Past-paper walk-through

Energy of Simple Harmonic Oscillators ▪ 7.4

eXercise

Questions in this set

- 2025 Q2
- 2023 Set 1 Q2
- 2023 Set 2 Q2

Reading the mark scheme

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

Question 2

2025 ▪ Q2

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

Question 2

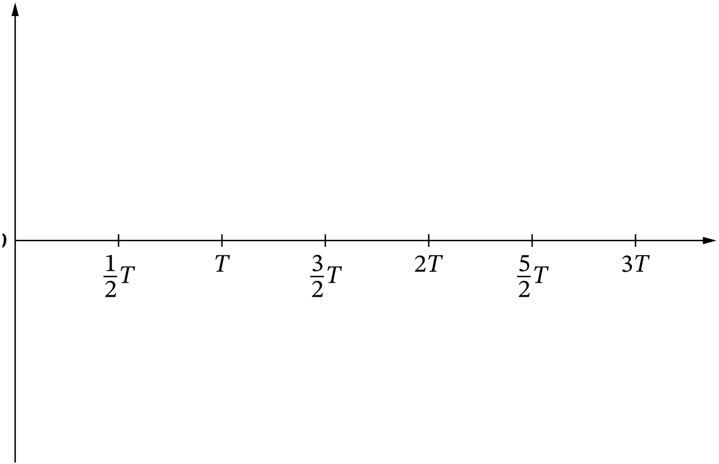
is shown at top right with $+y$ (up) and $+x$ (right) directions labeled. The positions $x = 0$ and $x = x_1$ are marked on the horizontal surface.]

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

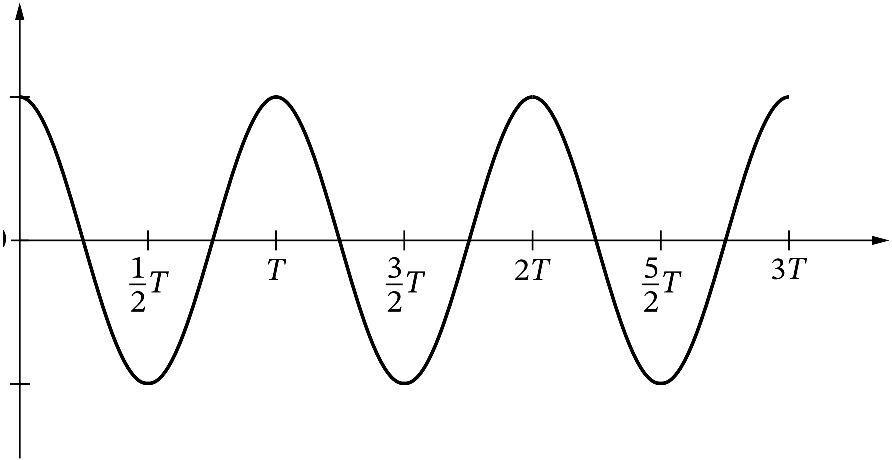
- The height of the shaded bars should be proportional to the relative values of U_A, U_B, and K_{block}. - Any energy that is equal to zero should be represented by a distinct line on the zero-energy line.

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

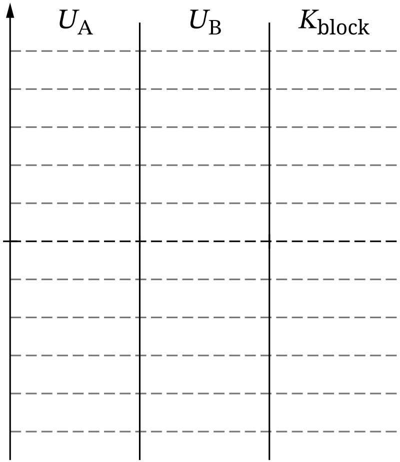
Question 2



Question 2



Question 2



Question 2

2025 ▪ Q2

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

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

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

Question 2

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Question 2

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

Question 2

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

Question 2

2025 ▪ Q2

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

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

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

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

Question 2

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

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

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

Briefly **justify** your answer.

