclined ramp that makes angle θ with the horizontal (a right triangle shown in profile, with the wheel resting at the top of the incline).]
(a)(i) On the diagram below, draw and label the forces (not components) that act on the wheel as it rolls down the ramp, which is indicated by the dashed line. To clearly indicate at which point on the wheel each force is exerted, draw each force as a distinct arrow starting on, and pointing away from, the point at which the force is exerted. The lengths of the arrows need not indicate the relative magnitudes of the forces.

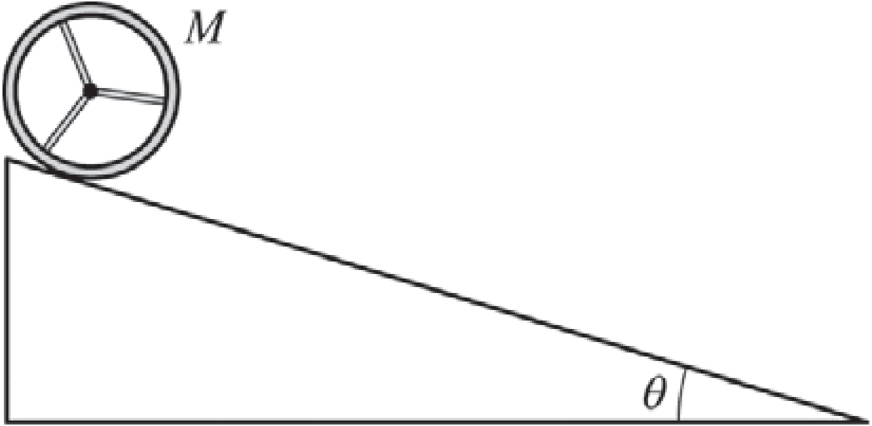
Question 1

[Diagram: a wheel with spokes resting on a dashed line representing the ramp surface, for the student to draw force vectors on.]

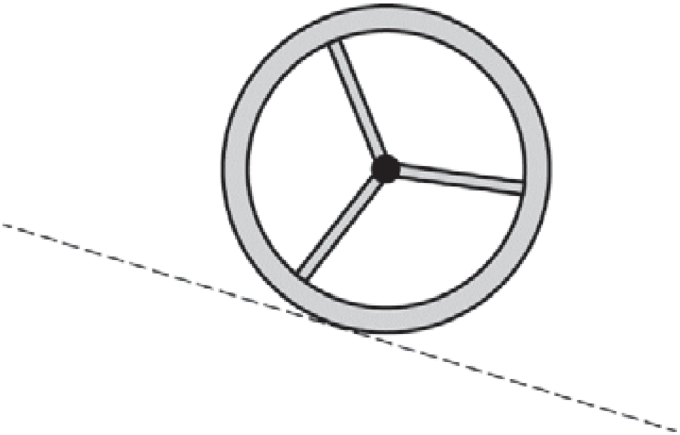
(a)(ii) As the wheel rolls down the ramp, which force causes a change in the angular velocity of the wheel with respect to its center of mass?

Briefly explain your reasoning.

Question 1



Question 1



Question 1

2016 ▪ Q1

A wooden wheel of mass M, consisting of a rim with spokes, rolls down a ramp that makes an angle θ with the horizontal, as shown above. The ramp exerts a force of static friction on the wheel so that the wheel rolls without slipping.

[Figure at top of page: A wheel of mass M sits at the top of an inclined ramp that makes angle θ with the horizontal (a right triangle shown in profile, with the wheel resting at the top of the incline).]

(b) For this ramp angle, the force of friction exerted on the wheel is less than the maximum possible static friction force. Instead, the magnitude of the force of static friction exerted on the wheel is 40 percent of the magnitude of the force or force component directed opposite to the force of friction. Derive an expression for the linear acceleration of the wheel's center of mass in terms of M, θ, and physical constants, as appropriate.

Question 1

2016 ▪ Q1

A wooden wheel of mass M, consisting of a rim with spokes, rolls down a ramp that makes an angle θ with the horizontal, as shown above. The ramp exerts a force of static friction on the wheel so that the wheel rolls without slipping.

[Figure at top of page: A wheel of mass M sits at the top of an inclined ramp that makes angle θ with the horizontal (a right triangle shown in profile, with the wheel resting at the top of the incline).]

(c) In a second experiment on the same ramp, a block of ice, also with mass M, is released from rest at the same instant the wheel is released from rest, and from the same height. The block slides down the ramp with negligible friction.

(c)(i) Which object, if either, reaches the bottom of the ramp with the greatest speed?

_____ Wheel _____ Block _____ Neither; both reach the bottom with the same speed.

Question 1

Briefly explain your answer, reasoning in terms of forces.

