2024

# AP® Physics C: Mechanics

## Sample Student Responses and Scoring Commentary Set 2

**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 sphere 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**

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

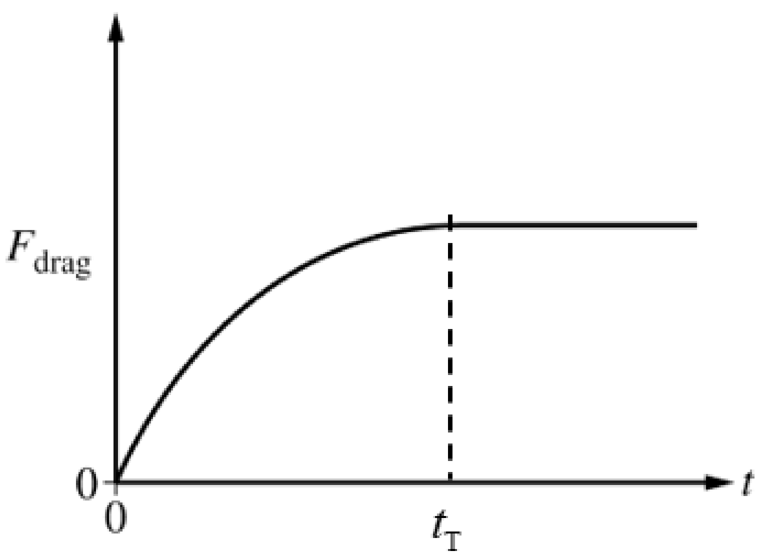
**Example Solution**

$$\Sigma F = ma$$
$$F_g - F_{\text{drag}} = ma$$
$$mg - bv = ma$$
$$m\frac{dv}{dt} = mg - bv$$

**Total for part (a) — 3 points**

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

**Example Response**



| | | |
|---|---|---|
| **(b)(ii)** | For a response that references the slope of the graph or the rate at which the slope changes | **1 point** |
| | For correctly relating a feature of the graph to the forces exerted on the sphere as the sphere reaches terminal speed | **1 point** |

**Example Response**

*For the times leading up to* $t_T$*, the slope of the graph is positive which means that the magnitude of the drag force is still increasing. After* $t_T$*, the slope of the graph is zero which means that the magnitude of the drag force is constant and equal to the downward gravitational force, which indicates that the net force is zero and that the sphere has reached a constant terminal velocity.*