Solution 2

(a) Mark scheme

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

Solution 2

(b) Mark scheme

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

Solution 2

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

Solution 2

(c)(i) Mark scheme

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

Solution 2

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

Solution 2

(d) Mark scheme

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

Solution 2

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

Question 2

2023 Set 1 ▪ Q2

[Figure 1: A torsional pendulum with a single uniform disk ($N = 1$) suspended from a light wire, showing an angular displacement θ_0 from the untwisted position. Figure 2: The same torsional pendulum with a second identical disk attached below the first ($N = 2$), also displaced by angle θ_0.]

A student makes a torsional pendulum by suspending a uniform disk of mass M and radius R from a light wire with torsion constant κ that is attached to the center of the disk as shown in Figure 1. The rotational inertia of the disk is given by $I = \frac{1}{2}MR^2$.

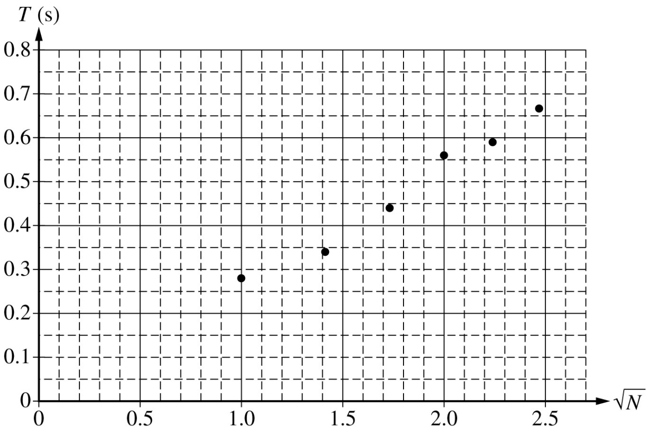
The student conducts an investigation to determine the relationship between the period of oscillation T of the torsional pendulum and the number N of identical disks that are suspended from the wire.

Question 2

The student starts with a single disk. Holding the disk at a small initial angular displacement θ_0 from the untwisted position, the student releases the disk from rest and the pendulum oscillates. The student records the period of oscillation for a single disk. An additional identical disk is attached, as shown in Figure 2, and the procedure is repeated for $N = 2$ disks. This procedure is repeated through $N = 10$ identical disks. Assume the disks move together as one system.

(a) Using $T = 2\pi\sqrt{\frac{I}{\kappa}}$, derive an expression for T as a function of N. Express your answer in terms of M, R, κ, N, and physical constants, as appropriate.

Question 2



Question 2

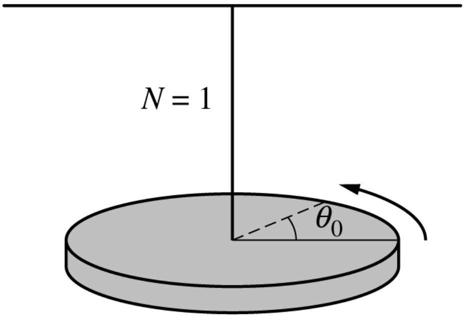


Figure 1

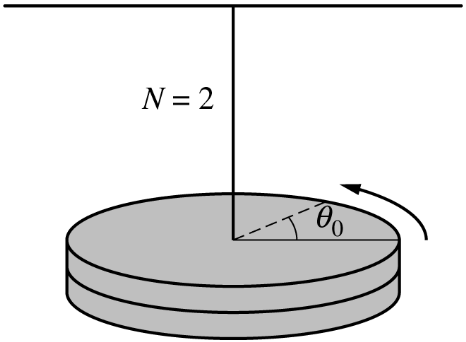


Figure 2

Question 2

Question 2

2023 Set 1 ▪ Q2

[Figure 1: A torsional pendulum with a single uniform disk ($N = 1$) suspended from a light wire, showing an angular displacement θ_0 from the untwisted position. Figure 2: The same torsional pendulum with a second identical disk attached below the first ($N = 2$), also displaced by angle θ_0.]

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Question 2

disk is attached, as shown in Figure 2, and the procedure is repeated for $N = 2$ disks. This procedure is repeated through $N = 10$ identical disks. Assume the disks move together as one system.

