2024

AP®

# AP® Physics C: Mechanics

## Sample Student Responses and Scoring Commentary Set 1

**Inside:**

Free-Response Question 2

☑ Scoring Guidelines

☑ Student Samples

☑ Scoring Commentary

## Question 2: Free-Response Question — 15 points

**(a)** For a multi-step derivation that includes Newton's second law of motion — **1 point**

For indicating that the net force exerted on the cylinder includes only the gravitational force and a drag force — **1 point**

**Example Response**

$$F_{\text{net}} = F_g - F_{\text{drag}}$$

For a correct differential equation that is in terms of the given variables — **1 point**

**Scoring Note:** Variables do not have to be separated for this point to be earned.

**Example Response**

$$m\frac{dv}{dt} = mg - bv^2$$

**Example Solution**

$$\Sigma F = ma$$

$$F_g - F_{\text{drag}} = ma_y$$

$$mg - bv^2 = ma_y$$

$$m\frac{dv}{dt} = mg - bv^2$$

**Total for part (a) — 3 points**

**(b)(i)** For a vertical line labeled $t_1$ at the approximate location at which the line becomes horizontal — **1 point**

**Example Response**

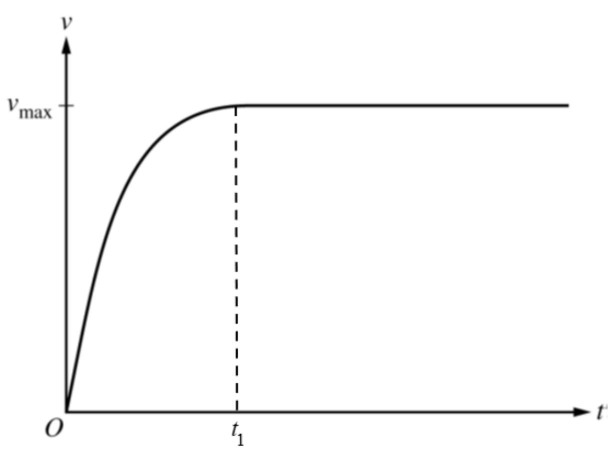



Figure 2

| | | |
|---|---|---|
| **(b)(ii)** | For relating $t_1$ to the time at which the velocity versus time graph is constant or the slope of the line is zero | **1 point** |
| | For indicating that a constant velocity indicates that the net force is zero | **1 point** |

**Example Response**

*Because the sketched line is horizontal after $t_1$, the velocity is constant. If the velocity is constant, then the acceleration is zero. Therefore, the net force is zero, which means that the gravitational and drag forces are equal in magnitude.*

**Total for part (b) 3 points**

| | | |
|---|---|---|
| **(c)** | For selecting "Equal to" with an attempt at a relevant justification | **1 point** |
| | For a correct justification | **1 point** |

