2026

BURKE TUTORING

AP® Physics 1: Work, Energy, and Power

Practice Free-Response Questions

Eight questions on Unit 3 in two sets of four, written in the exam's four free-response formats, with scoring guidelines for every part.

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PHYSICS 1: WORK, ENERGY, AND POWER
PRACTICE FREE-RESPONSE QUESTIONS
TIME: 95 MINUTES PER SET

Directions:

This booklet has eight free-response questions on Unit 3 of AP Physics 1. Questions 1 to 4 form Set A, and Questions 5 to 8 form Set B. Each set contains one question of each type used on the exam: mathematical routines, translation between representations, experimental design and analysis, and qualitative/quantitative translation.

Allow 95 minutes for each set, matching the free-response section starting with the May 2027 exam. (The 2026 exam allowed 100 minutes.) One workable pace is about 25 minutes for each of the first three questions and 20 minutes for the last one.

You may use a calculator, a ruler, and the AP Physics 1 reference information. Use $g = 9.8\ \text{m/s}^2$ and treat air resistance as negligible unless a question says otherwise.

Write your answers on separate paper, labeled with the part (A, B, C, D) and sub-part (i, ii, iii) they answer. Draw bars, graphs, data points, and best-fit lines directly on the figures in this booklet, using one color of ink or pencil.

Show your work. Credit depends on choosing the right physics principles, writing derivations and explanations that someone else can follow, and giving units with numerical answers.

Scoring guidelines for all eight questions begin on page 17.

Reference information. The AP Physics 1 equation sheet is posted by College Board at apcentral.collegeboard.org/media/pdf/ap-physics-1-equations-sheet.pdf.

Review pages for these topics. Kinetic and potential energy guide: burketutoringinfremont.com/ap-physics-1-kinetic-and-potential-energy-problems/
Work, energy, and power guide: burketutoringinfremont.com/ap-physics-1-work-energy-and-power-problems/

Online version. Each scoring guide also sits under its question at burketutoringinfremont.com/ap-physics-1-work-energy-and-power-frq/.

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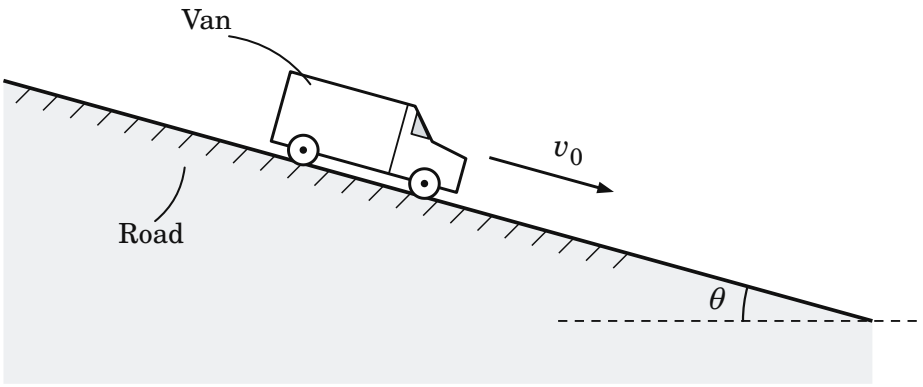
Question 1: Mathematical Routines

1. An electric delivery van of mass M travels down a straight road on a hill that makes an angle θ with the horizontal, as shown in Figure 1. On the way down, the van's motor exerts no force on the wheels and the driver does not use the brakes. The van rolls down the hill at a constant speed v_0. The air and the road exert resistive forces on the van. The total magnitude F_R of these resistive forces depends only on the speed of the van and is greater when the van moves faster.

Figure 1



Note: Figure not drawn to scale.

Part A

The van rolls a distance D along the road at speed v_0. Starting with the work-energy theorem, **derive** an expression for F_R. Express your answer in terms of M, θ, and physical constants, as appropriate. Include the work done on the van by each force exerted on it.

Part B

i. Consider the system that consists of the van and Earth. **Derive** an expression for the rate at which the mechanical energy of this system decreases while the van rolls at speed v_0. Express your answer in terms of M, v_0, θ, and physical constants, as appropriate.

ii. Briefly **describe** what happens to the mechanical energy that the van-Earth system loses.

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Part C

Later, the van travels up the same hill at the same constant speed v_0, with the motor driving the wheels.

i. **Derive** an expression for the power P_{up} that the motor must deliver to keep the van moving up the hill at speed v_0. Express your answer in terms of M, v_0, θ, and physical constants, as appropriate.

ii. The van has mass $M = 2{,}500$ kg, the hill makes an angle $\theta = 3.0°$ with the horizontal, and $v_0 = 25$ m/s. **Calculate** P_{up}.

Part D

The driver then drives up the same hill at a constant speed of $\frac{1}{2}v_0$. Let P_{slow} be the power the motor must deliver at this speed. **Indicate** whether P_{slow} is greater than, less than, or equal to $\frac{1}{2}P_{up}$ by writing one of the following.

- $P_{slow} > \frac{1}{2}P_{up}$
- $P_{slow} < \frac{1}{2}P_{up}$
- $P_{slow} = \frac{1}{2}P_{up}$

Justify your answer.

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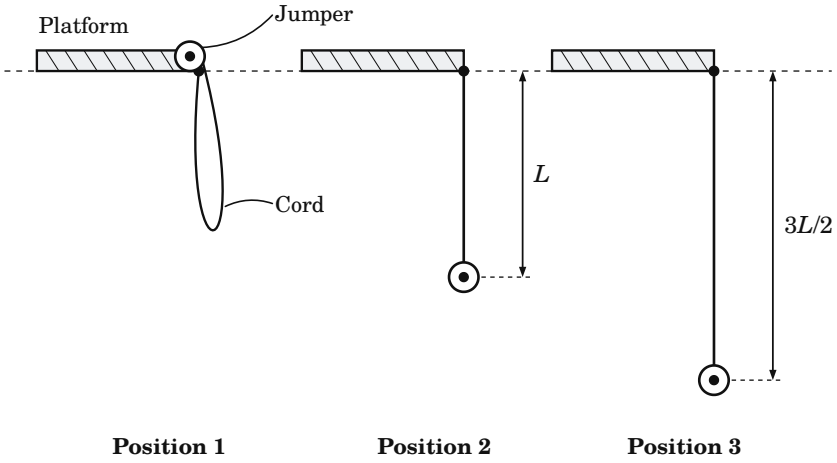
Question 2: Translation Between Representations

2. A bungee jumper of mass m steps off a high platform and falls straight down, starting from rest. One end of an elastic cord is tied to the edge of the platform, and the other end is attached to the jumper's harness. The cord has unstretched length L. While the cord is slack, it exerts no force on the jumper. When the cord is stretched, it behaves like an ideal spring with spring constant k. Figure 1 shows the jumper at three positions.

- Position 1: at rest on the platform, before the jump.
- Position 2: a distance L below the platform, at the instant the cord becomes taut.
- Position 3: a distance $\frac{3}{2}L$ below the platform, the lowest point, where the jumper is momentarily at rest.

Air resistance and the mass of the cord are negligible. Model the jumper as a particle.

Figure 1



Note: Figure not drawn to scale.

Part A

Figure 2 shows an energy bar chart for the system that consists of the jumper, the cord, and Earth when the jumper is at Position 1. The gravitational potential energy U_g of the system is defined to be zero when the jumper is at Position 3. On the charts for Position 2 and Position 3, **draw** shaded bars to represent the kinetic energy K, the gravitational potential energy U_g, and the spring potential energy U_s of the system.

- Start each bar at the line that represents zero energy.
- Make the heights of the bars consistent with the chart for Position 1.
- If an energy is zero, write 0 in its column.