(b) The potential energy stored in the torsional pendulum when the disks are displaced is $U = \frac{1}{2}\kappa(\Delta\theta)^2$. On the following axes, sketch a graph of the maximum kinetic energy K_{max} of the torsional pendulum as a function of N for $N \geq 1$.
[Blank axes provided: y-axis labeled K_{max}, x-axis labeled N, for the student to sketch a curve.]

Question 2

2023 Set 1 ▪ Q2

[Figure 1: A torsional pendulum with a single uniform disk ($N = 1$) suspended from a light wire, showing an angular displacement θ_0 from the untwisted position. Figure 2: The same torsional pendulum with a second identical disk attached below the first ($N = 2$), also displaced by angle θ_0.]

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Question 2

disk is attached, as shown in Figure 2, and the procedure is repeated for $N = 2$ disks. This procedure is repeated through $N = 10$ identical disks. Assume the disks move together as one system.

(c)(i) [Figure: Graph of T (s) on the y-axis from 0 to 0.8 in increments of 0.1, versus $\sqrt{N}$ on the x-axis from 0 to 2.5 in increments of 0.5. Scattered data points are plotted showing an approximately linear increasing trend, roughly from $(\sqrt{N} \approx 0.7, T \approx 0.25)$ up to $(\sqrt{N} \approx 2.3, T \approx 0.65)$, for the student to draw a best-fit line through.]

The student plots the data for T as a function of $\sqrt{N}$, as shown.

Draw the best-fit line for the data.

(c)(ii) The student previously determined that the radius of a disk is $R = 0.2$ m and found that $\kappa = 1.6$ N $\cdot$ m. Using the graph, calculate the mass M of a single disk.

(c)(iii) The student finds that the value given by the manufacturer for the mass of the disk is less than the value determined experimentally in part (c)(ii). Determine a single

Question 2

source of experimental error that could result in the observed difference in the value of M. Justify your answer.

Question 2

2023 Set 1 ▪ Q2

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Question 2

disk is attached, as shown in Figure 2, and the procedure is repeated for $N = 2$ disks. This procedure is repeated through $N = 10$ identical disks. Assume the disks move together as one system.

(d)(i) The student repeats the experiment, but now the disks have a density that varies as a function of the radius of the disk according to $\rho = 0.3r$. Would the slope of the best-fit line for this new data be greater than, less than, or the same as the slope of the best-fit line in part (c)(i)?

_______ greater than _______ less than _______ the same as

Justify your answer.

(d)(ii) When $N = 1$, the maximum angular speed of the torsional pendulum with a uniform disk is found to be ω_{U}. When $N = 1$, the maximum angular speed of the torsional pendulum with a nonuniform disk is $\omega_{\text{non-U}}$. Which of the following correctly compares ω_{U} and $\omega_{\text{non-U}}$?

Question 2

$\omega_{\text{U}} > \omega_{\text{non-U}}$ $\omega_{\text{U}} < \omega_{\text{non-U}}$ $\omega_{\text{U}} = \omega_{\text{non-U}}$
Briefly justify your answer.

Question 2

2023 Set 2 ▪ Q2

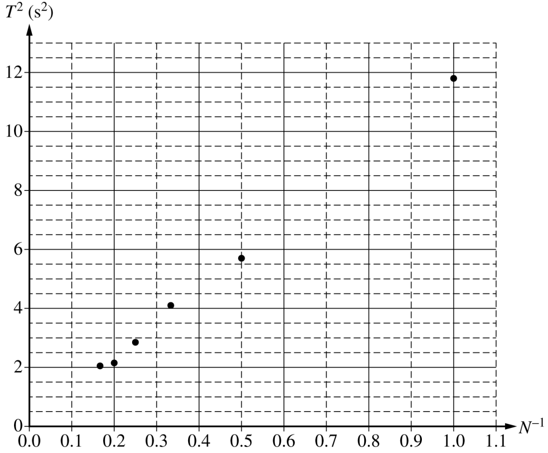
A student conducts an investigation to determine the relationship between the period of oscillation T of a system consisting of a block and N attached springs. The student starts with a block of mass m attached to a single ideal spring of spring constant k, as shown in Figure 1. The student holds the block so that the spring is neither stretched nor compressed at a vertical height 1.00 m above a motion detector. The student releases the block from rest and records the period of oscillation for the system consisting of the single spring and block. An additional identical spring is attached in parallel, as shown in Figure 2, and the procedure is repeated for $N = 2$ springs. This procedure is repeated through $N = 10$ springs.
[Figure 1: A spring of spring constant k (labeled "$N = 1$") hangs from a fixed support, with a block of mass m attached below it, positioned 1.00 m above a motion detector on the ground.]