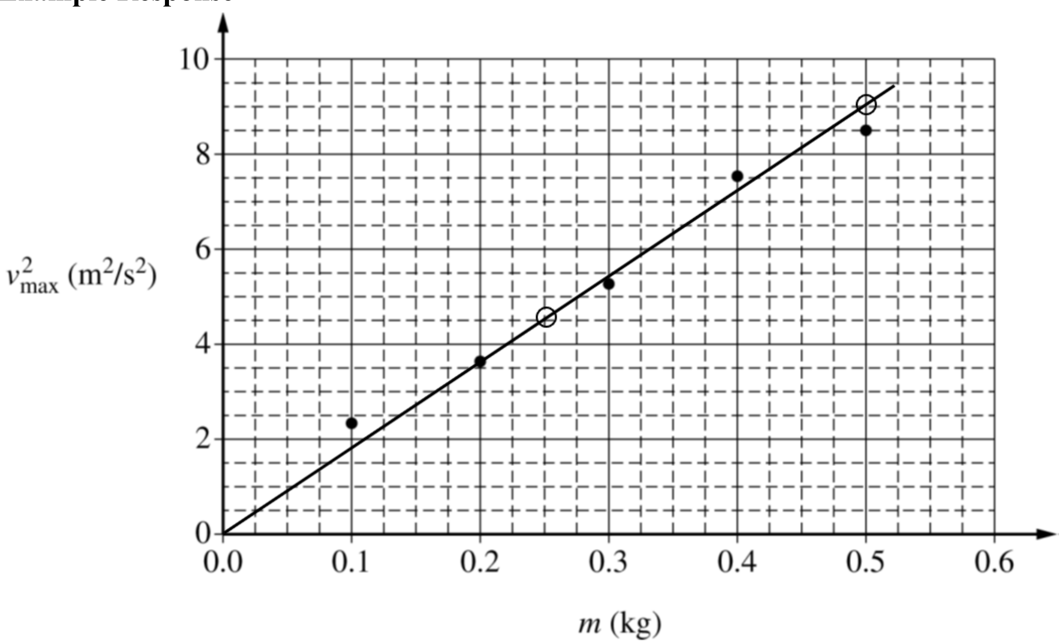
**Example Response**

*At its peak, the cylinder will have a speed of* $0\ \text{m/s}$. *Therefore, the cylinder would reach the same $v_{max}$ as if the student had dropped the cylinder from rest at that height. Because the cylinder reached $v_{max}$ from the initial drop, the two max speeds are equal.*

**Total for part (c) 2 points**

| | | |
|---|---|---|
| **(d)(i)** | For drawing an appropriate line of best fit that approximates the data | **1 point** |

**Example Response**



**(d)(ii)** For calculating a value for the slope of the line using two points on the best-fit line **1 point**

**Scoring Note:** Using data points that fall on the best-fit line is acceptable.

**Example Response**

$$\text{slope} = \frac{9\text{ m}^2/\text{s}^2 - 4.5\text{ m}^2/\text{s}^2}{0.5\text{ kg} - 0.25\text{ kg}}$$

For using the correct relationship between the slope of the best-fit line and the value of $b$ **1 point**

**Example Response**

$$\text{slope} = \frac{g}{b}$$

For a calculated value of $b$ that is $0.45\text{ kg/m} \le b \le 0.75\text{ kg/m}$ **1 point**

**Example Response**

$$b = 0.544\text{ kg/m}$$

**Example Solution**

$$mg - bv^2 = 0$$
$$bv^2 = mg$$
$$\frac{v^2}{m} = \frac{g}{b}$$
$$\text{slope} = \frac{g}{b}$$
$$b = \frac{g}{\text{slope}}$$
$$b = \frac{9.8\text{ m/s}^2}{\dfrac{9\text{ m}^2/\text{s}^2 - 4.5\text{ m}^2/\text{s}^2}{0.5\text{ kg} - 0.25\text{ kg}}}$$

$$b = 0.544\text{ kg/m}$$

**Total for part (d) 4 points**

| | | |
|---|---|---|
| **(e)(i)** | For indicating that the length of the cylinder should be graphed | **1 point** |
| | For indicating that the maximum velocity of the cylinder should be graphed | **1 point** |
| **(e)(ii)** | For describing how the quantities graphed are related to the conclusions of the experiment | **1 point** |

**Example Response**

*The slope of the length vs. maximum velocity graph can be used to determine if length affects terminal velocity.*

**Total for part (e) 3 points**

**Total for question 2 15 points**

## Question 2

Begin your response to **QUESTION 2** on this page.

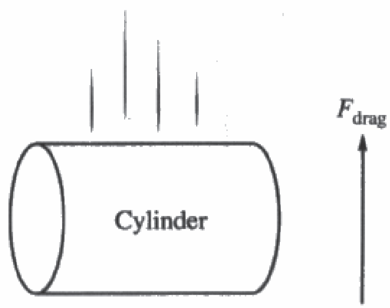
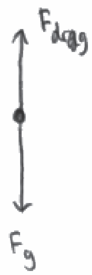



Figure 1

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

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




$$F_{net} = ma = mg - F_{drag}$$

$$\rightarrow m\frac{dv}{dt} = mg - bv^2$$



Use a pencil or a pen with black or dark blue ink. Do NOT write your name. Do NOT write outside the box.