**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** |

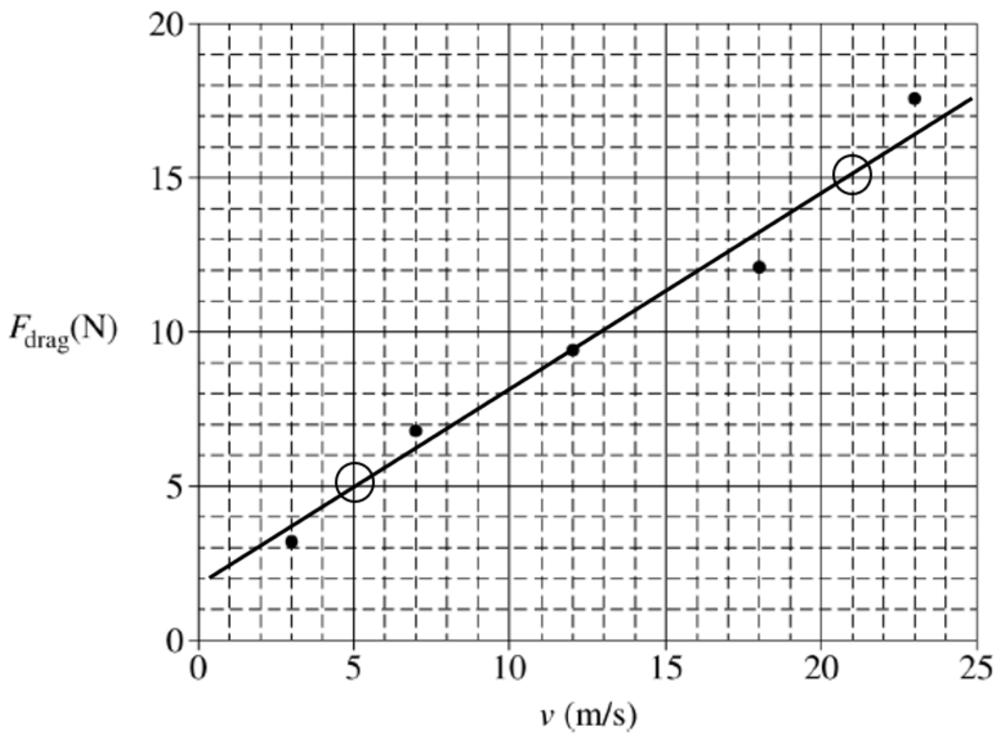
**Example Response**

*The magnitude of the drag force at terminal speed does not change since the mass of the sphere is not changed and the drag force at terminal speed does not depend on the initial speed of the sphere.*

**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 earns this point.

**Example Response**

$$\text{slope} = \frac{15\text{ N} - 5\text{ N}}{21\text{ m/s} - 5\text{ m/s}}$$

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

**Example Response**

$$\text{slope} = \frac{|F_{\text{drag}}|}{v}$$
$$\text{slope} = b$$

For a calculated value of $b$ that is $0.6\text{ kg/s} < b < 0.8\text{ kg/s}$ **1 point**

**Example Response**

$$b = 0.625\text{ kg/s}$$

**Example Solution**

$$|F_{\text{drag}}| = bv$$
$$\frac{|F_{\text{drag}}|}{v} = b$$
$$\text{slope} = b$$
$$b = \frac{15\text{ N} - 5\text{ N}}{21\text{ m/s} - 5\text{ m/s}}$$
$$b = 0.625\text{ kg/s}$$

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

| | | |
|---|---|---|
| **(e)(i)** | For indicating the diameter of the sphere should be graphed | **1 point** |
| | For indicating the terminal velocity of the sphere should be graphed | **1 point** |
| **(e)(ii)** | For describing how the quantities graphed are related to the conclusion of the experiment | **1 point** |

**Example Response**

*The slope of the diameter vs terminal velocity graph can be used to determine if sphere diameter 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.

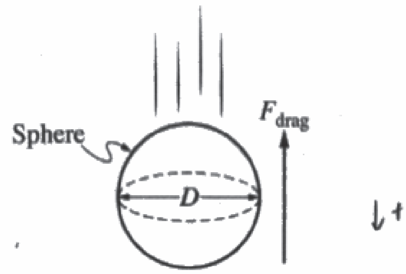



Figure 1

2. A student drops a sphere of mass $m$ from rest. The air exerts a drag force of magnitude $F_{drag}$ on the sphere, as shown in Figure 1. The student models the magnitude of the drag force as $F_{drag} = bv$, where $v$ is the speed of the sphere 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 sphere as a function of time $t$. Express your answer in terms of given quantities and physical constants, as appropriate.

$$F = ma = m\frac{dv}{dt}$$

$$F_g - bv = m\frac{dv}{dt}$$

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



GO ON TO THE NEXT PAGE.

## Question 2

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

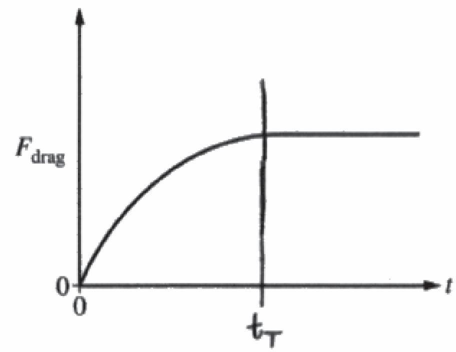



Figure 2

(b) The student sketches the drag force $F_{drag}$ exerted on the sphere 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 $F_{drag}$ is equal to the magnitude of the weight of the sphere, which occurs when the sphere reaches terminal speed. Label this time as $t_T$ on the time axis.

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

Fdrag will remain constant once the ball reaches terminal speed since Fdrag = bv, thus, $t_T$ is where the graph of Fdrag vs t first reaches a slope of 0.

(c) Suppose the student throws the same sphere downward with a nonzero initial speed. The magnitude of the new drag force at terminal speed after being thrown downward is $F_{new}$.

**Indicate** whether $F_{new}$ would be greater than, less than, or equal to the magnitude of $F_{drag}$ at terminal speed represented in Figure 2.

____ Greater than ____ Less than __X__ Equal to

Briefly **justify** your answer.