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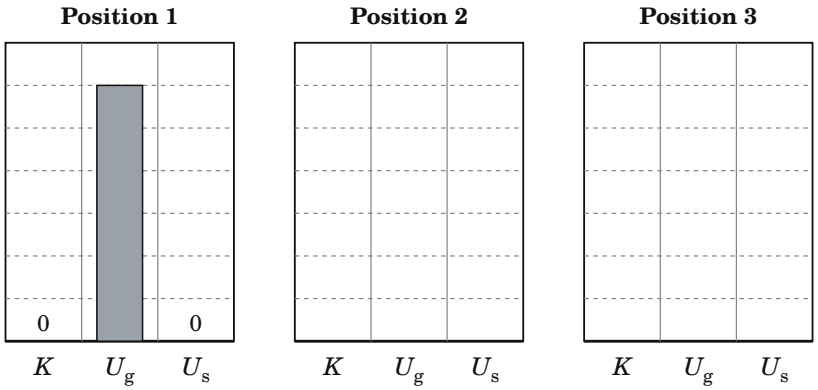
Figure 2



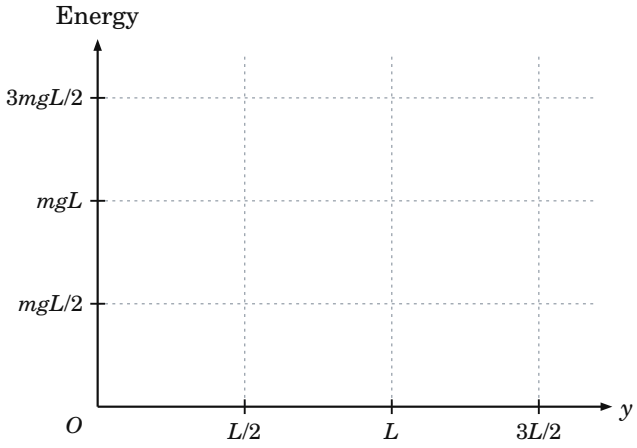
Part B

Derive an expression for the greatest speed v_{max} that the jumper reaches during the fall. Express your answer in terms of L and physical constants, as appropriate. Begin with a fundamental physics principle or an equation from the reference information, and show the steps that lead to your answer.

Part C

On the axes in Figure 3, **sketch** graphs of K, U_g, and U_s for the system as functions of the distance y of the jumper below the platform, from $y = 0$ to $y = \frac{3}{2}L$. **Label** each graph.

Figure 3



Part D

A student claims that the jumper's speed is greatest at Position 2, because the cord starts to slow the jumper as soon as it becomes taut. Using the slopes of your graphs from Part C, **explain** why the student's claim is incorrect.

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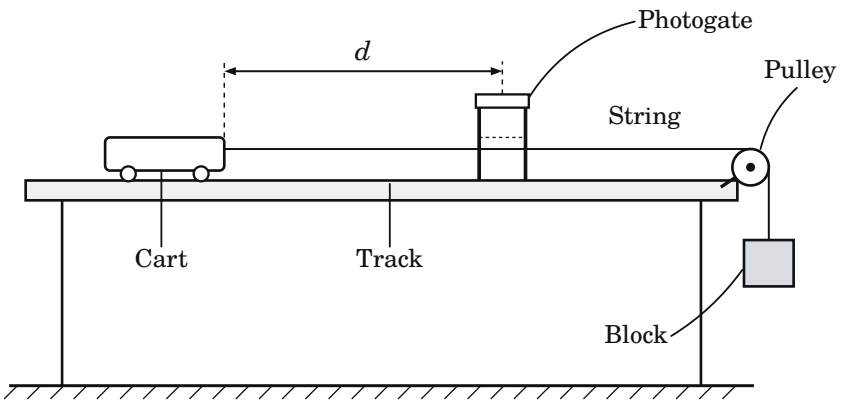
Question 3: Experimental Design and Analysis

The following information applies to Parts A and B.

3. A group of students wants to determine the mass M of a cart. The cart is on a long, level track. A light string tied to the cart passes over a pulley at the end of the track and is tied to a hanging block, as shown in Figure 1. When the cart is released from rest, the block falls and the cart speeds up. Friction on the cart, the mass of the string, and the mass and friction of the pulley are negligible.

Figure 1



Note: Figure not drawn to scale.

The students have the cart and track, the pulley, a set of hanging blocks of known masses, a meterstick, and a photogate that records the speed of the cart as the cart passes through it.

Part A

i. **Indicate** the quantities the students should measure so that they can determine M from a linear graph. Include the quantity they will vary from one trial to the next.

ii. Briefly **describe** one way the students could reduce the experimental uncertainty in these measurements.

Part B

i. **Indicate** the quantities the students could plot on the horizontal and vertical axes to produce a linear graph from which M can be determined. State clearly which quantity goes on each axis.

ii. Briefly **describe** how M is related to a feature of the graph from Part B(i). You may include an equation that relates M to that feature.

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The following information applies to Parts C and D.

In their experiment, the students use a hanging block of mass m = 0.050 kg. For each trial they release the cart from rest a distance d from the photogate, so the block also falls a distance d before the cart reaches the photogate. Table 1 shows the speed v of the cart at the photogate for five values of d.

The students make a graph with d plotted on the horizontal axis.

Table 1

d (m)	v (m/s)
0.20	0.62
0.40	0.89
0.60	1.08
0.80	1.26
1.00	1.39

Part C

i. **Label** the vertical axis of Figure 2 with a measured or calculated quantity, with units if it has any. Choose a quantity that makes the graph linear and lets you determine M.

ii. On the grid in Figure 2, make a graph that can be used to determine M.

- Add a numerical scale to the vertical axis.
- **Plot** the data points.
- Table 2 gives space for the values you plot and is not scored.

Figure 2

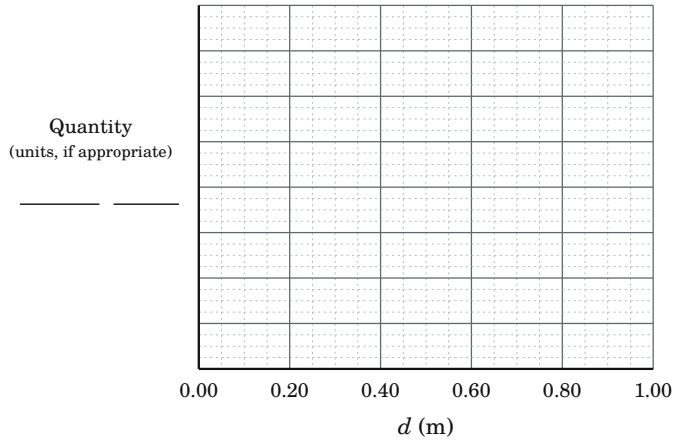

Table 2

d (m)	v (m/s)	
0.20	0.62	
0.40	0.89	
0.60	1.08	
0.80	1.26	
1.00	1.39	

iii. **Draw** a best-fit line through the data you plotted in Part C(ii).

Part D

Use your best-fit line from Part C(iii) to **calculate** an experimental value for M.

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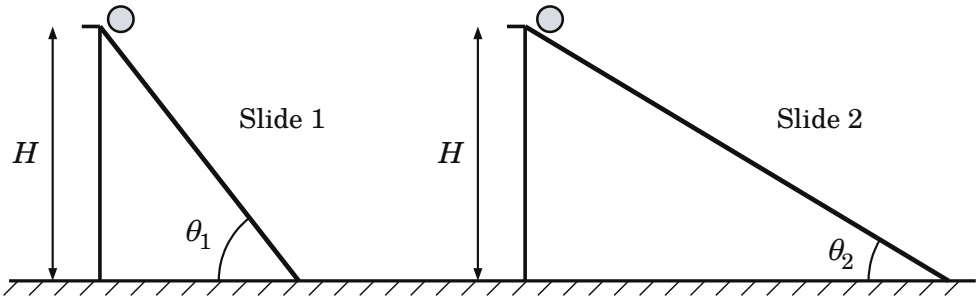
Question 4: Qualitative/Quantitative Translation

4. A playground has two straight slides that each start at the same height H above the ground. Slide 1 makes an angle θ_1 with the horizontal, and Slide 2 makes a smaller angle θ_2 with the horizontal, as shown in Figure 1. A child of mass m starts from rest at the top of each slide and slides all the way to the bottom. The coefficient of kinetic friction between the child and each slide is μ_k. Air resistance is negligible. The speed of the child at the bottom of Slide 1 is v_1, and the speed at the bottom of Slide 2 is v_2.

Figure 1



Note: Figure not drawn to scale.

Part A

Indicate whether v_1 is greater than, less than, or equal to v_2 by writing one of the following.

- $v_1 > v_2$
- $v_1 < v_2$
- $v_1 = v_2$

Justify your answer in words, without using equations.

Part B

Derive an expression for the speed v of the child at the bottom of a slide that starts at height H and makes an angle θ with the horizontal. Express your answer in terms of H, θ, μ_k, and physical constants, as appropriate. Begin with a fundamental physics principle or an equation from the reference information, and show the steps that lead to your answer.

Part C

Explain how your expression from Part B supports your reasoning in Part A.

END OF SET A

Set B begins with Question 5.