## Question 2

**Continue your response to QUESTION 2 on this page.**

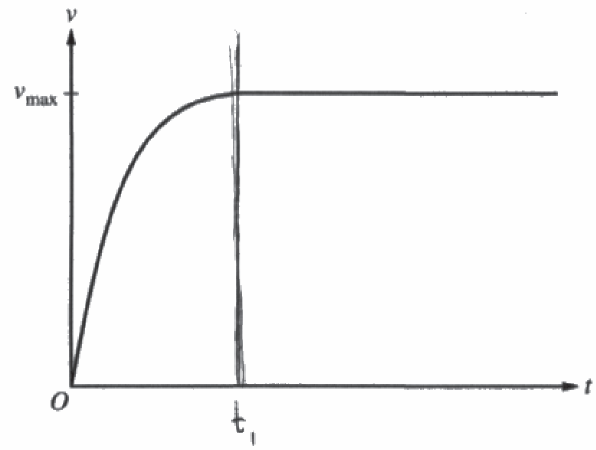



Figure 2

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

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

ii. **Justify** the location of $t_1$. Explicitly reference appropriate features of the sketch in Figure 2.

When $F_{drag} = F_g$, net force on the cylinder is 0. Thus it experiences no acceleration, so velocity must be constant, or a horizontal line. $t_1$ is when the graph first becomes a horizontal line

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

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

____ Greater than ____ Less than __✓__ Equal to

Briefly **justify** your answer.

At its peak, the cylinder will have velocity 0 m/s. Thus it would reach the same $V_{max}$ as if the student had dropped it from rest at that height. Since the cylinder reached $V_{max}$ from the initial drop, the 2 max velocities are equal.

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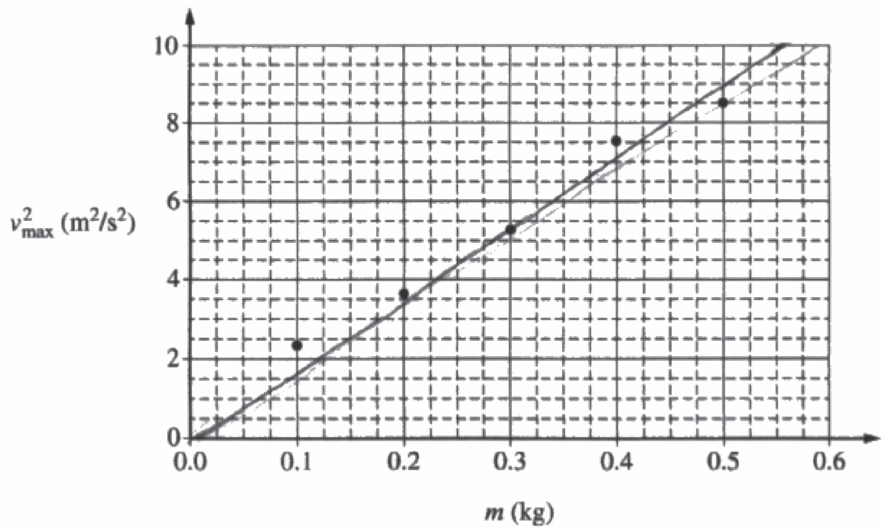
## Question 2

Continue your response to **QUESTION 2** on this page.

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

0.3 5.25




i. **Draw** the best-fit line for the data.