(c)(ii) Briefly explain your answer again, now reasoning in terms of energy.

Solution 1

(a)(i) Mark scheme

- Force diagram on the wheel: (1) a labeled arrow for the gravitational force mg, starting at the wheel's center and pointing straight down [1 pt]. (2) labeled arrows for the friction force F_f and normal force F_n (or a single arrow for their resultant), with no extraneous forces [1 pt] — F_f starts at the wheel-ramp contact point and points up the ramp (along the ramp surface); F_n starts at the wheel-ramp contact point and is perpendicular to the ramp, directed toward the wheel's center (does not need to pass exactly through the center, just reasonably close). Scoring: 1 pt for the correct mg arrow from the center downward; 1 pt for correct F_f/F_n (or resultant) arrows at the contact point with correct directions and no extra forces.

Solution 1

(a)(ii)

Mark scheme

- Correct answer: the friction force. No credit if the wrong force is named. Explanation: friction is the only one of the three forces (mg, F_n, F_f) that exerts a torque about the wheel's center of mass — both mg and F_n act through/toward the center, so they produce no torque about it — so friction is what changes the wheel's angular velocity. Full credit is also given for a causal-chain answer: gravity leads to a normal force (and acceleration down the ramp), which leads to a frictional force, which exerts a torque that changes the angular velocity.

Solution 1

(b) Mark scheme

- Along the ramp: $\sum F_{\|} = Mg\sin\theta - F_f$ [1 pt for recognizing there are two force components parallel to the ramp; the expression need not be correct or consistent with the force diagram in part (a)]. The friction force is 40

Solution 1

(c)

Mark scheme

- Context only, no response scored on this leaf: describes a second experiment on the same ramp in which a block of ice, also of mass M, is released from rest at the same instant and same height as the wheel, sliding down with negligible friction. This setup is used by parts (c)(i) and (c)(ii).

Solution 1

(c)(i)

Mark scheme

- Correct answer: Block. No credit for an answer without explanation. Explanation in terms of forces: the wheel experiences a counteracting frictional force (which reduces its linear acceleration along the ramp), so the block — with negligible friction — has a greater net force along the ramp and therefore greater acceleration, reaching the bottom with greater speed.

Solution 1

(c)(ii)

Mark scheme

- Explanation in terms of energy conservation: both the wheel-Earth system and the block-Earth system lose the same amount of gravitational potential energy (same mass, same height drop), so they gain the same total kinetic energy. With the ice block — but not the wheel — all of that kinetic energy is translational, and none is rotational, so the block's translational (linear) speed at the bottom is greater than the wheel's.

Question 1

2015 ▪ Q1

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

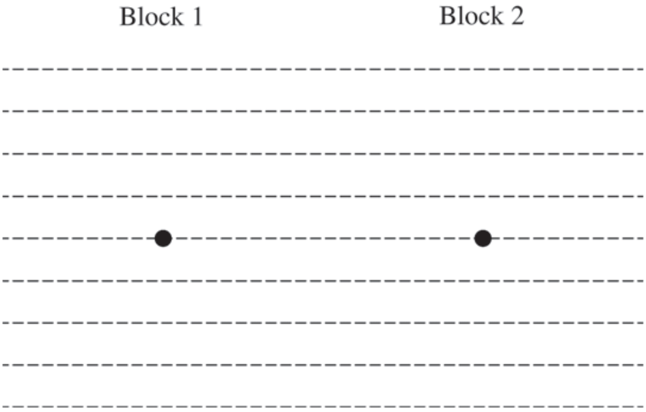
Two blocks are connected by a string of negligible mass that passes over massless pulleys that turn with negligible friction, as shown in the figure above. The mass m_2 of block 2 is greater than the mass m_1 of block 1. The blocks are released from rest.

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

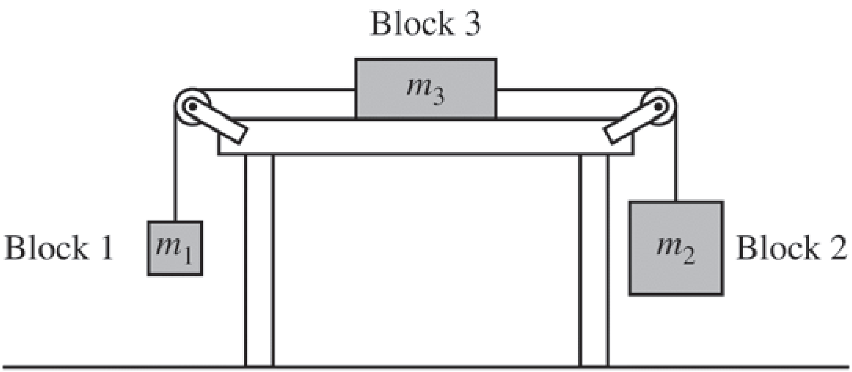
[Two blank labeled diagrams, each showing a single dot on a set of horizontal dashed reference lines, for the student to draw force vectors on: one labeled “Block 1”, one labeled “Block 2”.]

