Past-paper walk-through

Work ▪ 3.2

eXercise

Questions in this set

- 2024 Set 1 Q1
- 2023 Set 1 Q1
- 2022 Set 1 Q1
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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

2024 Set 1 ▪ Q1

Block A and Block B of masses m and $3m$, respectively, are arranged in a setup consisting of an ideal spring with spring constant k and a horizontal surface. Friction between the surface and the blocks is negligible except in a region of length D, where the coefficient of kinetic friction between Block A and the surface is μ. Block B is attached to a string of length ℓ and negligible mass, as shown in Figure 1. Block A is held against the spring, compressing the spring a distance x_c.

[Figure 1: A horizontal setup on surface with position axis x from 0 to x_3. Block A (mass m) sits at the left against a spring, with a labelled distance x_c from Block A to a dashed reference line. A region of length D with friction coefficient μ (shaded) lies between positions x_1 and x_2. Block B (mass $3m$) hangs from a string of length ℓ attached to the ceiling, positioned at x_3 on the right. Marked positions along the x-axis: $0, x_0, x_1, x_2, x_3$. Note: Figure not drawn to scale.]

Question 1

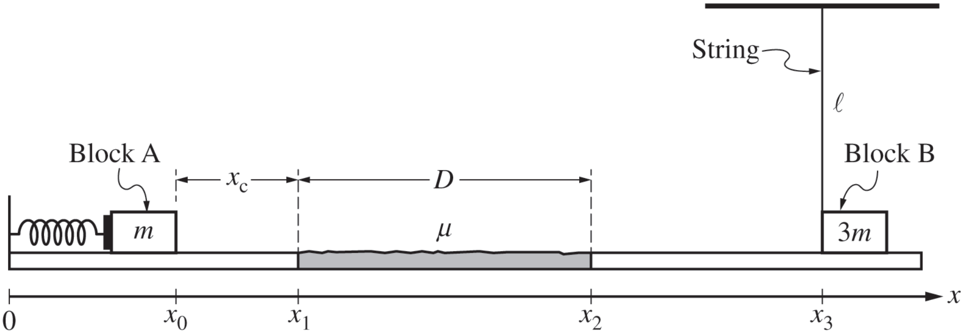
At time $t = 0$, Block A is located at position $x = x_0$ and is released from rest. After the block is released, the following occurs.
- At time $t = t_1$, Block A is at $x = x_1$ after traveling a distance x_c. Block A moves with speed v, and the spring is at its equilibrium position. - At time $t = t_2$, the left side of Block A is at $x = x_2$ after passing through a distance D across the region with nonnegligible friction. - At time $t = t_3$, Block A is at $x = x_3$ and Block A collides with and sticks to Block B.

(a) For parts (a)(i) and (a)(ii), express your answer in terms of m, k, D, μ, x_c, and physical constants, as appropriate.

(a)(i) Derive an expression for the speed v of Block A at time t_1.

(a)(ii) Derive an expression for the speed $v_{A,B}$ of the two-block system immediately after the collision at time t_3.

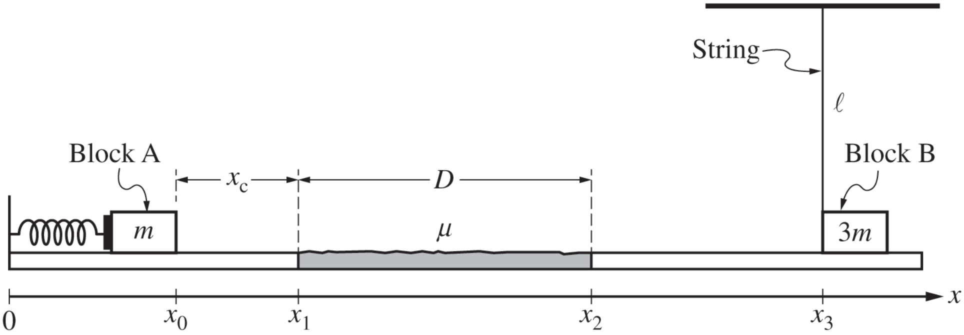
Question 1



Note: Figure not drawn to scale.