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

$mg = bv_{max}^2 \rightarrow v_{max}^2 = \frac{g}{b}M \rightarrow \frac{g}{b} = $ slope of line

Slope: $\frac{9-0}{0.5-0} = 18 = \frac{g}{b} \rightarrow b = \frac{g}{18} = 0.544$

## Question 2

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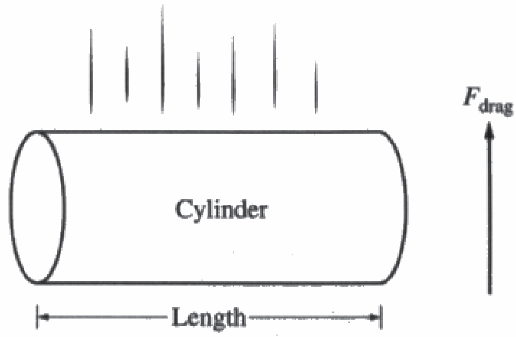


Figure 3

A student claims that the magnitude of the maximum speed of a cylinder dropped from rest depends on the length of the cylinder. The student designs an experiment to collect data that can be used to provide evidence to support the claim. The student drops cylinders with the orientation shown in Figure 3.

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

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

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

Vertical axis: $v_{max}$ Horizontal axis: length of cylinder from set 2

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

Plot $v_{max}$ with cylinder lengths and find slope of line of best fit. Then, $v_{max} = m \cdot l$, where m is the calculated slope, and $l$ is the length of the cylinder.



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## Question 2

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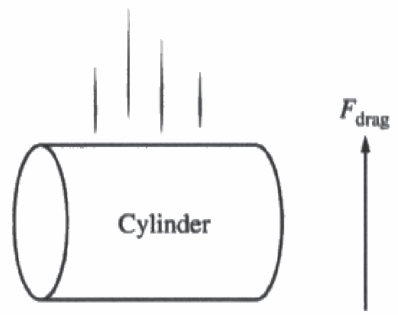


Figure 1

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

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

$\Sigma F$: $mg - F_{drag} = ma$

$\Leftrightarrow mg - bv^2 = ma$

$\Leftrightarrow mg - bv^2 = \frac{dv}{dt}$

## Question 2

**Continue your response to QUESTION 2 on this page.**

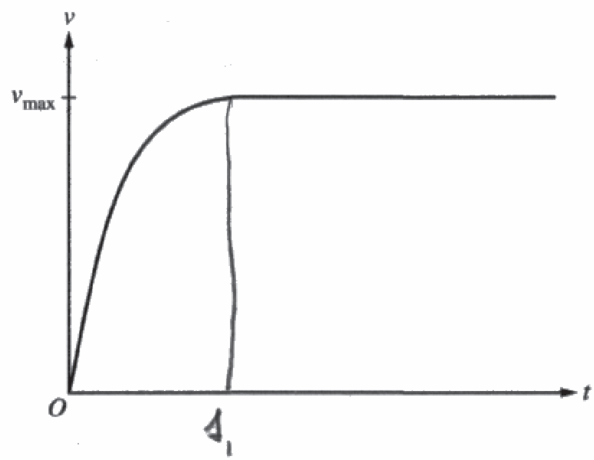


Figure 2

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

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

ii. **Justify** the location of $t_1$. Explicitly reference appropriate features of the sketch in Figure 2.

Once $F_{drag}$ is equal to the magnitude of the weight, then

$mg - F_{drag} = 0\,N$

Thus, $a = 0$ and $v$ remains constant at $v_{max}$.

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

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

____ Greater than     ____ Less than     _X_ Equal to

Briefly **justify** your answer.

Definition of terminal velocity: The cylinder will not exceed $v_{max}$





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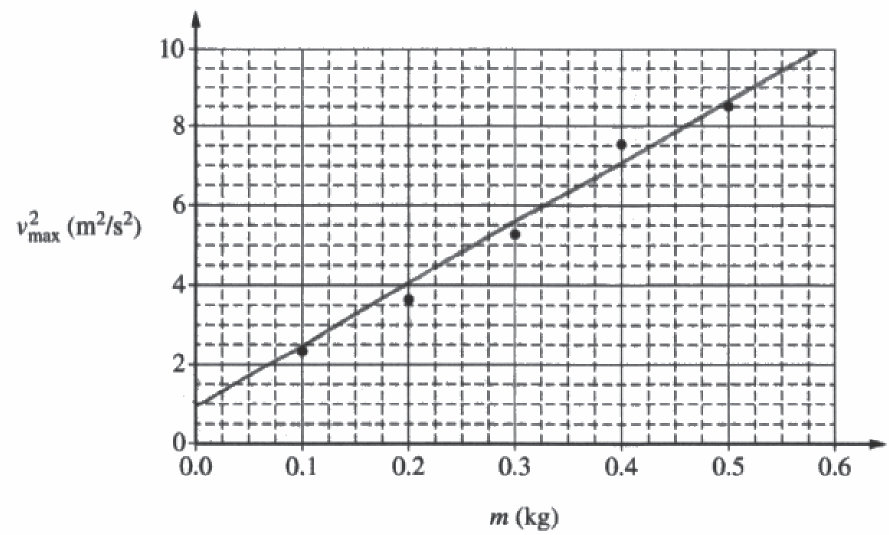
## Question 2

