Past-paper walk-through

Newton's Second Law ▪ 2.5

eXercise

Questions in this set

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Reading the mark scheme

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

Question 1

2026 ▪ Q1

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

Question 1

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

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

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

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

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

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

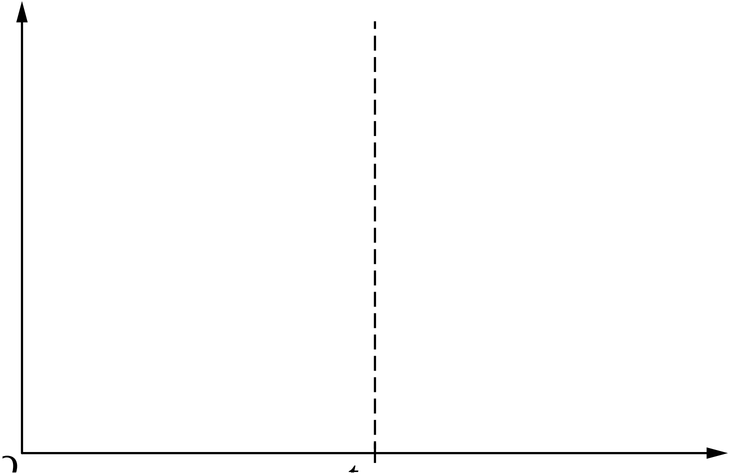
Question 1

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

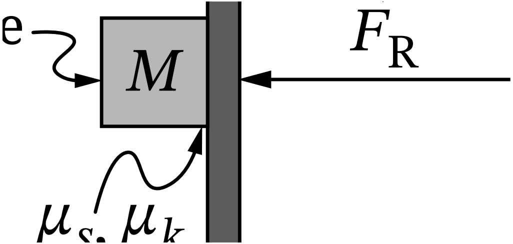
(a)(iii) On the axes shown in Figure 2, **sketch** a graph of the magnitude F_f of the frictional force exerted on the cube by the wall of the box as a function of t from $t = 0$ until immediately before the cube reaches the bottom of the box.

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

Question 1



Question 1



Question 1

Question 1

2026 ▪ Q1

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Question 1

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

Question 2

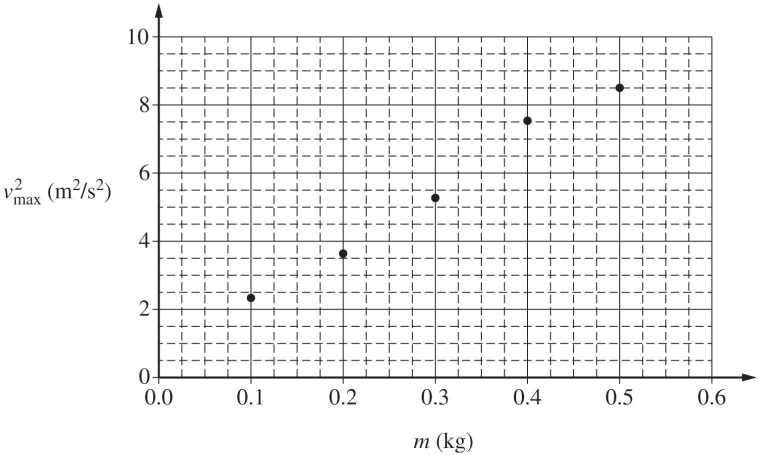
2024 Set 1 ▪ Q2

[Figure 1: A horizontal cylinder is shown falling, with several downward arrows above it indicating the direction it was dropped from (air resistance direction shown), and an upward arrow labeled F_{drag} acting on the cylinder.]

A student drops a cylinder of mass m from rest. The air exerts a drag force of magnitude F_{drag} on the cylinder, as shown in Figure 1. The student models the magnitude of the drag force as $F_{drag} = bv^2$, where v is the speed of the cylinder and b is a positive constant with appropriate units.