Figure 1

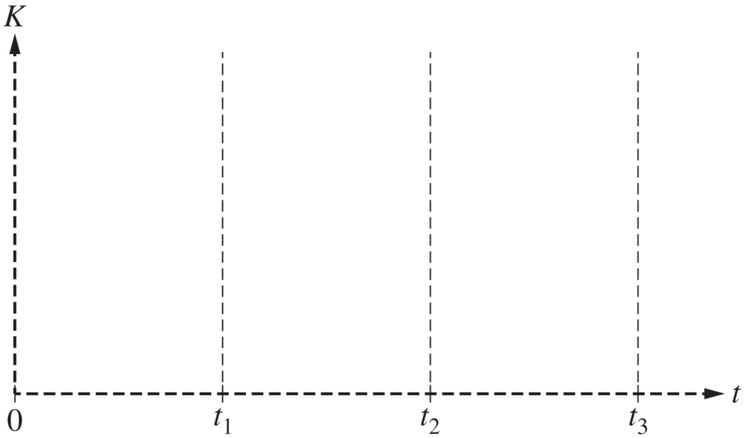
Question 1



Note: Figure not drawn to scale.

Figure 1

Question 1



Question 1

2024 Set 1 ▪ Q1

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[Figure 1: A horizontal setup on surface with position axis x from 0 to x_3. Block A (mass m) sits at the left against a spring, with a labelled distance x_c from Block A to a dashed reference line. A region of length D with friction coefficient μ (shaded) lies between positions x_1 and x_2. Block B (mass $3m$) hangs from a string of length ℓ attached to the ceiling, positioned at x_3 on the right. Marked positions along the x-axis: $0, x_0, x_1, x_2, x_3$. Note: Figure not drawn to scale.]

At time $t = 0$, Block A is located at position $x = x_0$ and is released from rest. After the block is released, the following occurs.

Question 1

- At time $t = t_1$, Block A is at $x = x_1$ after traveling a distance x_c. Block A moves with speed v, and the spring is at its equilibrium position. - At time $t = t_2$, the left side of Block A is at $x = x_2$ after passing through a distance D across the region with nonnegligible friction. - At time $t = t_3$, Block A is at $x = x_3$ and Block A collides with and sticks to Block B.

(a) For parts (a)(i) and (a)(ii), express your answer in terms of m, k, D, μ, x_c, and physical constants, as appropriate.

(b)(i) [Figure 1 repeated: same horizontal setup with Block A (mass m) against the spring, distance x_c, friction region of length D with coefficient μ between x_1 and x_2, and Block B (mass $3m$) hanging by a string of length ℓ at x_3. Positions marked $0, x_0, x_1, x_2, x_3$ along axis x. Note: Figure not drawn to scale.]

On the following axes, sketch a graph of the kinetic energy K of Block A as a function of time t from time $t = 0$ to t_3.

Question 1

[Blank graph: vertical axis K, horizontal axis t with gridlines/tick marks at t_1, t_2, t_3 (origin at 0); axes given with no curve drawn — student is to sketch the curve.]

(b)(ii) Use principles of work and energy to justify the graph drawn in part (b)(i) for the time interval $t = 0$ to $t = t_1$. Explicitly reference features of the shape of the graph you drew in part (b)(i).

Question 1

2024 Set 1 ▪ Q1

Block A and Block B of masses m and $3m$, respectively, are arranged in a setup consisting of an ideal spring with spring constant k and a horizontal surface. Friction between the surface and the blocks is negligible except in a region of length D, where the coefficient of kinetic friction between Block A and the surface is μ. Block B is attached to a string of length ℓ and negligible mass, as shown in Figure 1. Block A is held against the spring, compressing the spring a distance x_c.

[Figure 1: A horizontal setup on surface with position axis x from 0 to x_3. Block A (mass m) sits at the left against a spring, with a labelled distance x_c from Block A to a dashed reference line. A region of length D with friction coefficient μ (shaded) lies between positions x_1 and x_2. Block B (mass $3m$) hangs from a string of length ℓ attached to the ceiling, positioned at x_3 on the right. Marked positions along the x-axis: $0, x_0, x_1, x_2, x_3$. Note: Figure not drawn to scale.]

At time $t = 0$, Block A is located at position $x = x_0$ and is released from rest. After the block is released, the following occurs.

Question 1

- At time $t = t_1$, Block A is at $x = x_1$ after traveling a distance x_c. Block A moves with speed v, and the spring is at its equilibrium position. - At time $t = t_2$, the left side of Block A is at $x = x_2$ after passing through a distance D across the region with nonnegligible friction. - At time $t = t_3$, Block A is at $x = x_3$ and Block A collides with and sticks to Block B.

(a) For parts (a)(i) and (a)(ii), express your answer in terms of m, k, D, μ, x_c, and physical constants, as appropriate.