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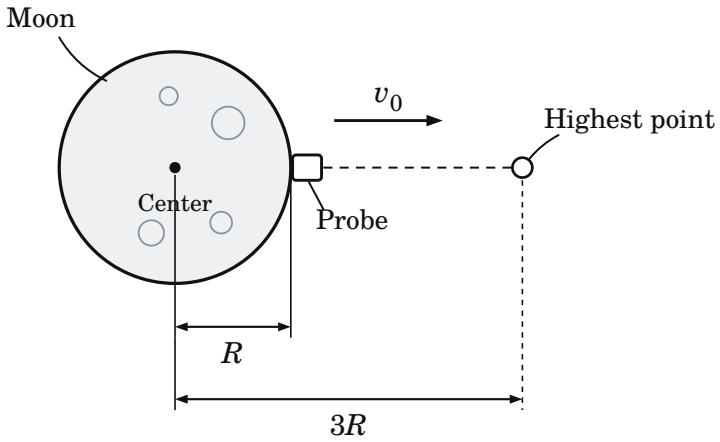
Question 5: Mathematical Routines

5. A small probe of mass m is launched straight up from the surface of a moon that has no atmosphere. The moon is a uniform sphere of mass M and radius R. The probe leaves the surface with speed v_0, moves directly away from the center of the moon, and is momentarily at rest when it is a distance $3R$ from the center of the moon, as shown in Figure 1. The gravitational potential energy U_G of the probe-moon system is defined to be zero when the probe and the moon are infinitely far apart. Gravitational forces from all other objects are negligible, and the motion of the moon can be ignored. Let $U_0 = \frac{GMm}{R}$.

Figure 1



Note: Figure not drawn to scale.

Part A

On the axes in Figure 2, **sketch** graphs of U_G of the probe-moon system and the kinetic energy K of the probe as functions of the distance r between the probe and the center of the moon, from $r = R$ to $r = 3R$. **Label** each graph.

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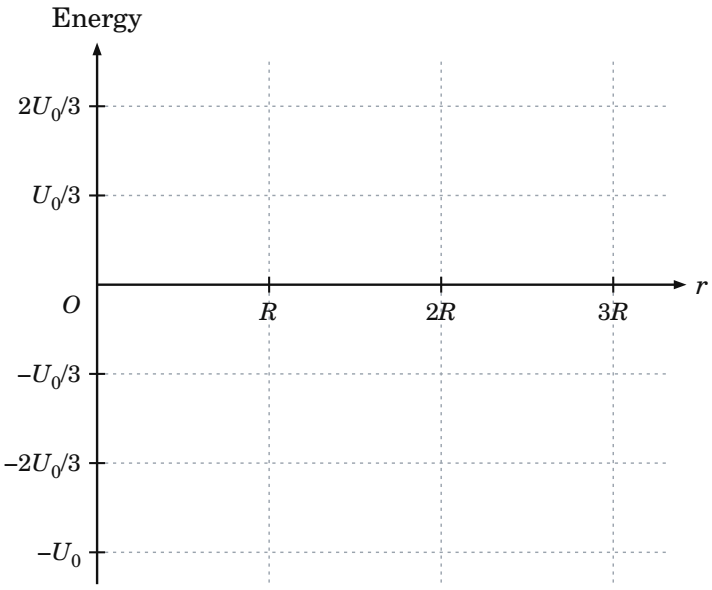
Figure 2



Part B

Derive an expression for v_0. Express your answer in terms of M, R, and physical constants, as appropriate. Begin with a fundamental physics principle or an equation from the reference information, and show the steps that lead to your answer.

Part C

The moon has mass $M = 7.35 \times 10^{22}$ kg and radius $R = 1.74 \times 10^{6}$ m. **Calculate** v_0.

Part D

A student finds the launch speed with the equation $\Delta U_g = mg\Delta y$, using $\Delta y = 2R$ and the gravitational field strength at the moon's surface, $g_s = \frac{GM}{R^2}$, for g. Let v_s be the launch speed the student finds.

Indicate whether v_s is greater than, less than, or equal to v_0 by writing one of the following.

- $v_s > v_0$
- $v_s < v_0$
- $v_s = v_0$

Justify your answer.

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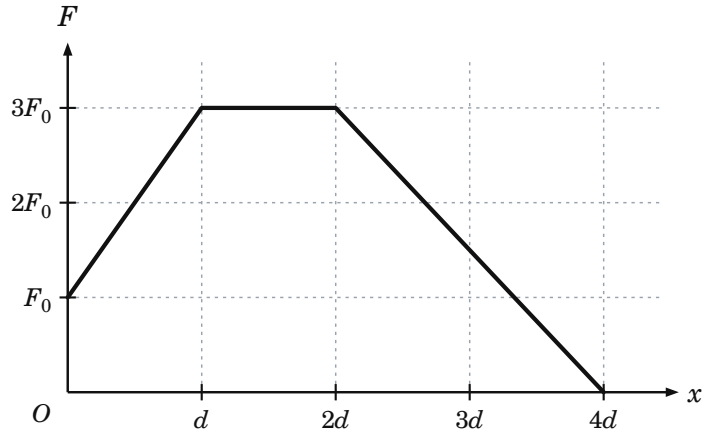
Question 6: Translation Between Representations

6. An archer uses a compound bow to shoot an arrow of mass m horizontally. Wheels at the ends of the bow change how the force from the string varies as the arrow moves. Figure 1 shows the horizontal force F that the string exerts on the arrow as a function of the arrow's position x, where x is the distance the arrow has moved forward from the point where it is released from rest. The arrow leaves the string at $x = 4d$. During the launch, the force from the string is the only force that does work on the arrow. The masses of the string and of the bow's limbs are negligible.

Figure 1

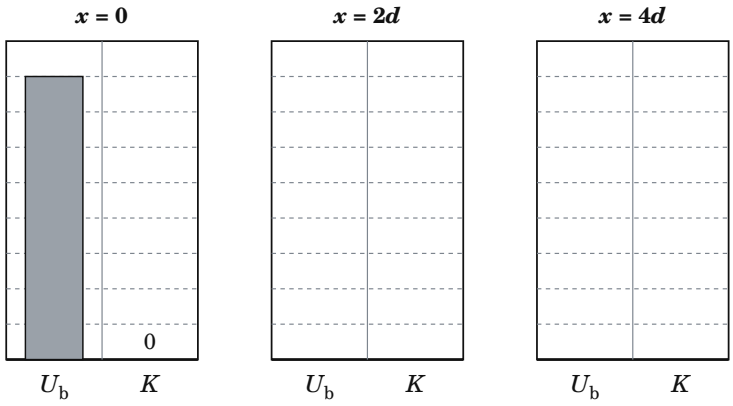


Part A

Figure 2 shows an energy bar chart for the system that consists of the bow and the arrow at $x = 0$. U_b is the elastic potential energy stored in the bow, and K is the kinetic energy of the arrow. Each horizontal line on the charts represents an energy F_0d. On the charts for $x = 2d$ and $x = 4d$, **draw** shaded bars to represent U_b and K.

- Start each bar at the line that represents zero energy.
- If an energy is zero, write 0 in its column.

Figure 2



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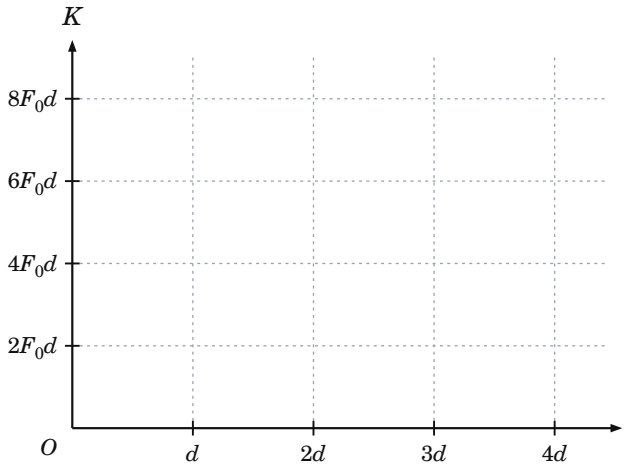
Part B

Derive an expression for the speed v_f of the arrow when it leaves the string. Express your answer in terms of m, F_0, d, and physical constants, as appropriate. Begin with a fundamental physics principle or an equation from the reference information, and show the steps that lead to your answer.

Part C

On the axes in Figure 3, **sketch** a graph of the kinetic energy K of the arrow as a function of x, from $x = 0$ to $x = 4d$.

Figure 3



Part D

Indicate which of the positions $x = d$, $x = 2d$, or $x = 3d$ has the greatest instantaneous power delivered to the arrow by the string. **Justify** your answer using Figure 1 and your graph from Part C.

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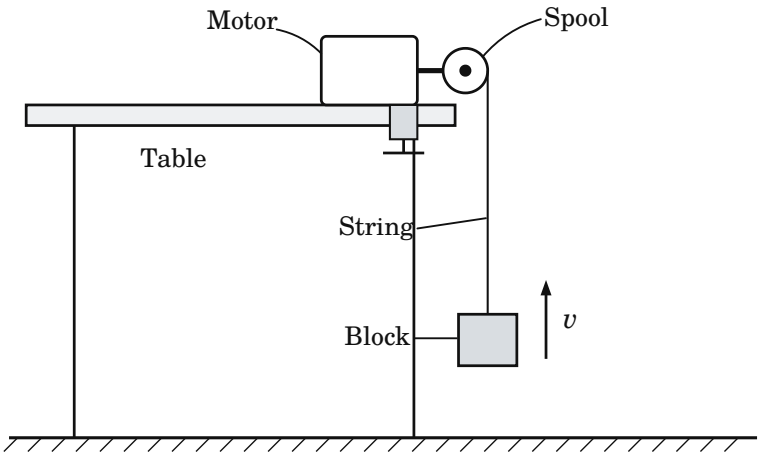
Question 7: Experimental Design and Analysis

The following information applies to Parts A and B.