Question 2

[Figure 2: Two identical springs, each of spring constant k, attached in parallel (labeled "$N = 2$") hang from a fixed support, with a block of mass m attached below them, positioned 1.00 m above a motion detector on the ground.]

(a) Derive an expression for T as a function of N. Express your answer in terms of m, k, N, and physical constants as appropriate.

Question 2



Question 2

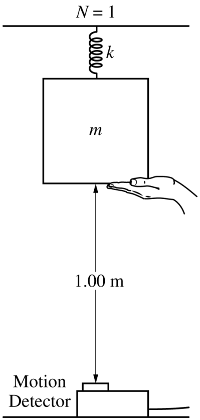


Figure 1

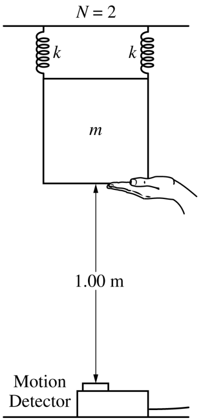


Figure 2

Question 2

Question 2

2023 Set 2 ▪ Q2

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[Figure 1: A spring of spring constant k (labeled "$N = 1$") hangs from a fixed support, with a block of mass m attached below it, positioned 1.00 m above a motion detector on the ground.]

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Question 2

(b) On the following axes, sketch a graph of T as a function of N for $N \geq 1$.
[Grid: axes labeled T (vertical) vs. N (horizontal), both unlabeled with values, blank for the student to sketch on.]

Question 2

2023 Set 2 ▪ Q2

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Question 2

(c)(i) The student plots the data for T^2 as a function of N^{-1}, as shown.
[Graph: T^2 (s^2) vs. N^{-1}; y-axis from 0 to 12 in increments of 2, x-axis from 0.0 to 1.1 in increments of 0.1; scattered data points roughly along an increasing linear trend, approximately at $(0.1, 1)$, $(0.15, 1.5)$, $(0.2, 2)$, $(0.33, 4)$, $(0.5, 6)$, $(1.0, 12)$.]
Draw the best-fit line for the data.
(c)(ii) The mass of the block is measured to be $m = 1.5$ kg. Using the graph, calculate an experimental value for the spring constant k for a single spring.
(c)(iii) The student finds that the value given by the manufacturer for the spring constant is larger than the value determined experimentally in part (c)(ii). Determine a single source of experimental error that could result in the observed difference in the value for k. Briefly justify your answer.

Question 2

2023 Set 2 ▪ Q2

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Question 2

(d)(i) The student conducts a similar investigation to determine the relationship between the period of oscillation T of a block-spring system and a number N of identical springs horizontally on a table, as shown in Figure 3. Frictional forces between the table and the block are negligible. In each trial, the block is displaced the same horizontal distance from equilibrium and released from rest.
[Figure 3: A block of mass m attached to $N = 2$ springs on a horizontal table, springs shown attached to a wall on the left and the block on the right.]
The student plots T^2 as a function of N^{-1} for this new investigation. Would the slope of the best-fit line from this new investigation be greater than, less than, or the same as the slope of the best-fit line in part (c)(i)?
______ greater than ______ less than ______ the same as
Briefly justify your answer.

Question 2

(d)(ii) When $N = 1$, the maximum speed of the block is found to be v_{max}. When N increases, will v_{max} increase, decrease, or stay the same?

______ increase ______ decrease ______ stay the same

Justify your answer.