Question 1

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

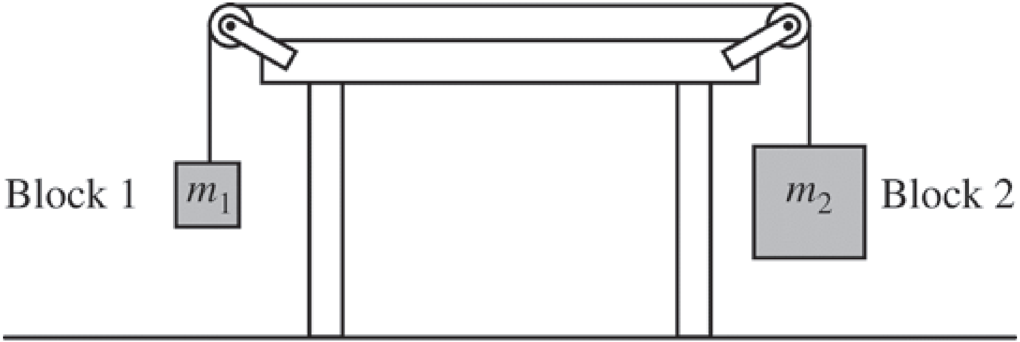


Question 1



Note: Figure not drawn to scale.

Question 1



Note: Figure not drawn to scale.

Question 1

2015 ▪ Q1

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

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

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

Question 1

2015 ▪ Q1

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

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

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

Question 1

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

Solution 1

(a) Mark scheme

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

Solution 1

(b) Mark scheme

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

Solution 1

(c) Mark scheme

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

Solution 1

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

Question 4

2015 ▪ Q4

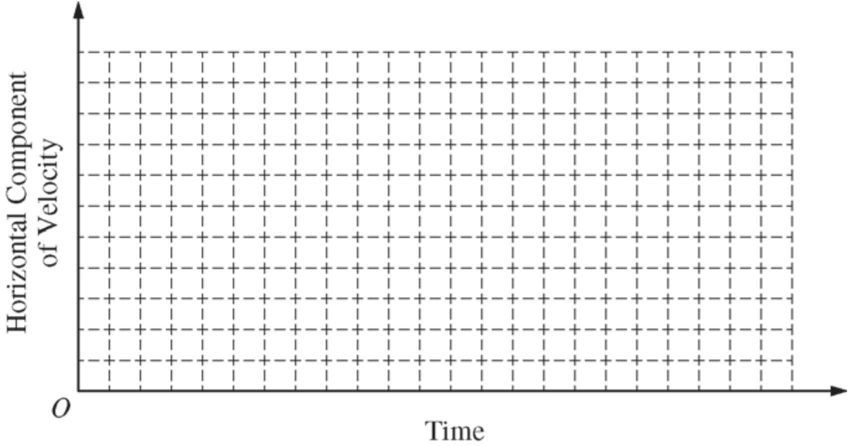
[Figure: A raised platform (table) with two spheres, Sphere A and Sphere B, resting at the same height H above the lower ground level. Sphere A is positioned at the edge of the upper level and drops straight down (dashed vertical line to a position on the lower ground directly below). Sphere B is positioned slightly to the right, launched horizontally, and follows a dashed parabolic trajectory landing a horizontal distance D from the point directly below its release point. The height H is marked as the vertical drop from the upper level to the lower ground, and D is marked as the horizontal distance from directly below Sphere B's start to its landing point.]

Two identical spheres are released from a device at time $t = 0$ from the same height H, as shown above. Sphere A has no initial velocity and falls straight down. Sphere B is given an initial horizontal velocity of magnitude v_0 and travels a horizontal distance D