(a) Derive, but do NOT solve, a differential equation that could be used to determine the speed v of the cylinder as a function of time t. Express your answer in terms of given quantities and physical constants, as appropriate.

Question 2



Question 2

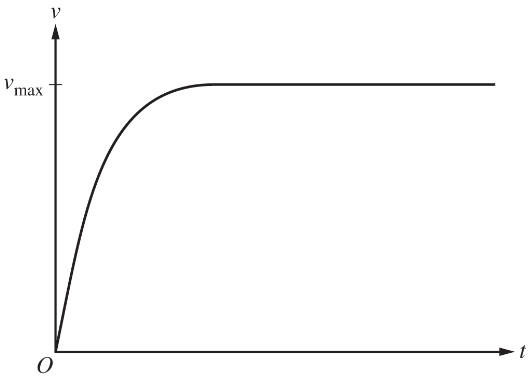


Figure 2

Question 2

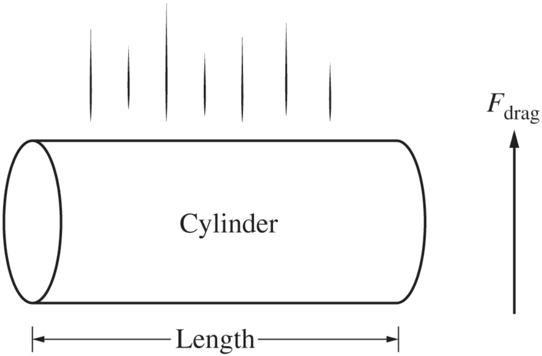


Figure 3

Question 2

2024 Set 1 ▪ Q2

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(b)(i) [Figure 2: Graph of speed v (vertical axis) versus time t (horizontal axis), starting at origin O. The curve rises steeply at first, curving over and leveling off asymptotically at a horizontal line labeled v_{max}.]

The student correctly sketches the speed v of the cylinder as a function of time t, as shown in Figure 2.

Question 2

Draw a vertical line on the sketch in Figure 2 to indicate the earliest time at which F_{drag} on the cylinder is equal to the magnitude of the weight of the cylinder. Label this time as t_1 on the time axis.

(b)(ii) Justify the location of t_1. Explicitly reference appropriate features of the sketch in Figure 2.

Question 2

2024 Set 1 ▪ Q2

[Figure 1: A horizontal cylinder is shown falling, with several downward arrows above it indicating the direction it was dropped from (air resistance direction shown), and an upward arrow labeled F_{drag} acting on the cylinder.]

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(c) Rather than dropping the cylinder from rest, the student throws the cylinder upward with a nonzero initial speed. The cylinder is in the same orientation as when the cylinder was previously dropped. The student allows the cylinder to fall toward the ground.

Question 2

Indicate whether the magnitude of the cylinder's maximum downward speed after being thrown upward would be greater than, less than, or equal to the maximum speed v_{max} in Figure 2.

_______ Greater than _______ Less than _______ Equal to

Briefly justify your answer.

Question 2

2024 Set 1 ▪ Q2

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(d)(i) The student conducts an experiment to better understand the relationship between maximum speed v_{max} and mass. The student collects data to determine the maximum speed for cylinders dropped from rest, each with the same physical size and shape but a different mass m. The student then graphs v_{max}^2 as a function of mass.

Question 2

[Scatter plot: vertical axis v_{max}^2 ($\mathrm{m}^2/\mathrm{s}^2$) from 0 to 10 in increments of 2; horizontal axis m (kg) from 0.0 to 0.6 in increments of 0.1. Data points approximately at: $(0.1, 2.6)$, $(0.15, 3.3)$, $(0.2, 4.0)$, $(0.3, 5.6)$, $(0.35, 6.0)$, $(0.45, 7.6)$, $(0.5, 7.5)$, $(0.55, 8.6)$. Gridlines shown at every 0.05 kg horizontally and 0.5 $\mathrm{m}^2/\mathrm{s}^2$ vertically.]
Draw the best-fit line for the data.