7. A group of students wants to determine the power P that a small electric motor delivers when it lifts objects. The motor is clamped at the edge of a table. It winds a string onto a spool and lifts a hanging block straight up, as shown in Figure 1. A control circuit keeps the power the motor delivers to the string equal to P for every block the students use. Shortly after the motor starts, the block rises at a constant speed.

Figure 1



Note: Figure not drawn to scale.

The students have the motor and its control circuit, a set of blocks of different known masses, a meterstick, and a stopwatch.

Part A

i. **Indicate** the quantities the students should measure so that they can determine P from a linear graph. Include the quantity they will vary from one trial to the next.

ii. Briefly **describe** one way the students could reduce the experimental uncertainty in these measurements.

Part B

i. **Indicate** the quantities the students could plot on the horizontal and vertical axes to produce a linear graph from which P can be determined. State clearly which quantity goes on each axis.

ii. Briefly **describe** how P is related to a feature of the graph from Part B(i). You may include an equation that relates P to that feature.

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The following information applies to Parts C and D.

In another experiment, the students use a motion sensor to measure the constant upward speed v of blocks of different masses m. Table 1 shows the data. The students make a graph with m plotted on the horizontal axis.

Table 1

m (kg)	v (m/s)
0.10	0.608
0.20	0.311
0.30	0.201
0.40	0.155
0.50	0.121

Part C

i. **Label** the vertical axis of Figure 2 with a measured or calculated quantity, with units if it has any. Choose a quantity that makes the graph linear and lets you determine P.

ii. On the grid in Figure 2, make a graph that can be used to determine P.

- Add a numerical scale to the vertical axis.
- **Plot** the data points.
- Table 2 gives space for the values you plot and is not scored.

Figure 2

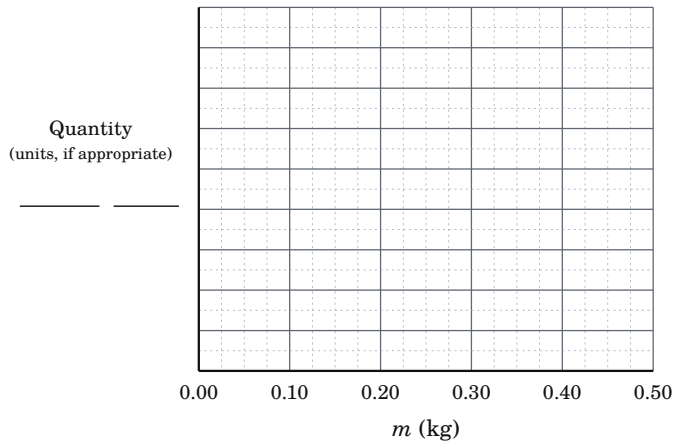

Table 2

m (kg)	v (m/s)	
0.10	0.608	
0.20	0.311	
0.30	0.201	
0.40	0.155	
0.50	0.121	

iii. **Draw** a best-fit line through the data you plotted in Part C(ii).

Part D

Use your best-fit line from Part C(iii) to **calculate** an experimental value for P.

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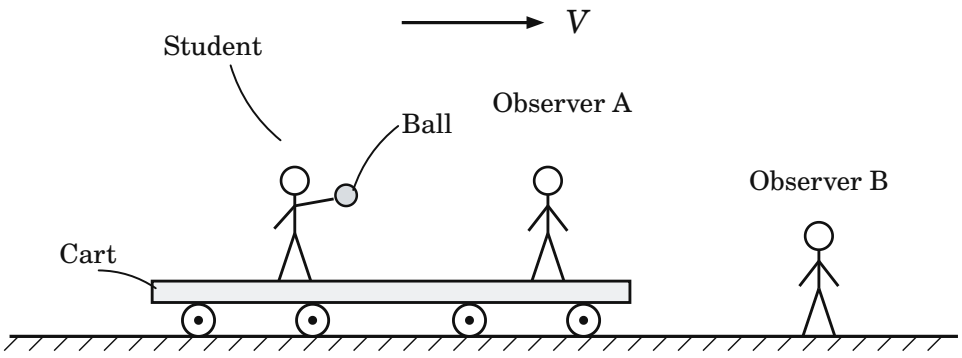
Question 8: Qualitative/Quantitative Translation

8. A large flat cart moves along a level floor at a constant speed V. A student standing on the cart throws a ball of mass m horizontally forward, in the direction the cart is moving. During the throw, the speed of the ball relative to the cart increases from zero to u. The speed of the cart does not change during the throw. Observer A rides on the cart, and Observer B stands at rest on the floor, as shown in Figure 1. Each observer measures the kinetic energy of the ball in their own reference frame.

Figure 1



Note: Figure not drawn to scale.

Part A

Let ΔK_A and ΔK_B be the changes in the ball's kinetic energy during the throw measured by Observer A and by Observer B. **Indicate** whether ΔK_B is greater than, less than, or equal to ΔK_A by writing one of the following.

- $\Delta K_B > \Delta K_A$
- $\Delta K_B < \Delta K_A$
- $\Delta K_B = \Delta K_A$

Justify your answer in words, without using equations.

Part B

Derive expressions for ΔK_A and ΔK_B. Express your answers in terms of m, u, V, and physical constants, as appropriate. Begin with a fundamental physics principle or an equation from the reference information, and show the steps that lead to your answer.

Part C

Explain how your expressions from Part B are consistent with your reasoning in Part A.

STOP

END OF SET B

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Scoring Guidelines

Point totals follow the 2026 AP Physics 1 scoring guidelines: 10 points for mathematical routines, 12 for translation between representations, 10 for experimental design and analysis, and 8 for qualitative/quantitative translation, so each set is worth 40 points. Each point is listed with what earns it, and the example responses show one correct way to earn them.

General scoring note. Equivalent physics reasoning and derivations earn the same points as the example responses. When a criterion names one method, the matching step in another correct method earns that point, except where the question itself names the method, as Part A of Question 1 does. In Questions 3 and 7, any quantity that makes the graph linear earns credit, as long as the line, usually its slope, is then related to the unknown correctly for that quantity.

Question 1: Mathematical Routines (MR) — 10 points

Part A — 3 points

A1	For the work done by the gravitational force, $MgD \sin\theta$, and the work done by the normal force, zero, as the van rolls a distance D.	1 point
A2	For the work done by the resistive force, $-F_R D$, and setting the sum of the work done by all forces equal to $\Delta K = 0$, because the speed is constant.	1 point
A3	For $F_R = Mg \sin\theta$.	1 point

EXAMPLE RESPONSE

$W_g + W_N + W_R = \Delta K$

Gravity makes an angle of $90° - \theta$ with the displacement, so $W_g = MgD \cos(90° - \theta) = MgD \sin\theta$.

The normal force is perpendicular to the road, so $W_N = 0$. The resistive force points up the hill, opposite the displacement, so $W_R = -F_R D$.

$MgD \sin\theta + 0 - F_R D = 0$, so $F_R = Mg \sin\theta$

Scoring note: The question asks for the work-energy theorem. A derivation from Newton's second law alone earns point A3 but not points A1 and A2.

Part B — 2 points

B1	For an expression equivalent to $Mgv_0 \sin\theta$, with supporting reasoning, such as: the kinetic energy is constant and the van drops a height $v_0 \sin\theta$ each second, or the resistive forces remove energy at the rate $F_R v_0$.	1 point
B2	For describing that the lost mechanical energy becomes internal (thermal) energy of the van, the road, and the air, through the work done by the resistive forces.	1 point

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EXAMPLE RESPONSE

Each second the van moves a distance v_0 along the road and drops a height $v_0 \sin \theta$. Its kinetic energy does not change, so the mechanical energy decreases at the same rate as the gravitational potential energy. The change ΔE_{mech} is negative, so the rate of decrease is written with a minus sign:

$$-\frac{\Delta E_{\text{mech}}}{\Delta t} = Mg(v_0 \sin \theta) = Mgv_0 \sin \theta = F_{\text{R}} v_0$$

The last step uses $F_{\text{R}} = Mg \sin \theta$ from Part A, so the resistive forces remove energy at the same rate. They convert it into internal energy: the tires, the road, and the air around the van warm up slightly.