Fdrag has to equal Fg on the ball in order for it to be at the constant terminal speed. Fg will not change, so Fnew will be equal to Fdrag at terminal speed in Fig. 2.



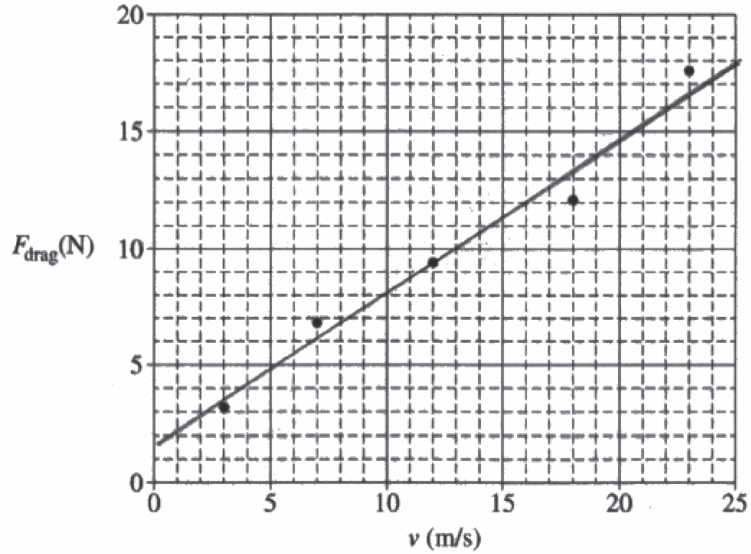


[redacted]

## Question 2

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

(d) The student conducts an experiment to better understand the relationship between $F_{drag}$ and $v$. The student makes measurements to calculate and graph the magnitude of $F_{drag}$ as a function of $v$ for the falling sphere.




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

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

$F_{drag} = bv$ slope $= \frac{\Delta F_{drag}}{\Delta v} = \frac{18-12}{25-16} = \frac{6}{9} = 0.667$

slope $= b =$ **0.67**

## Question 2

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

A student claims that the terminal speed $v_T$ of the sphere depends on the diameter $D$ of the sphere. The student designs an experiment to collect data that can be used to provide evidence to support the claim.

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

- Sphere Set 1: spheres of the same known mass with different known diameters
- Sphere Set 2: spheres of the same known diameter with different known masses
- 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 diameter of the sphere affects the terminal speed.

Vertical axis: terminal speed Horizontal axis: diameter

ii. Briefly **describe** how the quantities graphed could be used to determine the relationship between sphere diameter and terminal speed.

By making the diameters of the spheres the independent variable and the terminal speed reached by each sphere the dependent variable, the student can see if the different diameters result in different terminal speeds.

## Question 2

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

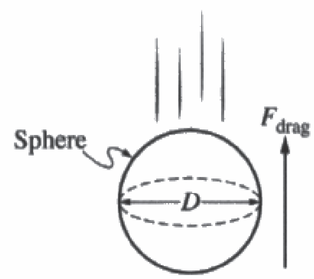



Figure 1

2. A student drops a sphere of mass $m$ from rest. The air exerts a drag force of magnitude $F_{drag}$ on the sphere, as shown in Figure 1. The student models the magnitude of the drag force as $F_{drag} = bv$, where $v$ is the speed of the sphere 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 sphere as a function of time $t$. Express your answer in terms of given quantities and physical constants, as appropriate.

$\Sigma F = ma$

$mg - bv = ma$

$mg - bv = m\left(\frac{dv}{dt}\right)$

## Question 2

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

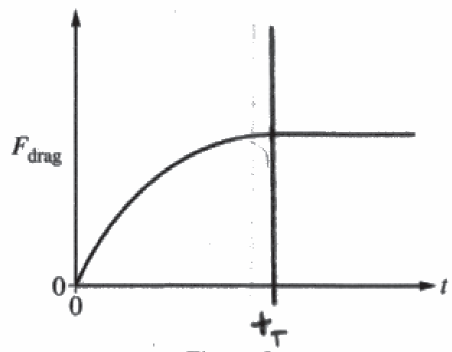



Figure 2

(b) The student sketches the drag force $F_{drag}$ exerted on the sphere 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 $F_{drag}$ is equal to the magnitude of the weight of the sphere, which occurs when the sphere reaches terminal speed. Label this time as $t_T$ on the time axis.