(d)(ii) Use the best-fit line to calculate an experimental value for *b*.

Question 2

2024 Set 1 ▪ Q2

[Figure 1: A horizontal cylinder is shown falling, with several downward arrows above it indicating the direction it was dropped from (air resistance direction shown), and an upward arrow labeled F_{drag} acting on the cylinder.]

A student drops a cylinder of mass m from rest. The air exerts a drag force of magnitude F_{drag} on the cylinder, as shown in Figure 1. The student models the magnitude of the drag force as $F_{drag} = bv^2$, where v is the speed of the cylinder and b is a positive constant with appropriate units.

(e)(i) [Figure 3: A horizontal cylinder shown with several downward arrows above it (direction from which it was dropped) and an upward arrow labeled F_{drag}; a labeled dimension "Length" with an arrow spanning the cylinder's length.]

A student claims that the magnitude of the maximum speed of a cylinder dropped from rest depends on the length of the cylinder. The student designs an experiment to

Question 2

collect data that can be used to provide evidence to support the claim. The student drops cylinders with the orientation shown in Figure 3.

The student has access to but does not have to use all of the following equipment.

- Cylinder Set 1: cylinders of the same known length with different known masses
- Cylinder Set 2: cylinders of the same known mass with different known lengths
- A motion detector that can measure velocity as a function of time

Indicate two quantities that when graphed could be used to determine whether the length of the cylinder affects the maximum speed.

Vertical axis: ____________________ Horizontal axis: ____________________

(e)(ii) Briefly describe how the quantities graphed could be used to determine the relationship between cylinder length and maximum speed.

Solution 2

(a) Mark scheme

- Apply Newton's second law to the falling cylinder, where the only forces are gravity and drag: $\Sigma F = ma \Rightarrow F_g - F_{drag} = ma_y \Rightarrow mg - bv^2 = ma_y$ (using the given quadratic drag force). Writing $a_y = dv/dt$: $m\dfrac{dv}{dt} = mg - bv^2$. (Variables do not need to be separated to earn full credit.) Points: (1) a multi-step derivation that includes Newton's second law; (2) indicating the net force includes only the gravitational force and a drag force; (3) a correct differential equation in terms of the given quantities.

Solution 2

(b)(i)

Mark scheme

- Draw a vertical line labeled t_1 at the approximate location on the v-t graph where the curve first becomes (essentially) horizontal, i.e., where v first reaches v_{max} — this is the earliest time the drag force equals the cylinder's weight in magnitude. Point: correct approximate placement of the vertical line at that location.

Solution 2

(b)(ii)

Mark scheme

- Because the sketched line is horizontal after t_1, the velocity is constant. If the velocity is constant, the acceleration is zero. Therefore the net force is zero, which means the gravitational and drag forces are equal in magnitude at t_1 (terminal velocity reached). Points: (1) relating t_1 to the time the v-t graph becomes constant / has zero slope; (2) indicating that constant velocity means the net force (and hence acceleration) is zero, so drag equals weight.

Solution 2

(c)

Mark scheme

- Answer: "Equal to." Justification: at its peak (after being thrown upward), the cylinder momentarily has a speed of 0 m/s — the same initial condition as when it was dropped from rest. Because the cylinder then falls from that height under the same forces (gravity and the same v^2 drag law) as in the original drop-from-rest scenario, it reaches the same v_{max}. Points: (1) selecting "Equal to" with an attempt at a relevant justification; (2) a correct justification (recognizing zero speed at the peak makes the subsequent fall identical to a drop from rest).

Solution 2

(d)(i)

Mark scheme

- Draw a straight line of best fit through the origin (approximately) that follows the trend of the plotted v_{max}^2 vs. m data points, e.g. passing near $(0.25\ \text{kg}, 4.5\ \text{m}^2/\text{s}^2)$ and $(0.5\ \text{kg}, 9\ \text{m}^2/\text{s}^2)$. Point: an appropriate straight line that reasonably approximates the data (not simply connecting dots).