Scoring note: A rate of change written as $\frac{\Delta E_{\text{mech}}}{\Delta t} = -Mgv_0 \sin \theta$ also earns point B1, because the minus sign shows that the mechanical energy decreases.

Part C		3 points
C1	For recognizing that at the same speed the resistive force has the same magnitude, $F_{\text{R}} = Mg \sin \theta$, but now points down the hill, so the forward force on the van must be $Mg \sin \theta + F_{\text{R}} = 2Mg \sin \theta$. The equivalent energy reasoning also earns this point: the system gains gravitational potential energy at the rate $Mgv_0 \sin \theta$ and loses the same amount each second to the resistive forces.	1 point
C2	For $P_{\text{up}} = 2Mgv_0 \sin \theta$.	1 point
C3	For a value between 6.4×10^4 W and 6.5×10^4 W, with units.	1 point

EXAMPLE RESPONSE

Up the hill at constant speed: $F_{\text{drive}} - Mg \sin \theta - F_{\text{R}} = 0$, so $F_{\text{drive}} = 2Mg \sin \theta$

$P_{\text{up}} = F_{\text{drive}} v_0 = 2Mgv_0 \sin \theta$

$P_{\text{up}} = 2(2{,}500 \text{ kg})(9.8 \text{ m/s}^2)(25 \text{ m/s}) \sin 3.0° = 64{,}100 \text{ W} \approx 6.4 \times 10^4 \text{ W}$

Scoring note: At $v_0 = 25$ m/s on this hill, the resistive force is $Mg \sin \theta = 1{,}280$ N. The motor supplies about 32 kW against gravity and another 32 kW against the resistive forces.

Part D		2 points
D1	For indicating $P_{\text{slow}} < \frac{1}{2} P_{\text{up}}$, with an attempt at a relevant justification.	1 point
D2	For a justification that at the lower speed the resistive force is smaller than $Mg \sin \theta$, so the forward force needed is less than $2Mg \sin \theta$, and the power, that force times $\frac{1}{2} v_0$, is less than $(2Mg \sin \theta)(\frac{1}{2} v_0) = \frac{1}{2} P_{\text{up}}$.	1 point

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EXAMPLE RESPONSE

$P_{slow} < \frac{1}{2}P_{up}$. The resistive force gets smaller as the speed decreases, so at $\frac{1}{2}v_0$ it is less than its value at v_0, which was $Mg \sin \theta$. The motor has to supply a force that balances $Mg \sin \theta$ plus this smaller resistive force, which is less than $2Mg \sin \theta$. The power is this force times $\frac{1}{2}v_0$, so it is less than $(2Mg \sin \theta)(\frac{1}{2}v_0)$, which is $\frac{1}{2}P_{up}$.

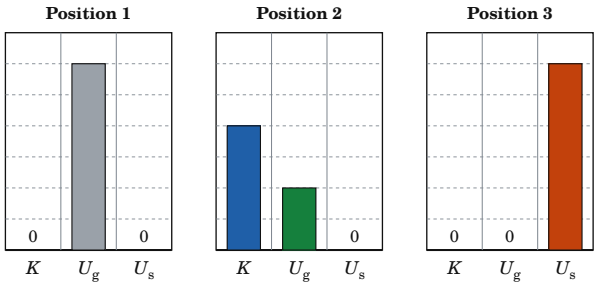
Scoring note: Reasoning about energy per second also earns point D2: at half the speed the van gains gravitational potential energy at half the rate, while the resistive forces remove energy at less than half their earlier rate, because both the force and the speed are smaller.

Question 2: Translation Between Representations (TBR) — 12 points

Part A — 3 points

A1	For Position 2: $U_s = 0$, and K and U_g both nonzero, with their total equal to the total at Position 1 (6 units).	1 point
A2	For Position 2: $K = 4$ units and $U_g = 2$ units.	1 point
A3	For Position 3: $U_s = 6$ units, with $K = 0$ and $U_g = 0$.	1 point

EXAMPLE RESPONSE



KEY

- Kinetic energy K: 4 units at Position 2 (mgL)
- Gravitational U_g: 2 units at Position 2
- Spring U_s: 6 units at Position 3

Scoring note: The total at Position 1 is $U_g = mg(\frac{3}{2}L)$, six units, so one unit is $\frac{mgL}{4}$. At Position 2 the jumper is $\frac{L}{2}$ above Position 3, so $U_g = mg(\frac{L}{2})$ is 2 units, and the remaining 4 units are kinetic energy.

Part B — 4 points

B1	For using conservation of energy between Positions 1 and 3 to find k, such as $mg(\frac{3}{2}L) = \frac{1}{2}k(\frac{L}{2})^2$, which gives $k = \frac{12mg}{L}$.	1 point
B2	For identifying that the speed is greatest where the force from the cord equals the gravitational force, $kx = mg$, which gives a stretch $x = \frac{mg}{k} = \frac{L}{12}$.	1 point

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B3	For an energy equation from Position 1 to the point of greatest speed that includes both potential energies, such as $mg(L + x) = \frac{1}{2}mv_{max}^2 + \frac{1}{2}kx^2$.	1 point
B4	For $v_{max} = \sqrt{\frac{25gL}{12}}$, or an equivalent expression, about $1.44\sqrt{gL}$.	1 point

EXAMPLE RESPONSE

Position 1 to Position 3, with $K = 0$ at both: $mg(\frac{3}{2}L) = \frac{1}{2}k(\frac{L}{2})^2$, so $k = \frac{12mg}{L}$

The speed stops increasing when the net force is zero: $kx = mg$, so $x = \frac{mg}{k} = \frac{L}{12}$

Position 1 to that point: $mg(L + \frac{L}{12}) = \frac{1}{2}mv_{max}^2 + \frac{1}{2}(\frac{12mg}{L})(\frac{L}{12})^2$

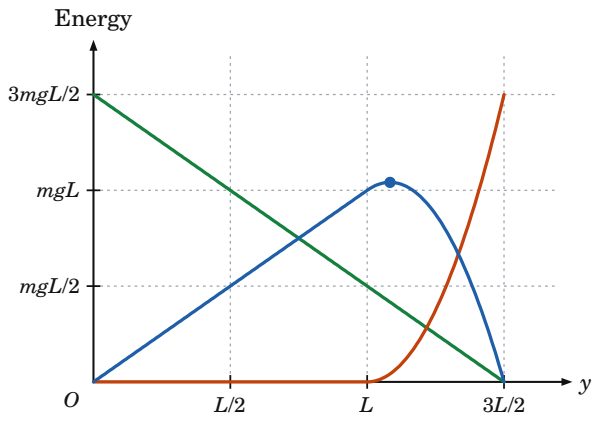
$\frac{13}{12}mgL = \frac{1}{2}mv_{max}^2 + \frac{1}{24}mgL$, so $\frac{1}{2}mv_{max}^2 = \frac{25}{24}mgL$

$v_{max} = \sqrt{\frac{25gL}{12}} \approx 1.44\sqrt{gL}$

Scoring note: Writing K as a function of the stretch x and finding where it is largest also earns points B2 and B3.

Part C		**3 points**
C1	For U_g as a straight line that decreases from $\frac{3}{2}mgL$ at $y = 0$ to zero at $y = \frac{3}{2}L$.	1 point
C2	For U_s equal to zero from $y = 0$ to $y = L$, then increasing with increasing slope to $\frac{3}{2}mgL$ at $y = \frac{3}{2}L$.	1 point
C3	For K increasing in a straight line from zero to mgL at $y = L$, continuing to increase to a maximum a short distance below $y = L$, then decreasing to zero at $y = \frac{3}{2}L$.	1 point

EXAMPLE RESPONSE



KEY

- Kinetic energy K: rises in a straight line to mgL at $y = L$, peaks at $25mgL/24$ when $y = 13L/12$ (dot), then falls to zero
- Gravitational U_g: straight line from $3mgL/2$ down to zero
- Spring U_s: zero until $y = L$, then curves up to $3mgL/2$

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Scoring note: At every y, the three energies add up to $\frac{3}{2}mgL$, because no outside force does work on the system and no energy becomes thermal energy. The maximum of K, $\frac{25}{24}mgL$ at $y = \frac{13}{12}L$, does not need to be marked.

Part D		2 points
D1	For explaining that just below Position 2 the U_s graph starts out flat, with a slope much smaller in magnitude than the slope of the U_g graph, so U_g decreases faster than U_s increases and K keeps increasing.	1 point
D2	For explaining that K stops increasing only where the slopes of the U_s and U_g graphs are equal in magnitude, which is below Position 2, so the greatest speed occurs below Position 2.	1 point

EXAMPLE RESPONSE

Just after Position 2 the cord is stretched very little, so its force is small and the U_s graph starts out nearly flat. The U_g graph keeps the same slope, $-mg$. For each small step down, the system loses more U_g than it gains U_s, so K still increases. K reaches its maximum where the U_s graph is as steep as the U_g graph, which happens where $kx = mg$, at $y = \frac{13}{12}L$. That point is below Position 2, so the jumper is still speeding up when the cord becomes taut.