(c) [Figure 2: The two-block system (combined mass $m + 3m$) hangs from a string of length ℓ attached to a fixed support at the top. The string makes an angle θ_{max} with the vertical (dashed vertical reference line shown), with the block system displaced to one side at time t_4, having swung from its position at time t_3 (shown hanging straight down). Note: Figure not drawn to scale.]

After the collision, the two-block system instantaneously comes to rest at time t_4, which occurs when the string makes a small angle θ_{max} with the vertical, as shown in

Question 1

Figure 2. For times $t > t_4$, the system oscillates with frequency f_i. The support holding the string is raised, and the procedure is then repeated using a new string of length 2ℓ. Indicate how the new frequency of oscillation $f_{2\ell}$ of the system on the new string of length 2ℓ will compare to the frequency of oscillation f_i from the original procedure.

_______ $f_{2\ell} > f_i$ _______ $f_{2\ell} < f_i$ _______ $f_{2\ell} = f_i$

Briefly justify your answer.

Solution 1

(a)(i)

Mark scheme

- Apply conservation of mechanical energy: all of the initial energy is stored as spring potential energy U_s, so $E_{initial} = E_{final}$ gives $\frac{1}{2}kx_c^2 = \frac{1}{2}mv^2$. Solving for v: $v = x_c\sqrt{k/m}$. Point 1: multi-step energy derivation that identifies the initial energy as entirely spring PE U_s. Point 2: correct algebraic solution for v.

Solution 1

(a)(ii) Mark scheme

- Step 1 (energy or kinematics to get the speed v_2 at x_2, after friction acts over distance D): Energy method — $K_{x_1} - \Delta E_{friction} = K_{before\ collision}$: $\frac{1}{2}m\left(x_c\sqrt{k/m}\right)^2 - \mu mgD = \frac{1}{2}mv_2^2 \Rightarrow v_2 = \sqrt{\frac{kx_c^2}{m} - 2\mu gD}$. (Equivalently by kinematics: $a = -\mu g$ from $-\mu mg = ma$, then $v_2^2 = v^2 + 2aD = \left(x_c\sqrt{k/m}\right)^2 - 2\mu gD$, same result.) Step 2 (perfectly inelastic collision, conservation of momentum): $\Sigma p_{before} = \Sigma p_{after}$: $mv_2 = (m+3m)v_{A,B} = 4m\,v_{A,B}$. Solving: $v_{A,B} = \dfrac{m\sqrt{\frac{kx_c^2}{m} - 2\mu gD}}{4m} = \dfrac{1}{4}\sqrt{\dfrac{kx_c^2}{m} - 2\mu gD}$. Points: (1) energy or kinematics

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application to find speed at x_2; (2) correct expression for friction energy loss or deceleration ($\Delta E_{friction} = \mu mgD$ or $a = -\mu g$); (3) attempt at conservation of momentum $m_{initial}v_{initial} = m_{A,B}v_{A,B}$; (4) correctly substituting the consistent speed and masses into the momentum equation.

Solution 1

(b)(i) Mark scheme

- Sketch: $K = 0$ at $t = 0$; the curve rises nonlinearly and increases throughout $0 \leq t \leq t_1$, reaching a maximum at t_1 (when Block A leaves the spring). From t_1 to t_2 (the friction region) the curve decreases but does NOT reach zero, and is concave up (a constant friction deceleration makes v decrease linearly in time, so $K = \frac{1}{2}mv^2$ decreases at a decreasing rate). From t_2 to t_3 (after leaving the friction region, coasting to the collision) the curve is a horizontal line at a constant value greater than zero, and the whole curve from t_1 to t_3 is continuous (no jump at t_2). Points: (1) nonlinear sketch beginning at zero and increasing throughout $0 \leq t \leq t_1$; (2) decreasing throughout $t_1 \leq t \leq t_2$ without reaching

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zero; (3) concave up on $t_1 \leq t \leq t_2$; (4) a continuous function on $t_1 \leq t \leq t_3$ that is a horizontal line greater than zero on $t_2 \leq t \leq t_3$.

Solution 1

(b)(ii) Mark scheme

- From $0 < t < t_1$, the kinetic energy of Block A increases. The force exerted on the block by the compressed spring transfers the elastic potential energy in the block-spring system to the kinetic energy of the block. Because the force exerted by the spring is not applied at a constant rate (it decreases as the spring relaxes), the kinetic energy of the block does not increase at a constant rate — hence the nonlinear shape. Points: (1) a statement about the change in KE consistent with the graph (KE increasing on this interval); (2) a correct explanation for why KE is increasing (positive work done on the block / mechanical energy conserved as spring PE converts to KE); (3) a correct explanation for why the graph is

Solution 1

nonlinear (the spring force — and hence the rate of work done — changes as the block moves, so KE does not increase at a constant rate).