Solution 2

(d)(ii) Mark scheme

- Using two points on the best-fit line, e.g. $(0.25\ \text{kg}, 4.5\ \text{m}^2/\text{s}^2)$ and $(0.5\ \text{kg}, 9\ \text{m}^2/\text{s}^2)$: slope $= \dfrac{9-4.5}{0.5-0.25} = 18\ (\text{m}^2/\text{s}^2)/\text{kg}$. At terminal velocity $mg - bv_{max}^2 = 0 \Rightarrow v_{max}^2 = (g/b)m$, so slope $= g/b \Rightarrow b = g/\text{slope} = \dfrac{9.8}{18} \approx 0.544\ \text{kg/m}$. Points: (1) calculating a slope value using two points on the best-fit line (points that fall on the line are acceptable); (2) using the correct relationship slope $= g/b$; (3) a calculated value of b in the range $0.45\ \text{kg/m} \leq b \leq 0.75\ \text{kg/m}$.

Solution 2

(e)(i)

Mark scheme

- The student should graph the length of the cylinder (independent variable) against the maximum (terminal) speed v_{max} of the cylinder (dependent variable), since the claim under test is that cylinder length affects maximum speed. Points: (1) indicating that the length of the cylinder should be graphed; (2) indicating that the maximum velocity of the cylinder should be graphed.

Solution 2

(e)(ii)

Mark scheme

- The slope of the length vs. maximum-velocity graph can be used to determine whether length affects terminal velocity (e.g., a nonzero slope indicates a relationship, and its sign/magnitude describes how v_{max} depends on length). Point: a correct description linking the graphed quantities to the experiment's conclusion.

Question 3

2023 Set 1 ▪ Q3

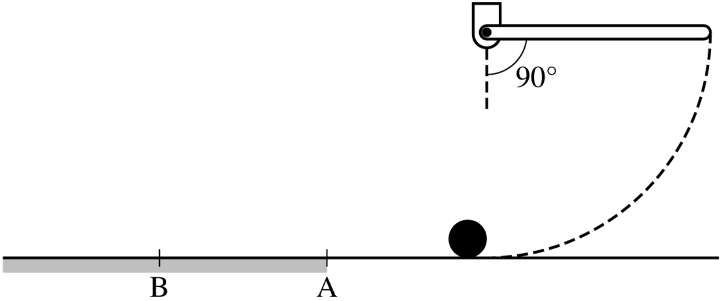
[Figure 1: A horizontal surface with Point B on the left and Point A near the middle marked by a black dot (the sphere's initial position at rest). A rod is shown above Point A, extending upward and connected at a pivot to a small block/weight at the top, with the rod initially vertical making a 90° angle at the pivot. A dashed curved arrow shows the rod swinging down from vertical to horizontal, striking the sphere at Point A. Note: Figure not drawn to scale.]
A system consists of a small sphere of mass m and radius R at rest on a horizontal surface and a uniform rod of mass $M = 2m$ and length ℓ attached at one end to a pivot with negligible friction, where $R \ll \ell$. There is negligible friction between the surface and the sphere to the right of Point A and nonnegligible friction to the left of Point A. The rod is held horizontally as shown in Figure 1, then is released from rest. The total

Question 3

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

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

Question 3



Note: Figure not drawn to scale.

Figure 1

Question 3

2023 Set 1 ▪ Q3

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

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Question 3

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

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

Question 3

2023 Set 1 ▪ Q3

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

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Question 3

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

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

[A circle is shown representing the sphere, for the student to draw and label force vectors starting on the circle.]