Question 3: Experimental Design and Analysis (LAB) — 10 points

Part A		2 points
A(i)	For indicating that the students measure the distance d from the cart's release point to the photogate and the speed v at the photogate, keeping the hanging mass the same and changing d. Changing the hanging mass m with d held constant also earns this point.	1 point
A(ii)	For a valid way to reduce uncertainty, such as repeating each trial and averaging the speeds, releasing the cart from rest without a push, measuring d to the same point on the cart every time, or using a wide range of distances.	1 point

Part B		2 points
B(i)	For a pair of quantities that gives a linear graph, such as v^2 on the vertical axis and d on the horizontal axis.	1 point
B(ii)	For relating a feature of the graph to M, such as: for v^2 versus d, the slope is $\frac{2mg}{M+m}$, so $M = \frac{2mg}{\text{slope}} - m$.	1 point

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EXAMPLE RESPONSE

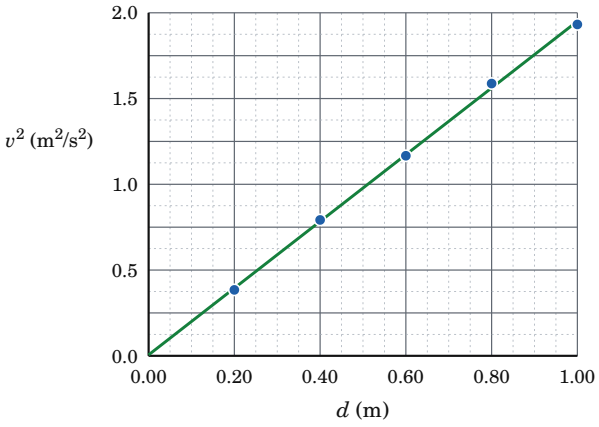
Take the cart, the block, and Earth as the system. The string's forces are internal, and no friction acts, so the gravitational potential energy the system loses becomes kinetic energy of both objects: $mgd = \frac{1}{2}(M + m)v^2$. Then $v^2 = \frac{2mg}{M + m}d$, a straight line through the origin when v^2 is plotted against d, with slope $\frac{2mg}{M + m}$. So $M = \frac{2mg}{\text{slope}} - m$.

Scoring note: Other linear choices earn credit in Parts A and B with a matching relationship. Plotting v against $\sqrt{d}$ gives a slope of $\sqrt{\frac{2mg}{M + m}}$, so $M = 2mg/(\text{slope})^2 - m$. With d held constant and m varied, $\frac{1}{v^2}$ versus $\frac{1}{m}$ is a line with slope $\frac{M}{2gd}$ and vertical intercept $\frac{1}{2gd}$, so M is the slope divided by the intercept.

Scoring note: These alternatives apply to Parts A and B only. Part C puts d on the horizontal axis, so Parts C and D are scored for a graph against d.

Part C		4 points
C(i)	For labeling the vertical axis with a quantity that makes the graph linear with d on the horizontal axis, such as v^2 in m^2/s^2.	1 point
C(ii)	For a linear numerical scale on the vertical axis.	1 point
C(iii)	For plotting the five data points correctly for the chosen quantity.	1 point
C(iv)	For a straight best-fit line that follows the trend of the data, with points on both sides of the line.	1 point

EXAMPLE RESPONSE



KEY

- Data points (d, v^2)
- Best-fit line: slope about 1.95 m/s^2, vertical intercept about 0

Values plotted

d (m)	v^2 (m^2/s^2)
0.20	0.384
0.40	0.792
0.60	1.166
0.80	1.588
1.00	1.932

Part D		2 points
D(i)	For relating the slope to M correctly for the quantity plotted in Part C. For v^2 versus d, $M = \frac{2mg}{\text{slope}} - m$.	1 point

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D(ii)	For a value of M between 0.43 kg and 0.48 kg that is consistent with the student's best-fit line.	1 point

EXAMPLE RESPONSE

Two points on the best-fit line: (0.20 m, 0.394 m^2/s^2) and (1.00 m, 1.951 m^2/s^2)

$$\text{slope} = \frac{1.951 - 0.394}{1.00 - 0.20} = 1.95 \text{ m/s}^2$$

$$M = \frac{2(0.050 \text{ kg})(9.8 \text{ m/s}^2)}{1.95 \text{ m/s}^2} - 0.050 \text{ kg} = 0.45 \text{ kg}$$

Question 4: Qualitative/Quantitative Translation (QQT) — 8 points

Part A — 3 points

A1	For indicating $v_1 > v_2$, with an attempt at a relevant justification.	1 point
A2	For explaining that the child-Earth system loses the same gravitational potential energy on both slides, because both start at the same height, so any difference in speed comes from friction.	1 point
A3	For explaining that friction converts less mechanical energy into thermal energy on Slide 1, because the steeper slide is shorter and presses on the child with a smaller normal force, so the friction force is smaller.	1 point

EXAMPLE RESPONSE

$v_1 > v_2$. Both slides lower the child through the same height, so the child-Earth system loses the same gravitational potential energy on either one. Friction turns part of that energy into thermal energy, and the rest is the child's kinetic energy at the bottom. Slide 1 is steeper, so it is shorter, and it pushes on the child with a smaller normal force because less of the child's weight presses into it. A smaller friction force acting over a shorter distance converts less energy, so more kinetic energy is left at the bottom of Slide 1.

Part B — 3 points

B1	For an energy equation, or the work-energy theorem, that includes the decrease in gravitational potential energy mgH and the energy converted by friction, the friction force times the length of the slide.	1 point
B2	For a friction force $\mu_k mg \cos\theta$ and a slide length $\frac{H}{\sin\theta}$.	1 point
B3	For $v = \sqrt{2gH(1 - \frac{\mu_k}{\tan\theta})}$, or an equivalent expression.	1 point

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EXAMPLE RESPONSE

Child-Earth system: $\frac{1}{2}mv^2 = mgH - F_f\ell$

$F_N = mg\cos\theta$, so $F_f = \mu_k mg\cos\theta$, and the slide length is $\ell = \frac{H}{\sin\theta}$

$\frac{1}{2}mv^2 = mgH - \mu_k mg\cos\theta(\frac{H}{\sin\theta}) = mgH(1 - \frac{\mu_k}{\tan\theta})$

$v = \sqrt{2gH(1 - \frac{\mu_k}{\tan\theta})}$

Part C		2 points
C1	For explaining that the friction term $\frac{\mu_k}{\tan\theta}$ gets smaller as θ increases, because $\tan\theta$ increases, so v increases with θ and $v_1 > v_2$.	1 point
C2	For connecting parts of the expression to the reasoning in Part A, such as: the factor $\cos\theta$ comes from the normal force and the factor $\frac{1}{\sin\theta}$ from the length of the slide, and both get smaller as the slide gets steeper, while the $2gH$ term is the same for both slides.	1 point

EXAMPLE RESPONSE

In $v = \sqrt{2gH(1 - \frac{\mu_k}{\tan\theta})}$, the term $2gH$ is the same for both slides because they start at the same height. The term $\frac{\mu_k}{\tan\theta}$ is the fraction of that energy friction takes away. It came from $\mu_k\cos\theta$, the smaller friction force on a steeper slide, times $\frac{1}{\sin\theta}$, the shorter length. As θ increases, $\tan\theta$ increases, so friction takes a smaller fraction and v is larger. Slide 1 has the larger angle, so $v_1 > v_2$.

Question 5: Mathematical Routines (MR) — 10 points

Part A		3 points
A1	For a U_G graph that is negative over the whole range and increases toward zero, from $-U_0$ at $r = R$ to $-\frac{U_0}{3}$ at $r = 3R$.	1 point
A2	For a U_G graph whose slope decreases as r increases, so the graph curves and gets less steep.	1 point
A3	For a K graph that decreases from $\frac{2U_0}{3}$ at $r = R$ to zero at $r = 3R$, getting less steep as r increases, so that $K + U_G$ stays constant.	1 point

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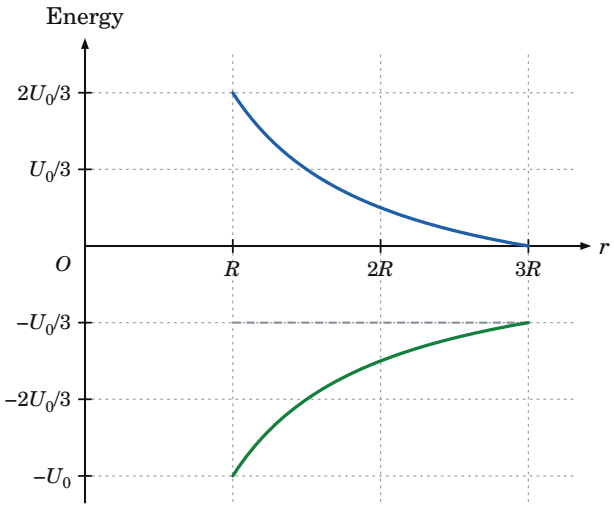
EXAMPLE RESPONSE



KEY

- U_G of the probe-moon system: negative, rising from $-U_0$ to $-U_0/3$, less steep as r grows
- Kinetic energy K: falls from $2U_0/3$ to zero at $3R$, less steep as r grows
- Total, $K + U_G = -U_0/3$ at every r (not required)

Scoring note: U_G at $3R$ is one third of its value at R, because U_G is inversely proportional to r. The kinetic energy at R is the difference, $\frac{2U_0}{3}$.