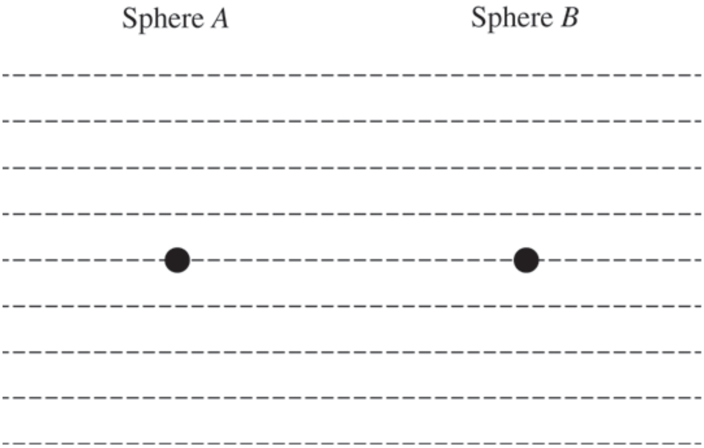
Question 4

before it reaches the ground. The spheres reach the ground at the same time t_f, even though sphere B has more distance to cover before landing. Air resistance is negligible.
(a) The dots below represent spheres A and B. Draw a free-body diagram showing and labeling the forces (not components) exerted on each sphere at time $\frac{t_f}{2}$.
[Two blank labeled diagrams, each showing a single dot on a set of horizontal dashed reference lines, for the student to draw force vectors on: one labeled "Sphere A", one labeled "Sphere B".]

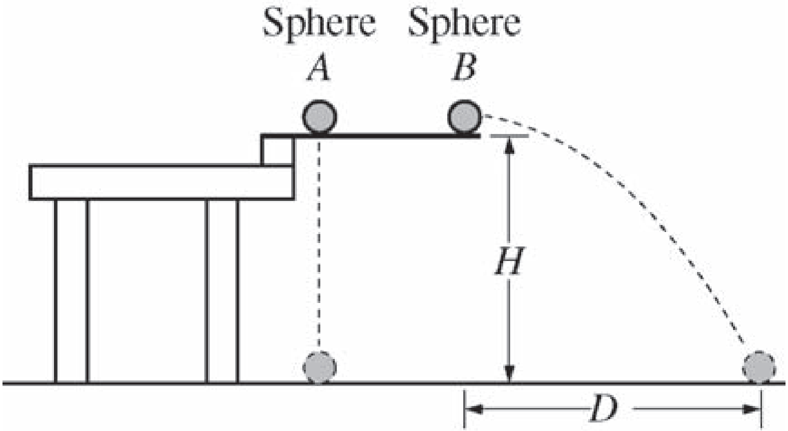
Question 4



Question 4



Question 4



Question 4

2015 ▪ Q4

[Figure: A raised platform (table) with two spheres, Sphere A and Sphere B, resting at the same height H above the lower ground level. Sphere A is positioned at the edge of the upper level and drops straight down (dashed vertical line to a position on the lower ground directly below). Sphere B is positioned slightly to the right, launched horizontally, and follows a dashed parabolic trajectory landing a horizontal distance D from the point directly below its release point. The height H is marked as the vertical drop from the upper level to the lower ground, and D is marked as the horizontal distance from directly below Sphere B's start to its landing point.]

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Question 4

(b) On the axes below, sketch and label a graph of the horizontal component of the velocity of sphere A and of sphere B as a function of time.
[Blank grid: vertical axis labeled "Horizontal Component of Velocity" (unmarked scale), horizontal axis labeled "Time" starting at O, for the student to sketch both graphs on.]

Question 4

2015 ▪ Q4

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Question 4

(c) In a clear, coherent, paragraph-length response, explain why the spheres reach the ground at the same time even though they travel different distances. Include references to your answers to parts (a) and (b).

Solution 4

(a)

Mark scheme

- Free-body diagrams for Sphere A and Sphere B at time $t_f/2$ (mid-flight): each sphere has exactly ONE force acting on it – a single vector pointing straight down, of equal length for both spheres, labeled as the force of gravity (mg). 1 point for sketching only one downward force per sphere and indicating it represents the force of gravity.

Solution 4

(b)

Mark scheme

- Graph of horizontal velocity component vs. time for both spheres: Sphere A's horizontal velocity is a horizontal line at (approximately) ZERO for all time; Sphere B's horizontal velocity is a horizontal line at some CONSTANT NON-ZERO value for all time (no horizontal force acts on either sphere once in flight, so each maintains its own constant horizontal velocity). 1 point for sketching a horizontal line at zero velocity for sphere A and a horizontal line at some non-zero velocity for sphere B.

Solution 4

(c) Mark scheme

- Paragraph explanation: The difference in horizontal motion between the spheres does not affect their vertical motion, because horizontal and vertical motions are independent. Both spheres start with the same vertical velocity. Both spheres have the same vertical acceleration (g), since gravity is the only force acting on each (per part (a)). Because they share the same initial vertical velocity, the same vertical acceleration, and fall the same height, they take the same time to reach the ground – regardless of their differing (and constant, per part (b)) horizontal velocities. Scoring (5 points, 1 each): (1) indicating the difference in horizontal motion does not affect vertical motion; (2) indicating both spheres start with the same vertical velocity; (3) indicating both spheres have the same vertical

Solution 4

acceleration; (4) indicating that falling the same height takes the same time; (5) for containing no incorrect or irrelevant statements, with explicit reference to parts (a) and (b).