Question 3

2023 Set 1 ▪ Q3

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

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Question 3

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

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

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

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

Question 3

2023 Set 1 ▪ Q3

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

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Question 3

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

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

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

Question 1

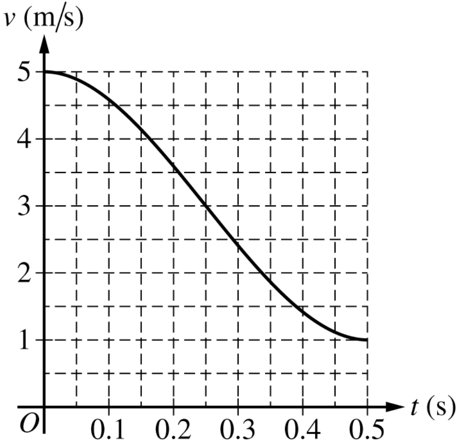
2023 Set 2 ▪ Q1

Scientists have created a new type of lightweight foam and are performing experiments to investigate the properties of the foam. The mass of Cart A is 1000 kg and the mass of Cart B is 2000 kg. A piece of foam with negligible mass is attached to the front of Cart A, as shown. Cart A moves with a constant speed toward Cart B, which is initially at rest. At time $t = 0$ s, the foam connected to Cart A makes contact with Cart B. The foam remains in contact with Cart B for 0.5 s, after which the carts separate and both carts move with constant velocities.
[Diagram: Cart A (with a block labeled "Foam" attached to its front) approaching Cart B along a horizontal track, both carts shown as boxes on wheels.]
(a)(i) The graph shows the velocity v of Cart A as a function of time t for the time interval when the foam and Cart B are in contact.

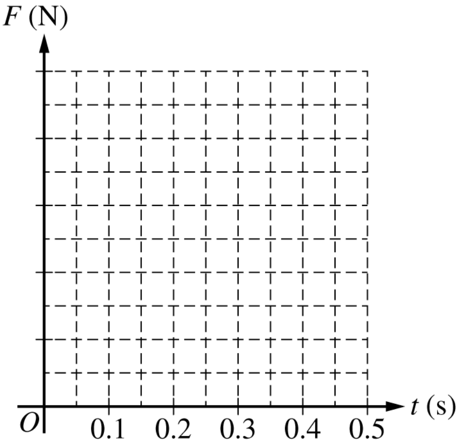
Question 1

[Graph: *v* (m/s) vs. *t* (s); y-axis from 0 to 5 m/s in increments of 1, x-axis from 0 to 0.5 s in increments of 0.1 s; curve starts at $(0, 5)$ and decreases smoothly, concave up, leveling off toward approximately $(0.5, 1)$.]
What feature(s) of the graph could be used to estimate the displacement of Cart A during the collision?
(a)(ii) Using the information shown in the graph, determine the speed of Cart B at $t = 0.5$ s.
(a)(iii) On the following grid, draw a smooth curve of the velocity of Cart B as a function of time.
[Grid: *v* (m/s) vs. *t* (s); y-axis from 0 to 5 m/s in increments of 1, x-axis from 0 to 0.5 s in increments of 0.1 s; the curve for Cart A is already plotted and labeled "Cart A," starting at $(0, 5)$ and decreasing to approximately $(0.5, 1)$.]

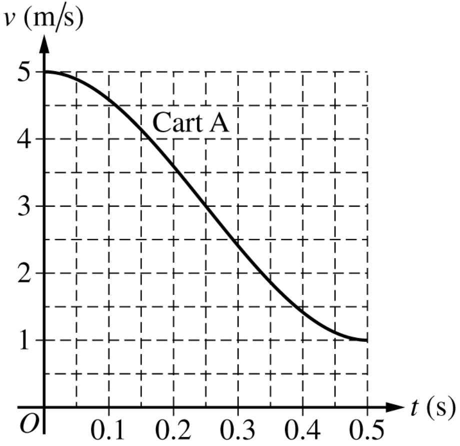
Question 1



Question 1



Question 1



Question 1

2023 Set 2 ▪ Q1

Scientists have created a new type of lightweight foam and are performing experiments to investigate the properties of the foam. The mass of Cart A is 1000 kg and the mass of Cart B is 2000 kg. A piece of foam with negligible mass is attached to the front of Cart A, as shown. Cart A moves with a constant speed toward Cart B, which is initially at rest. At time $t = 0$ s, the foam connected to Cart A makes contact with Cart B. The foam remains in contact with Cart B for 0.5 s, after which the carts separate and both carts move with constant velocities.