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

$t_T$ occurs when $F_{drag} = mg$, meaning $\Sigma F = 0$. when $\Sigma F = 0$, the velocity is constant, so the acceleration must be 0. $\Sigma F = ma$, so $\Sigma F = 0$ means $a = 0$. $a$ is directly related to F, so when the is constant, Fdrag should be the same magnitude (mg)

(c) Suppose the student throws the same sphere downward with a nonzero initial speed. The magnitude of the new drag force at terminal speed after being thrown downward is $F_{new}$. $F_{drag} = mg - ma$

**Indicate** whether $F_{new}$ would be greater than, less than, or equal to the magnitude of $F_{drag}$ at terminal speed represented in Figure 2.

____ Greater than     ____ Less than     X Equal to

Briefly **justify** your answer.

$F_{drag} = mg - ma$, since the same forces act on the sphere of the same mass, the magnitude of Fdrag at terminal velocity is ~~always~~ still $= mg$





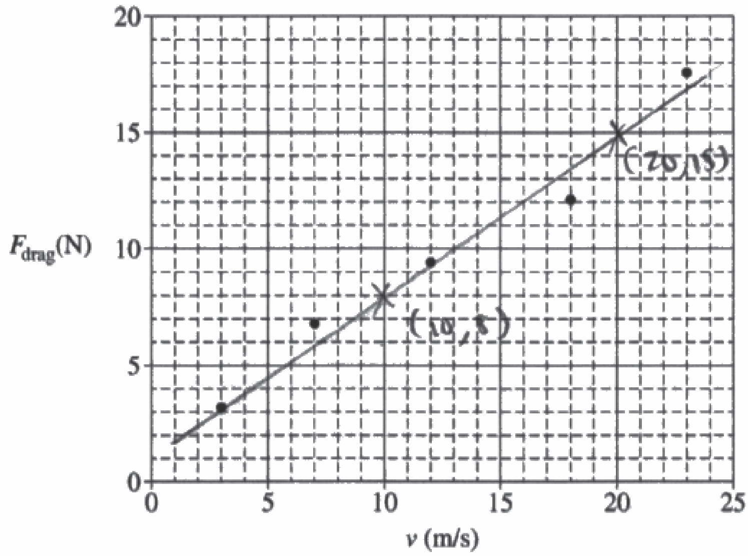
Use a pencil or a pen with black or dark blue ink. Do NOT write your name. Do NOT write outside the box.

[redacted]

## Question 2

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

(d) The student conducts an experiment to better understand the relationship between $F_{drag}$ and $v$. The student makes measurements to calculate and graph the magnitude of $F_{drag}$ as a function of $v$ for the falling sphere.




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

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

~~Fg - bv = ma~~

$\frac{F\,(N)}{v\,(m/s)}$

$F_{drag} = bv$

slope $= b = \frac{15-8}{20-10} = 0.7\ \frac{N}{m/s}$

## Question 2

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

A student claims that the terminal speed $v_T$ of the sphere depends on the diameter $D$ of the sphere. The student designs an experiment to collect data that can be used to provide evidence to support the claim.

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

- Sphere Set 1: spheres of the same known mass with different known diameters
- Sphere Set 2: spheres of the same known diameter with different known masses
- 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 diameter of the sphere affects the terminal speed.

Vertical axis: mass (kg) Horizontal axis: velocity (m/s)

~~mg = bv =~~ mg = bv + ma

ii. Briefly **describe** how the quantities graphed could be used to determine the relationship between sphere diameter and terminal speed.

finding the slope of the m vs. v graph could give slope = $\frac{b}{v}$. this can be compared to b to verify the mg = bv relationship

## Question 2

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

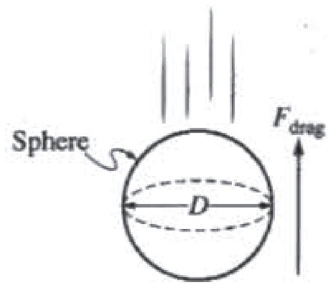



Figure 1

2. A student drops a sphere of mass $m$ from rest. The air exerts a drag force of magnitude $F_{drag}$ on the sphere, as shown in Figure 1. The student models the magnitude of the drag force as $F_{drag} = bv$, where $v$ is the speed of the sphere 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 sphere as a function of time $t$. Express your answer in terms of given quantities and physical constants, as appropriate.