Continue your response to **QUESTION 2** on this page.

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




i. **Draw** the best-fit line for the data.

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

$v_{max}^2(m) = 1 + 15m$

## Question 2

Continue your response to **QUESTION 2** on this page.

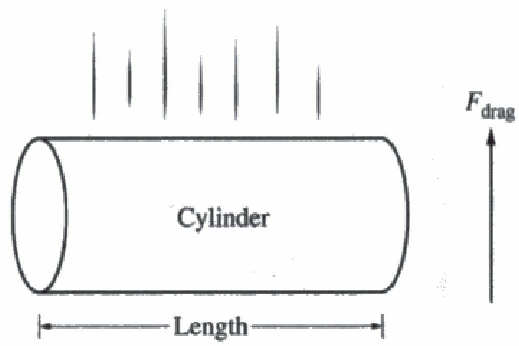



Figure 3

A student claims that the magnitude of the maximum speed of a cylinder dropped from rest depends on the length of the cylinder. The student designs an experiment to collect data that can be used to provide evidence to support the claim. The student drops cylinders with the orientation shown in Figure 3.

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

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

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

Vertical axis: $v_{max}$ Horizontal axis: length $\ell$

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

If all ~~data~~ the best-fit line for the datapoints has a slope of 0, then the length does not impact $v_{max}$, otherwise it does.

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## Question 2

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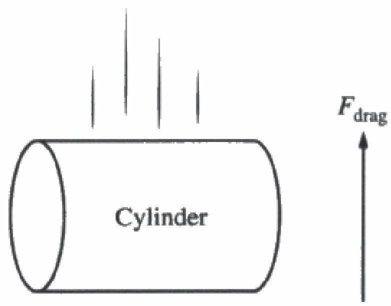


Figure 1

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

Fd

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

$\frac{d}{dx} F_d = bv^2$

$v\,dt = 2bv\,dv$

## Question 2

Continue your response to **QUESTION 2** on this page.

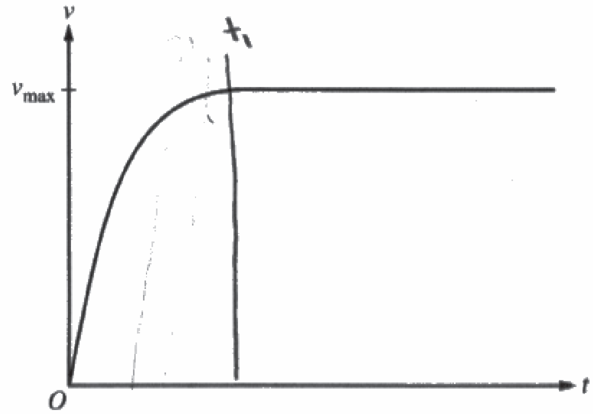


Figure 2

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

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

ii. **Justify** the location of $t_1$. Explicitly reference appropriate features of the sketch in Figure 2.

$t_1$ is there because its when ~~the graph~~ Fdrag on the graph starts to become constant, it finishes being rounded off and goes straight in t's direction

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

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

_X_ Greater than ____ Less than ____ Equal to

Briefly **justify** your answer.

The downward speed will be greater because the cylinder started its descent from a higher point.