[Diagram: Cart A (with a block labeled "Foam" attached to its front) approaching Cart B along a horizontal track, both carts shown as boxes on wheels.]

(b)(i) For $0 \leq t \leq 0.50$ s, the velocity v of Cart A can be described by the function $v(t) = 64t^3 - 48t^2 + 5$.

Calculate the magnitude of the maximum net force acting on Cart A during this interval.

Question 1

(b)(ii) On the following grid, draw a smooth curve of the magnitude of the force acting on Cart A as a function of time. Clearly indicate the value of the maximum force on the vertical axis.
[Grid: F (N) vs. t (s); x-axis from 0 to 0.5 s in increments of 0.1 s; y-axis unlabeled/blank for the student to fill in.]

Question 1

2023 Set 2 ▪ Q1

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[Diagram: Cart A (with a block labeled "Foam" attached to its front) approaching Cart B along a horizontal track, both carts shown as boxes on wheels.]

(c) The foam is removed from the front of Cart A and the experiment is repeated. The carts collide, with both Cart A and Cart B having the same initial and final velocities as in the original collision. The time intervals during which the carts are in contact are different in the collision with the foam and the collision without the foam.

Question 1

In the collision without the foam, Cart A is in contact with Cart B for a shorter duration than in the original collision, when the foam was present.
For the original collision when the foam is present, the magnitude of the average net force exerted on Cart B is F_1. For the collision without the foam, the magnitude of the average net force exerted on Cart B is F_2.
What is the relationship between the magnitude of the average net force F_1 exerted on Cart B for the collision with the foam and the magnitude of the average net force F_2 exerted on Cart B for the collision without the foam?
_____ $F_1 > F_2$ _____ $F_1 < F_2$ _____ $F_1 = F_2$
Justify your answer.

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

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

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

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

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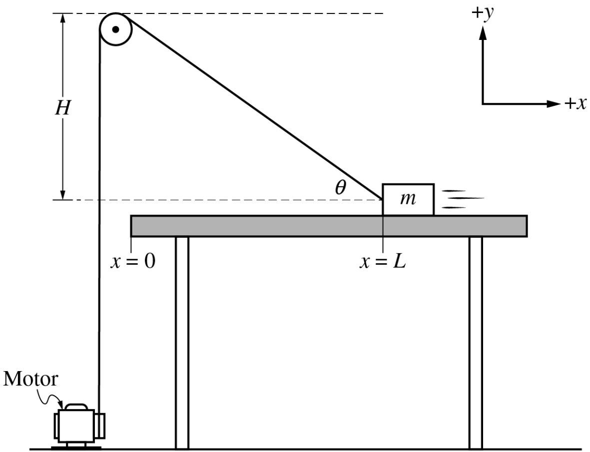

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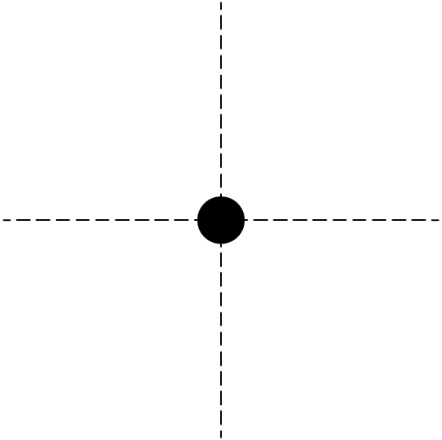

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[Diagram: A pulley (marked with a dot in a circle) is mounted at the top-left, at height H above a horizontal table. A dashed horizontal line runs from the pulley to the right, and a "+y" axis arrow points up with "+x" pointing right from a small axes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

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

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

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

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

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

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

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

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