Part B		3 points
B1	For using conservation of mechanical energy for the probe-moon system, with $U_G = -\frac{GMm}{r}$.	1 point
B2	For applying it between the surface and $r = 3R$, with $K = 0$ at $3R$: $\frac{1}{2}mv_0^2 - \frac{GMm}{R} = -\frac{GMm}{3R}$.	1 point
B3	For $v_0 = \sqrt{\frac{4GM}{3R}}$, or an equivalent expression such as $2\sqrt{\frac{GM}{3R}}$.	1 point

EXAMPLE RESPONSE

$K_1 + U_{G1} = K_2 + U_{G2}$

$\frac{1}{2}mv_0^2 - \frac{GMm}{R} = 0 - \frac{GMm}{3R}$

$\frac{1}{2}v_0^2 = \frac{GM}{R}(1 - \frac{1}{3}) = \frac{2GM}{3R}$

$v_0 = \sqrt{\frac{4GM}{3R}}$

Part C		1 point
C1	For a value of about 1.94×10^3 m/s, between 1.9×10^3 m/s and 2.0×10^3 m/s, with units.	1 point

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EXAMPLE RESPONSE

$\frac{GM}{R} = (6.67 \times 10^{-11}\ \text{N·m}^2/\text{kg}^2)(7.35 \times 10^{22}\ \text{kg}) \div (1.74 \times 10^{6}\ \text{m}) = 2.82 \times 10^{6}\ \text{m}^2/\text{s}^2$

$v_0 = \sqrt{\frac{4}{3}(2.82 \times 10^{6}\ \text{m}^2/\text{s}^2)} = 1.94 \times 10^{3}\ \text{m/s}$

Part D		3 points
D1	For indicating $v_s > v_0$, with an attempt at a relevant justification.	1 point
D2	For explaining that the gravitational force on the probe decreases as the probe moves away from the moon, so above the surface the force is weaker than its surface value.	1 point
D3	For explaining that the work done against gravity from R to $3R$, the increase in U_G, is therefore less than $mg_s(2R)$, so the student's method overestimates the kinetic energy, and the launch speed, that the probe needs.	1 point

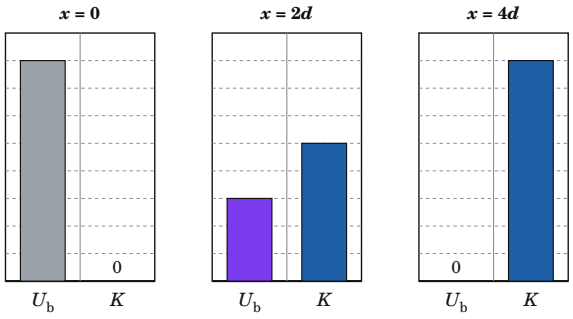
EXAMPLE RESPONSE

$v_s > v_0$. The gravitational pull on the probe gets weaker as the probe moves away from the moon. The student's equation treats the pull as keeping its surface value for the whole trip, so it gives a larger increase in potential energy than the real one. The student's method therefore calls for more kinetic energy at launch than the probe needs, which means a larger launch speed. With the student's equation, $v_s = \sqrt{\frac{4GM}{R}} = \sqrt{3}\,v_0 \approx 3.36 \times 10^{3}\ \text{m/s}$.

Question 6: Translation Between Representations (TBR) — 12 points

Part A		3 points
A1	For $x = 2d$: $K = 5$ units, the area under Figure 1 from 0 to $2d$.	1 point
A2	For $x = 2d$: $U_b = 3$ units, so that $U_b + K$ is still 8 units.	1 point
A3	For $x = 4d$: $K = 8$ units and $U_b = 0$.	1 point

EXAMPLE RESPONSE



KEY

- Bow's elastic energy U_b: 3 units at $x = 2d$, zero at $x = 4d$
- Arrow's kinetic energy K: 5 units at $x = 2d$, 8 units at $x = 4d$

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Scoring note: From 0 to d the area is a trapezoid, $\frac{1}{2}(F_0 + 3F_0)d = 2F_0d$. From d to $2d$ it is a rectangle, $3F_0d$. From $2d$ to $4d$ it is a triangle, $\frac{1}{2}(3F_0)(2d) = 3F_0d$.

Part B		3 points
B1	For the work-energy theorem applied to the arrow, $W = \Delta K = \frac{1}{2}mv_f^2$, or conservation of energy for the bow-arrow system.	1 point
B2	For the work done by the string as the area under the force graph, $2F_0d + 3F_0d + 3F_0d = 8F_0d$.	1 point
B3	For $v_f = 4\sqrt{\frac{F_0d}{m}}$.	1 point

EXAMPLE RESPONSE

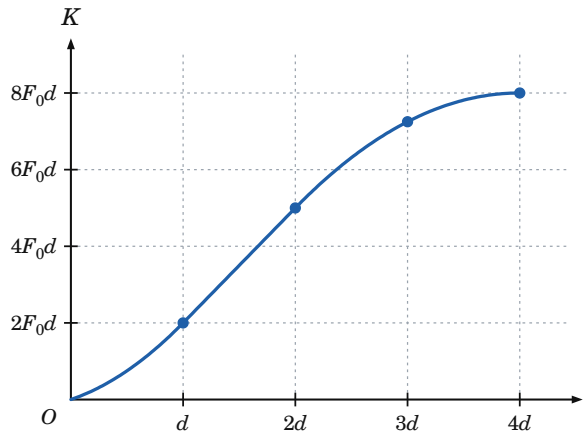
$W = \Delta K$, and the work done by the string is the area under Figure 1: $W = 8F_0d$

$8F_0d = \frac{1}{2}mv_f^2$

$v_f = \sqrt{\frac{16F_0d}{m}} = 4\sqrt{\frac{F_0d}{m}}$

Part C		4 points
C1	For K starting at zero at $x = 0$, increasing throughout, and reaching $8F_0d$ at $x = 4d$.	1 point
C2	For K curving upward with increasing slope from 0 to d, reaching $2F_0d$ at $x = d$.	1 point
C3	For a straight line from $x = d$ to $x = 2d$, rising to $5F_0d$.	1 point
C4	For K curving with decreasing slope from $2d$ to $4d$, with zero slope at $x = 4d$.	1 point

EXAMPLE RESPONSE



KEY

- K of the arrow: curves upward to $2F_0d$ at d, straight line to $5F_0d$ at $2d$, then bends over and is flat at $8F_0d$ when $x = 4d$
- Dots at d, $2d$, $3d$, $4d$: $K = 2$, 5, 7.25, and 8 F_0d (not required)

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Scoring note: The slope of the K graph at each x equals the force from Figure 1 at that x, which is why the graph is straight where the force is constant and flat where the force reaches zero.

Part D		2 points
D1	For indicating $x = 2d$, with a justification that the power is $P = Fv$ and that from $x = d$ to $x = 2d$ the force stays at $3F_0$ while K, and so the speed, is greater at $2d$.	1 point
D2	For justifying that the power at $3d$ is less than at $2d$: the force at $3d$ is half as large, while K rises only from $5F_0d$ to $7.25F_0d$, so the speed increases by a factor of about 1.2, much less than 2.	1 point

EXAMPLE RESPONSE

$x = 2d$. The power delivered by the string is $P = Fv$. At $x = d$ and $x = 2d$ the force is $3F_0$, but K is $2F_0d$ at d and $5F_0d$ at $2d$, so the arrow is moving faster at $2d$ and the power is greater there. At $x = 3d$ the force has dropped to $1.5F_0$, half of its value at $2d$, while K has grown only from $5F_0d$ to $7.25F_0d$. Speed is proportional to $\sqrt{K}$, so the speed is larger by a factor of $\sqrt{7.25/5} \approx 1.2$. Half the force at about 1.2 times the speed gives about 0.6 times the power, so the power at $3d$ is less than the power at $2d$.

Scoring note: In units of $F_0\sqrt{\frac{F_0d}{m}}$, the power is 6.0 at d, 9.5 at $2d$, and 5.7 at $3d$. These values are not required.