Solution 1

(c)

Mark scheme

- Select $f_{2\ell} < f_\ell$ (doubling the pendulum length decreases its frequency). Justification: the period of a pendulum is $T = 2\pi\sqrt{\ell/g}$. As the length increases, the period increases. Because frequency and period are inversely related ($f = 1/T$), an increase in period results in a decrease in frequency, so $f_{2\ell} < f_\ell$. Points: (1) selecting $f_{2\ell} < f_\ell$ with an attempt at a relevant justification; (2) correctly applying the pendulum period/frequency-length relationship $T = 2\pi\sqrt{\ell/g}$.

Question 1

2023 Set 1 ▪ Q1

[Figure 1: A block on an inclined ramp on the left, connected via the horizontal surface to Spring P mounted against a wall on the right. The spring is compressed a distance x from its natural length, with $x = 0$ marked at the wall-side end of the spring where it is uncompressed.]

A block sitting on a horizontal surface is pushed against a spring, Spring P, that is attached to a wall, compressing the spring a distance x, as shown in Figure 1. The block is then released from rest. The block slides along the horizontal surface and up a ramp, reaching a maximum height $h_{\text{max,P}}$. Frictional forces between the block and all surfaces are negligible.

A student compares $h_{\text{max,P}}$ for Spring P with the different height $h_{\text{max,Q}}$ achieved with a different spring, Spring Q. Each spring exerts a force of magnitude F on the block that varies as a function of the distance x the spring is compressed, as graphed in

Question 1

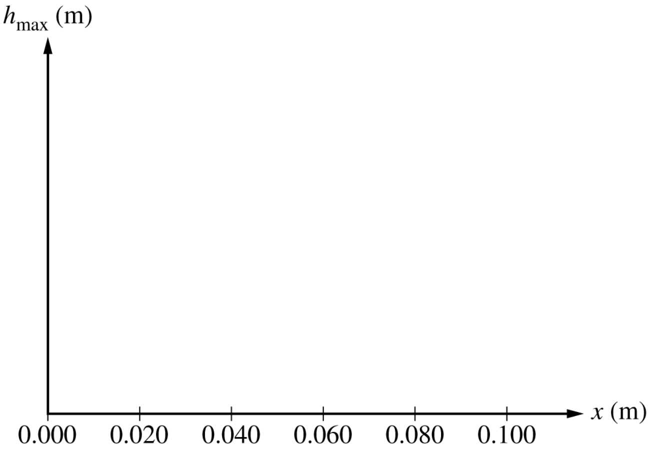
Figure 2. For Spring P, $F_P(x) = kx$, where $k = 100.0$ N/m, and for Spring Q, $F_Q(x) = Cx^{1/2}$, where $C = 20.0$ N/m$^{1/2}$.
[Figure 2: Graph of F (N) on the y-axis from 0.0 to 10.0, versus x (m) on the x-axis from 0.000 to 0.100, in increments of 0.020. Two curves are plotted: a solid line labeled "Spring P" that is straight, passing through the origin and rising linearly (consistent with $F_P(x) = kx$, reaching about 10.0 N at $x = 0.100$ m); a dashed curve labeled "Spring Q" that rises steeply at first and then levels off (consistent with $F_Q(x) = Cx^{1/2}$, reaching about 6.3 N at $x = 0.100$ m).]
(a) For the experiment, the block is pushed against one of the springs, compressing the spring a distance $x = 0.010$ m. The block is then released from rest. In Trial 1, Spring P is used, and in Trial 2, Spring Q is used. On the following representations of the block in Trials 1 and 2, draw and label the forces (non-components) that are exerted on the block at the instant the block is released. Each force must be

Question 1

represented by a distinct arrow starting on, and pointing away from, the dot. The lengths of the horizontal vectors should represent the relative magnitude of the horizontal forces and the lengths of the vertical vectors should represent the relative magnitude of the vertical forces.

[Two grid diagrams are shown, each with a dot at the center representing the block: "Trial 1 (Spring P)" on the left and "Trial 2 (Spring Q)" on the right. Each grid is for the student to draw labeled force vectors.]