$mg\Delta h = \frac{1}{2}mv^2$

2 m m

$2gh = v^2$

$\boxed{\sqrt{2gh} = v}$

## Question 2

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

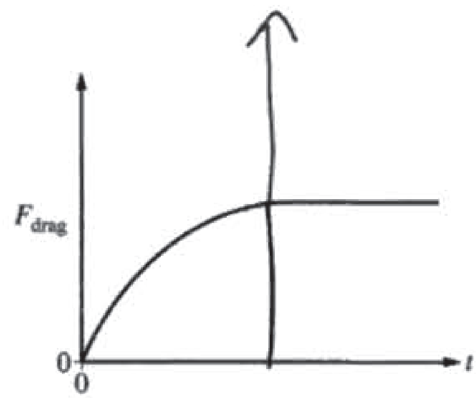


Figure 2

(b) The student sketches the drag force $F_{drag}$ exerted on the sphere 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 $F_{drag}$ is equal to the magnitude of the weight of the sphere, which occurs when the sphere reaches terminal speed. Label this time as $t_T$ on the time axis.

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

(c) Suppose the student throws the same sphere downward with a nonzero initial speed. The magnitude of the new drag force at terminal speed after being thrown downward is $F_{new}$.

**Indicate** whether $F_{new}$ would be greater than, less than, or equal to the magnitude of $F_{drag}$ at terminal speed represented in Figure 2.

____ Greater than    ____ Less than    _X_ Equal to

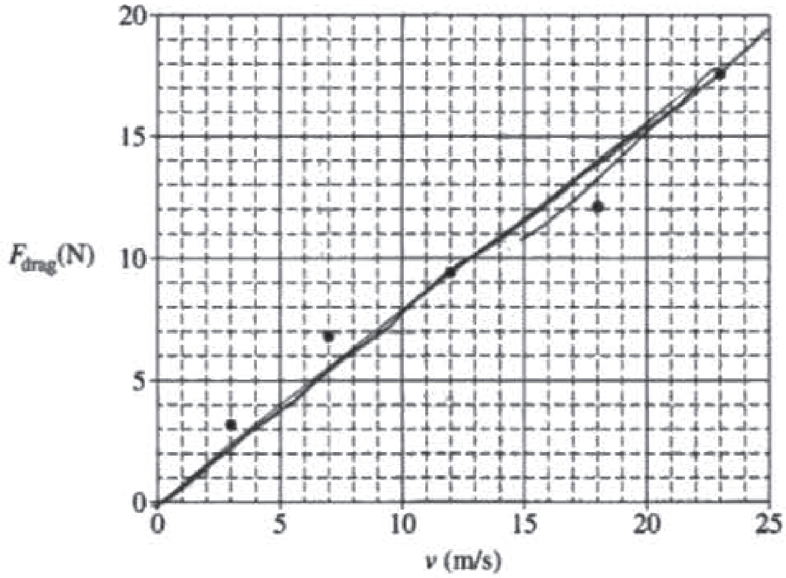
Briefly **justify** your answer.

The magnitude would be the same because the position doesnt affect magnitude.

## Question 2

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

(d) The student conducts an experiment to better understand the relationship between $F_{drag}$ and $v$. The student makes measurements to calculate and graph the magnitude of $F_{drag}$ as a function of $v$ for the falling sphere.




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

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

## Question 2

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

A student claims that the terminal speed $v_T$ of the sphere depends on the diameter $D$ of the sphere. The student designs an experiment to collect data that can be used to provide evidence to support the claim.

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

- Sphere Set 1: spheres of the same known mass with different known diameters
- Sphere Set 2: spheres of the same known diameter with different known masses
- 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 diameter of the sphere affects the terminal speed.

Vertical axis: ~~velocity~~ position    Horizontal axis: ~~acceleration~~ ~~velocity~~ Rotational inertia

ii. Briefly **describe** how the quantities graphed could be used to determine the relationship between sphere diameter and terminal speed.

~~the pos~~

the position would provide knowledge of the speed because you can derive it to find the velocity and acceleration. the rotational inertia would help us understand how ~~great~~ big the diameter is by either being small or large.

## 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:

- Derive the differential equation for speed as a function of time for a sphere experiencing a resistive drag force.
- Apply Newton's laws, including identifying and explaining the forces acting on an object experiencing a drag force with different initial conditions.
- Analyze and interpret sections of a force-time graph.
- Support a claim with evidence from experimental data by recognizing that equilibrium implies that the sum of forces 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.