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Use a pencil or a pen with black or dark blue ink. Do NOT write your name. Do NOT write outside the box.

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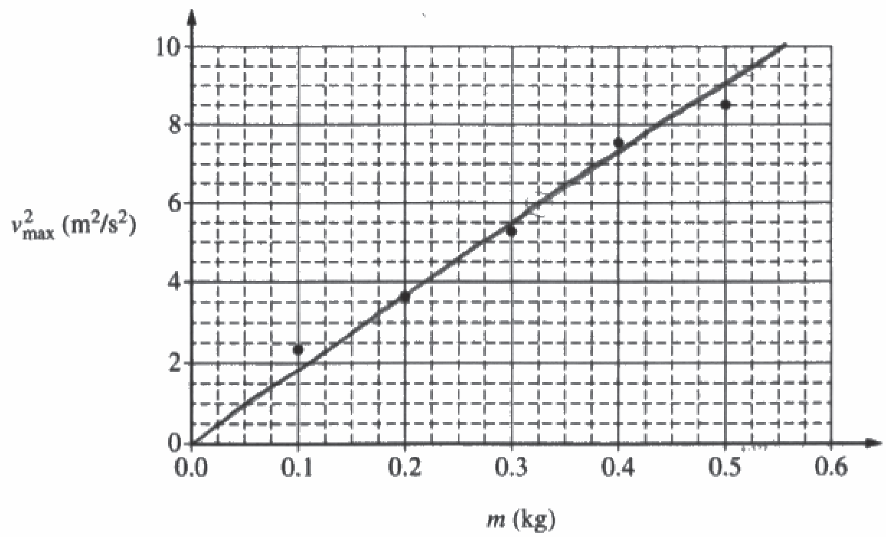
## Question 2

Continue your response to **QUESTION 2** on this page.

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




i. **Draw** the best-fit line for the data.

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

(0.325, 6)
(0.525, 8.75)

$$\frac{8.75-6}{0.525-0.325} = \frac{2.75}{0.2} = \boxed{13.75}$$

## Question 2

Continue your response to **QUESTION 2** on this page.

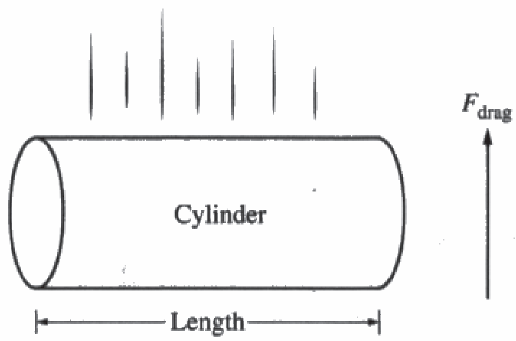



Figure 3

A student claims that the magnitude of the maximum speed of a cylinder dropped from rest depends on the length of the cylinder. The student designs an experiment to collect data that can be used to provide evidence to support the claim. The student drops cylinders with the orientation shown in Figure 3.

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

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

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

Vertical axis: Motion detector Horizontal axis: cylinder set 2

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

the motion detector could get put on the y-axis and the lengths on the x-axis because you would be able to see the variation in lengths and what v(t)'s response is.

## Question 2

**Note:** Student samples are quoted verbatim and may contain spelling and grammatical errors.

### Overview

The responses were expected to demonstrate the ability to:

- Determine the relationship between variables by deriving a differential equation applying Newton's second law to a falling object experiencing a drag force.
- Select relevant features on a velocity-time graph by recognizing when equilibrium occurs.
- Support a claim with evidence from experimental data by recognizing an object in equilibrium indicates that the sum of forces exerted on the object is equal to zero.
- Determine a line of best fit for given data.
- Explain how the graph illustrates a physics principle by calculating slope for a linear function and using this to calculate an unknown drag constant.
- Explain how the initial velocity given to an object influences the drag force.
- Describe how to determine the functional dependency between two variables in an experiment.