Question 1



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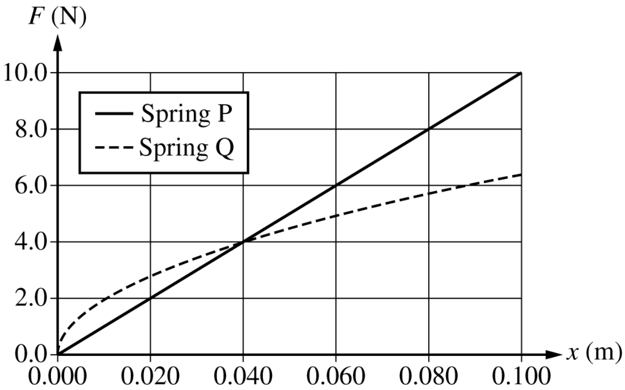
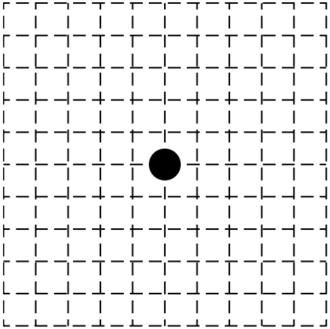


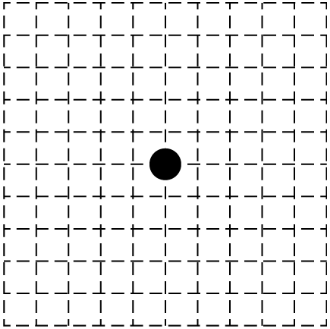
Figure 2

Question 1

Trial 1
(Spring P)



Trial 2
(Spring Q)



Question 1

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[Figure 1: A block on an inclined ramp on the left, connected via the horizontal surface to Spring P mounted against a wall on the right. The spring is compressed a distance x from its natural length, with $x = 0$ marked at the wall-side end of the spring where it is uncompressed.]
A block sitting on a horizontal surface is pushed against a spring, Spring P, that is attached to a wall, compressing the spring a distance x, as shown in Figure 1. The block is then released from rest. The block slides along the horizontal surface and up a ramp, reaching a maximum height $h_{\text{max,P}}$. Frictional forces between the block and all surfaces are negligible.
A student compares $h_{\text{max,P}}$ for Spring P with the different height $h_{\text{max,Q}}$ achieved with a different spring, Spring Q. Each spring exerts a force of magnitude F on the block that varies as a function of the distance x the spring is compressed, as graphed in Figure 2. For Spring P, $F_P(x) = kx$, where $k = 100.0$ N/m, and for Spring Q, $F_Q(x) = Cx^{1/2}$, where $C = 20.0$ N/m$^{1/2}$.
[Figure 2: Graph of F (N) on the y-axis from 0.0 to 10.0, versus x (m) on the x-axis from 0.000 to 0.100, in increments of 0.020. Two curves are plotted: a solid line labeled "Spring P" that is

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straight, passing through the origin and rising linearly (consistent with $F_P(x) = kx$, reaching about 10.0 N at $x = 0.100$ m); a dashed curve labeled "Spring Q" that rises steeply at first and then levels off (consistent with $F_Q(x) = Cx^{1/2}$, reaching about 6.3 N at $x = 0.100$ m).]

(b)(i) What feature(s) of the graph in Figure 2 could be used to estimate the work done on the block by each spring as each spring is compressed?

(b)(ii) There is one compression distance x_0 for which the maximum height h_{max} reached by the block is the same regardless of which spring, Spring P or Spring Q, is used. Predict whether the value of x_0 is greater than, less than, or equal to 0.040 m. Use the graph in Figure 2 to justify your answer.

(b)(iii) On the axes provided, for both Spring P and Spring Q, sketch a graph of the maximum height h_{max} reached by the block as a function of the distance x each spring is compressed for values of x ranging from 0 to 0.100 m. Clearly label the curve for Spring P and Spring Q.

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[Blank axes provided: y-axis labeled h_{max} (m), x-axis labeled x (m) from 0.000 to 0.100 in increments of 0.020, for the student to sketch two curves.]