### Sample: 2A
### Score: 15

Part (a) earned 3 points. The first point was earned for using a multi-step derivation that includes Newton's second law. The second point was earned for correctly substituting expressions for the drag and gravitational forces exerted on the sphere. The third point was earned for showing a correct differential equation using the given variables. Part (b) earned 3 points. The first point was earned for drawing and correctly labeling a vertical line where the curve transitions to a horizontal line. The second point was earned for referencing the slope of the graph to describe the rate at which the slope changes. The third point was earned for correctly relating the features of the graph to the forces on the sphere at terminal velocity. Part (c) earned 2 points. The first point was earned for correctly selecting "Equal to" with an attempt at a justification. The second point was earned for correctly identifying that $F_{\text{drag}}$ is equal to $F_g$ and because $F_g$ does not change, neither does $F_{\text{drag}}$. Part (d) earned 4 points. The first point was earned for an appropriate line of best fit for the given data points. The second point was earned for using two points on the line of best fit to calculate the slope. The third point was earned for correctly relating the slope of the line of best fit to the value of $b$. The fourth point was earned for a correct value for $b$ in the acceptable range. Part (e) earned 3 points. The first point was earned for correctly indicating that the diameter of the sphere should be graphed. The second point was earned for correctly indicating that the terminal velocity of the sphere should be graphed. The third point was earned for describing how the graphed quantities can be used to determine the relationship between the terminal velocity and diameter of the sphere.

## Question 2 (continued)

**Sample: 2B**
**Score: 12**

Part (a) earned 3 points. The first point was earned for using a multi-step derivation that includes Newton's second law. The second point was earned for correctly substituting expressions for the drag and gravitational forces exerted on the sphere. The third point was earned for a correct differential equation using given variables. Part (b) earned 3 points. The first point was earned for drawing and correctly labeling a vertical line where the curve transitions to a horizontal line. The second point was earned for referencing the slope of the graph to describe the rate at which the slope changes. The third point was earned for correctly relating the features of the graph to the forces on the sphere at terminal velocity. Part (c) earned 2 points. The first point was earned for correctly choosing "Equal to" with an attempt at a justification. The second point was earned for correctly identifying that $F_{\text{drag}}$ is equal to $F_g$ and because $F_g$ does not change, neither does $F_{\text{drag}}$. Part (d) earned 4 points. The first point was earned for an appropriate line of best fit for the given data points. The second point was earned for using two points on the line of best fit to calculate the slope. The third point was earned for correctly relating the slope of the line of best fit to the value of $b$. The fourth point was earned for a correct value for $b$ in the acceptable range. Part (e) did not earn any points. The first point was not earned because the response incorrectly indicates that the mass of the sphere should be graphed. The second point was not earned because the response incorrectly indicates that the velocity of the sphere, and not the terminal velocity of the sphere, should be graphed. The third point was not earned because the response cannot determine the relationship between the terminal velocity and the diameter of the sphere by graphing the mass versus the velocity of the sphere.

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

Part (a) did not earn any points. The first point was not earned because the response attempts to use conservation of energy and not Newton's second law. The second point was not earned because the response does not include expressions for the drag and gravitational forces exerted on the sphere. The third point was not earned because the response does not include the correct differential equation using the given variables. Part (b) earned 1 point for drawing a vertical line where the curve transitions to a horizontal line (label not required). The second point was not earned because the response does not attempt to reference the slope of the graph to describe the rate at which the slope changes. The third point was not earned because the response does not attempt to relate the features of the graph to the forces on the sphere at terminal velocity. Part (c) earned 1 point for selecting "Equal to" with an attempt at a justification with relevant concepts. The second point was not earned because the response incorrectly attempts a justification by relating the position of the sphere to $mg$. Part (d) earned 1 point for drawing an appropriate line of best fit for the given data points. The second point was not earned because the response does not attempt to calculate the slope. The third point was not earned because the response does not attempt to relate $b$ to the slope of the line of best fit. The fourth point was not earned because the response does not contain a value for $b$ in the acceptable range. Part (e) did not earn any points. The first point was not earned because the response incorrectly indicates that position should be graphed. The second point was not earned because the response incorrectly indicates that rotational inertia should be graphed. The third point was not earned because the response incorrectly attempts to relate the diameter of the sphere to its rotational inertia as its speed changes.