**Sample: 2A**
**Score: 15**

Part (a) earned 3 points. The first point was earned for correctly utilizing Newton's second law in a multi-step derivation. The second point was earned for correctly identifying that the only two forces were the force of gravity and the drag force. The third point was earned for showing the correct differential equation using the given variables. Part (b) earned 3 points. The first point was earned for showing a vertical line at the appropriate location where the line becomes horizontal and is labeled as $t_1$. The second point was earned for showing that $t_1$ occurs when the velocity is constant or that the graph has a slope of zero. The third point was earned for identifying that a constant velocity indicates a net force of zero. Part (c) earned 2 points. The first point was earned for selecting "Equal to." The second point was earned for correctly stating that when the cylinder reaches its maximum height it will have a velocity of zero; therefore, the same cylinder will reach the same maximum velocity as it falls. Part (d) earned 4 points. The first point was earned for drawing an appropriate line of best fit. The second point was earned for calculating the slope of the line using points on the line. The third point was earned for using the correct relationship between the slope and the constant $b$ : $b = \frac{g}{\text{slope}}$. The fourth point was earned for showing the correct calculation of the constant $b$. It is between $0.45$ and $0.75$. Part (e) earned 3 points. The first point was earned for indicating that the length of the cylinder should be graphed. The second point was earned for indicating that the maximum velocity should be graphed. The third point was earned for correctly describing how the quantities graphed are related to the conclusion of the experiment. The response states that the slope of the line will be utilized.

## Question 2 (continued)

**Sample: 2B**
**Score: 10**

Part (a) earned 2 points. The first point was earned for correctly utilizing Newton's second law in a multi-step derivation. The second point was earned for correctly identifying that the only two forces were the force of gravity and the drag force. The third point was not earned because the response shows an incorrect differential equation using the given variables. The response is missing an $m$ in the final equation. Part (b) earned 3 points. The first point was earned for showing a vertical line at the appropriate location that is labeled as $t_1$.The second point was earned for showing that $t_1$ occurs when the velocity is constant. The third point was earned for identifying that a constant velocity indicates a net force of zero. Part (c) earned 1 point for selecting "Equal to" and attempting a justification. The second point was not earned because the response just states the definition of terminal velocity. This is not a correct justification. Part (d) earned 1 point for drawing an appropriate line of best fit. The second point was not earned because the slope of the line is not calculated. The third point was not earned because the response does not have the correct relationship between the slope and the constant $b$. The fourth point was not earned because the response does not show the correct calculation of the constant $b$. It is not in the range between $0.45$ and $0.75$. Part (e) earned 3 points. The first point was earned for indicating that the length of the cylinder should be graphed. The second point was earned for indicating that the maximum velocity should be graphed. The third point was earned for correctly describing how the quantities graphed are related to the conclusion of the experiment.

**Sample: 2C**
**Score: 3**

Part (a) did not earn any points. The first point was not earned because the response does not correctly utilize Newton's second law in a multi-step derivation. The second point was not earned because the response does not correctly identify that the only two forces were the force of gravity and the drag force. The third point was not earned because the response does not show a correct differential equation using the given variables. Part (b) earned 1 point for showing a vertical line at the appropriate location that is labeled $t_1$. The second point was not earned because the response does not show that $t_1$ occurs when the velocity is constant or that the graph has a slope of zero. The third point was not earned because the response does not identify that a constant velocity indicates a net force of zero. Part (c) did not earn any points. The first point was not earned because "Equal to" was not selected. The second point was not earned because the response does not correctly state that the drag force does not change; therefore, the terminal velocity will not be different. Part (d) earned 2 points. The first point was earned for drawing an appropriate line of best fit. The second point was earned for calculating the slope of the line using points on the line. The third point was not earned because the response does not have the correct relationship between the slope and the drag constant $b$. The fourth point was not earned because the response does not correctly calculate the drag constant $b$. Part (e) did not earn any points. The first point was not earned because the response does not indicate that the length of the cylinder should be graphed. The second point was not earned because the response does not indicate that the maximum velocity should be graphed. The third point was not earned because the response does not correctly describe how the quantities graphed are related to the conclusion of the experiment.