Question 7: Experimental Design and Analysis (LAB) — 10 points

Part A		2 points
A(i)	For indicating that the students measure the mass m of each block and the time t it takes to rise a measured distance h at constant speed, so $v = h/t$, for several blocks of different mass.	1 point
A(ii)	For a valid way to reduce uncertainty, such as starting the stopwatch only after the block reaches constant speed (when it passes a mark some distance above its starting point), timing over a long distance, or repeating each trial and averaging the times.	1 point

Part B		2 points
B(i)	For a pair of quantities that gives a linear graph, such as $\frac{1}{v}$ on the vertical axis and m on the horizontal axis. Time versus mass for a fixed distance, or v versus $\frac{1}{m}$, also earns this point.	1 point
B(ii)	For relating a feature of the graph to P, such as: for $\frac{1}{v}$ versus m, the slope is $\frac{g}{P}$, so $P = \frac{g}{\text{slope}}$.	1 point

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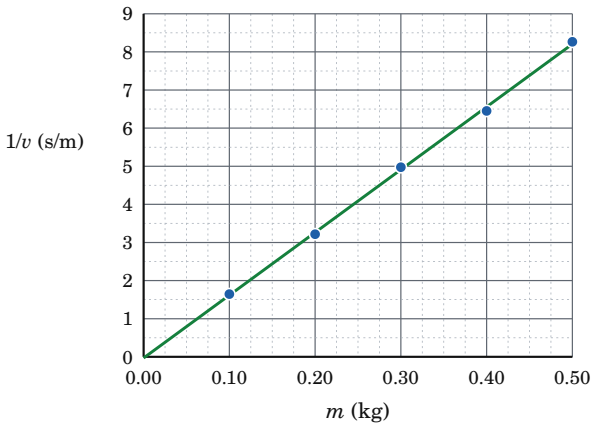
EXAMPLE RESPONSE

At constant speed the string pulls up on the block with a force equal to mg, so the power delivered to the block is $P = mgv$. Then $\frac{1}{v} = \frac{g}{P}m$: plotting $\frac{1}{v}$ on the vertical axis against m gives a straight line through the origin with slope $\frac{g}{P}$, so $P = \frac{g}{\text{slope}}$.

Scoring note: For time t versus m over a fixed distance h, the slope is $\frac{gh}{P}$. For v versus $\frac{1}{m}$, the slope is $\frac{P}{g}$. These alternatives apply to Parts A and B only. Part C puts m on the horizontal axis and gives speeds rather than times.

Part C		4 points
C(i)	For labeling the vertical axis with a quantity that makes the graph linear with m on the horizontal axis, such as $\frac{1}{v}$ in s/m.	1 point
C(ii)	For a linear numerical scale on the vertical axis.	1 point
C(iii)	For plotting the five data points correctly for the chosen quantity.	1 point
C(iv)	For a straight best-fit line that follows the trend of the data, with points on both sides of the line.	1 point

EXAMPLE RESPONSE



KEY

- Data points (m, $1/v$)
- Best-fit line: slope about 16.5 s/(m·kg), vertical intercept about 0

Values plotted

m (kg)	$1/v$ (s/m)
0.10	1.64
0.20	3.22
0.30	4.98
0.40	6.45
0.50	8.26

Part D		2 points
D(i)	For relating the best-fit line to P correctly for the quantity plotted in Part C. For $\frac{1}{v}$ versus m, $P = \frac{g}{\text{slope}}$.	1 point
D(ii)	For a value of P between 0.56 W and 0.64 W that is consistent with the student's best-fit line.	1 point

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EXAMPLE RESPONSE

Two points on the best-fit line: (0.10 kg, 1.62 s/m) and (0.50 kg, 8.21 s/m)

$$\text{slope} = \frac{8.21 - 1.62}{0.50 - 0.10} = 16.5 \text{ s/(m·kg)}$$

$$P = \frac{9.8 \text{ m/s}^2}{16.5 \text{ s/(m·kg)}} = 0.59 \text{ W}$$

Scoring note: A graph of mgv against m is a horizontal line at the value P. Reading P from the height of that line also earns both points.

Question 8: Qualitative/Quantitative Translation (QQT) — 8 points

Part A		3 points
A1	For indicating $\Delta K_B > \Delta K_A$, with an attempt at a relevant justification.	1 point
A2	For identifying a relevant difference between the frames: both observers measure the same push from the student's hand, but Observer B sees the ball move a greater distance during the throw because the ball is also moving forward with the cart. Identifying that both observers measure the same increase in speed, but Observer B's starts from the cart's speed rather than from rest, also earns this point.	1 point
A3	For connecting that difference to kinetic energy: the same force over a greater distance does more work, so the change in kinetic energy is greater for Observer B. Or: kinetic energy grows with the square of the speed, so the same increase in speed adds more kinetic energy when the starting speed is greater.	1 point

EXAMPLE RESPONSE

$\Delta K_B > \Delta K_A$. Both observers agree on how hard the student's hand pushes the ball. To Observer A the ball starts at rest and moves only the short distance the hand pushes it. To Observer B the ball is already moving forward with the cart, so it covers a greater distance while the hand is pushing it. The same push over a greater distance does more work on the ball, so Observer B measures a larger increase in kinetic energy.

Part B		3 points
B1	For $\Delta K_A = \frac{1}{2}mu^2$.	1 point
B2	For Observer B's speeds before and after the throw, V and $V + u$.	1 point
B3	For $\Delta K_B = \frac{1}{2}m(V+u)^2 - \frac{1}{2}mV^2 = \frac{1}{2}mu^2 + mVu$.	1 point

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EXAMPLE RESPONSE

Observer A: the speed goes from 0 to u, so $\Delta K_A = \frac{1}{2}mu^2 - 0 = \frac{1}{2}mu^2$

Observer B: the speed goes from V to $V + u$, so $\Delta K_B = \frac{1}{2}m(V + u)^2 - \frac{1}{2}mV^2$

$\Delta K_B = \frac{1}{2}m(V^2 + 2Vu + u^2) - \frac{1}{2}mV^2 = \frac{1}{2}mu^2 + mVu$

Part C		2 points
C1	For showing that $\Delta K_B - \Delta K_A = mVu$, which is positive because m, V, and u are all positive, so $\Delta K_B > \Delta K_A$.	1 point
C2	For connecting the extra term mVu to the reasoning in Part A, such as: it is zero when $V = 0$, when the two observers share a frame, and it grows with V, matching the extra distance the ball covers in Observer B's frame during the throw.	1 point

EXAMPLE RESPONSE

The two expressions differ by mVu, which is positive, so $\Delta K_B > \Delta K_A$. The extra term depends on the cart's speed V. If the cart were at rest, the term would be zero and the observers would agree. The faster the cart moves, the farther the ball travels in Observer B's frame during the throw, and the larger the extra work and the extra kinetic energy, as argued in Part A.

Score Tracker

Record the points you earned on each question. The middle column shows how the points split across the parts.

Question	Type	Points by part	Possible	Earned
Question 1	Mathematical Routines	A: 3 · B: 2 · C: 3 · D: 2	10	
Question 2	Translation Between Representations	A: 3 · B: 4 · C: 3 · D: 2	12	
Question 3	Experimental Design and Analysis	A: 2 · B: 2 · C: 4 · D: 2	10	
Question 4	Qualitative/Quantitative Translation	A: 3 · B: 3 · C: 2	8	
Set A total			**40**	
Question 5	Mathematical Routines	A: 3 · B: 3 · C: 1 · D: 3	10	
Question 6	Translation Between Representations	A: 3 · B: 3 · C: 4 · D: 2	12	
Question 7	Experimental Design and Analysis	A: 2 · B: 2 · C: 4 · D: 2	10	
Question 8	Qualitative/Quantitative Translation	A: 3 · B: 3 · C: 2	8	
Set B total			**40**	

Where to review.

- Energy bar charts, spring and gravitational potential energy (Questions 2, 5, and 6): kinetic and potential energy guide, burketutoringinfremont.com/ap-physics-1-kinetic-and-potential-energy-problems/
- Work by each force, force graphs, friction, and power (Questions 1, 4, 6, and 7): work, energy, and power guide, burketutoringinfremont.com/ap-physics-1-work-energy-and-power-problems/
- Linear graphs and best-fit lines in labs (Questions 3 and 7): Question 3 of the kinematics FRQ set, burketutoringinfremont.com/ap-physics-1-kinematics-frq/
- Relative motion and reference frames (Question 8): relative velocity guide, burketutoringinfremont.com/relative-velocity-vectors-motion-graphs/
- Forces on a slope and friction (Questions 1 and 4): dynamics study guide, burketutoringinfremont.com/ap-physics-1-dynamics-study-guide/

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