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[Figure 1: A block on an inclined ramp on the left, connected via the horizontal surface to Spring P mounted against a wall on the right. The spring is compressed a distance x from its natural length, with $x = 0$ marked at the wall-side end of the spring where it is uncompressed.]
A block sitting on a horizontal surface is pushed against a spring, Spring P, that is attached to a wall, compressing the spring a distance x, as shown in Figure 1. The block is then released from rest. The block slides along the horizontal surface and up a ramp, reaching a maximum height $h_{\text{max,P}}$. Frictional forces between the block and all surfaces are negligible.
A student compares $h_{\text{max,P}}$ for Spring P with the different height $h_{\text{max,Q}}$ achieved with a different spring, Spring Q. Each spring exerts a force of magnitude F on the block that varies as a function of the distance x the spring is compressed, as graphed in Figure 2. For Spring P, $F_P(x) = kx$, where $k = 100.0$ N/m, and for Spring Q, $F_Q(x) = Cx^{1/2}$, where $C = 20.0$ N/m$^{1/2}$.
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straight, passing through the origin and rising linearly (consistent with $F_P(x) = kx$, reaching about 10.0 N at $x = 0.100$ m); a dashed curve labeled "Spring Q" that rises steeply at first and then levels off (consistent with $F_Q(x) = Cx^{1/2}$, reaching about 6.3 N at $x = 0.100$ m).]

(c)(i) [Figure 3: Block A rests at the top of an inclined ramp of height H, connected by a string over the top of the ramp; Block B rests on the horizontal surface at the bottom of the ramp, connected to Spring Q which is attached to a wall, with $x = 0$ marked at the natural length position of the spring.]

Spring Q is attached to the wall and at equilibrium, as shown in Figure 3. Block A has a mass of 0.120 kg and Block B has a mass of 0.070 kg. Block A is held at rest at the top of the ramp on the horizontal surface. The change in vertical height of Block A is $H = 0.75$ m. The student releases Block A, and it moves down the ramp and collides with Block B. After the collision, the blocks stick together and move to the right,

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compressing the spring. Frictional forces between the blocks and all surfaces are negligible.

Calculate the velocity of the two-block system immediately after the collision between Blocks A and B.

(c)(ii) Calculate the maximum compression of the spring.

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[Figure 1: A block on an inclined ramp on the left, connected via the horizontal surface to Spring P mounted against a wall on the right. The spring is compressed a distance x from its natural length, with $x = 0$ marked at the wall-side end of the spring where it is uncompressed.]
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straight, passing through the origin and rising linearly (consistent with $F_P(x) = kx$, reaching about 10.0 N at $x = 0.100$ m); a dashed curve labeled "Spring Q" that rises steeply at first and then levels off (consistent with $F_Q(x) = Cx^{1/2}$, reaching about 6.3 N at $x = 0.100$ m).]

(d) Spring Q where $F_Q(x) = Cx^{1/2}$ is replaced by a different nonlinear spring, Spring R, and the procedure described in part (c) is repeated. For Spring R, $F_R(x) = Dx^{1/2}$. The maximum compression of Spring R is greater than the maximum compression of Spring Q. Which of the following correctly compares the constants C and D?

______ $C < D$ ______ $C > D$ ______ $C = D$

Briefly 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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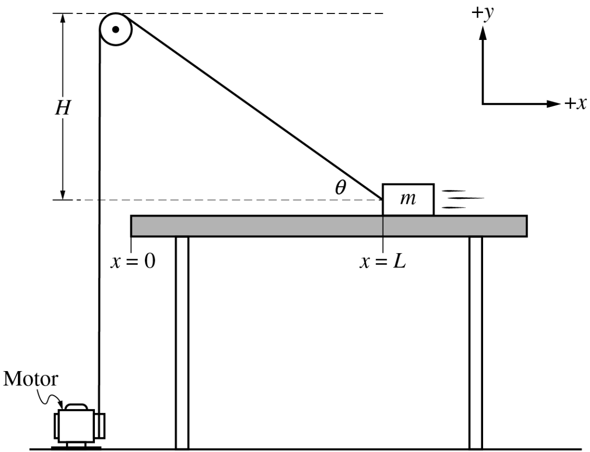

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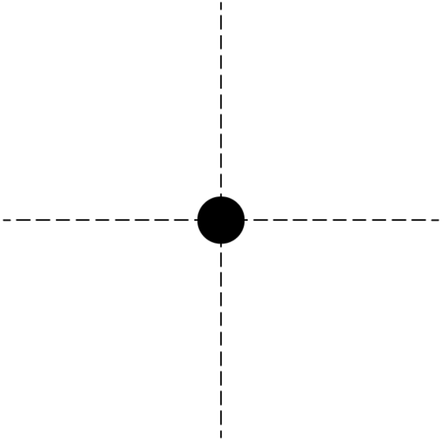

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2022 Set 1 ▪ Q1

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

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

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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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2022 Set 1 ▪ Q1

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

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

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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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(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 $x = 0$.