2023

AP

# AP® Physics C: Electricity and Magnetism

## Sample Student Responses and Scoring Commentary Set 1

**Inside:**

Free-Response Question 1

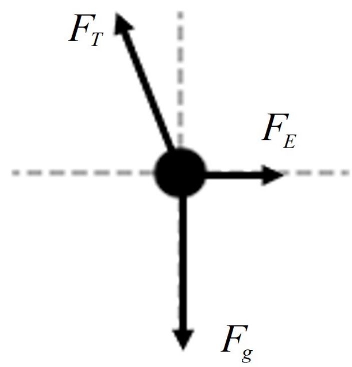
- ☑ Scoring Guidelines
- ☑ Student Samples
- ☑ Scoring Commentary

## Question 1: Free-Response Question 15 points

| | | |
|---|---|---|
| **(a)** | For correctly drawing and labeling the electrostatic force directed to the right | **1 point** |
| | For drawing the force of tension up and to the left and the gravitational force in the downward direction | **1 point** |

**Scoring Note**: A maximum of 1 point may be earned if extraneous forces are included.

**Example Response**




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

| | | |
|---|---|---|
| **(b)** | For equating the horizontal component of tension to the electrostatic force | **1 point** |

**Example Response**

$$F_E = F_T \sin(\theta)$$

| | |
|---|---|
| For equating the vertical component of tension to the gravitational force | **1 point** |

**Example Response**

$$F_g = F_{Ty}$$
$$Mg = F_T \cos\theta$$

| | |
|---|---|
| For an attempt to simultaneously solve the equations | **1 point** |

**Example Response**

$$\frac{1}{4\pi\varepsilon_0}\frac{Qq}{d^2}\frac{1}{\sin\theta}\cos\theta = Mg$$

**Example Solution**

$$\Sigma F_y = 0$$
$$F_{Ty} = F_g$$
$$F_T \cos\theta = Mg$$
$$F_{Tx} = F_E$$
$$F_T = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{d^2}\frac{1}{\sin\theta}$$
$$\frac{1}{4\pi\varepsilon_0}\frac{Qq}{d^2}\frac{1}{\sin\theta}\cos\theta = Mg$$
$$d^2 = \frac{Qq\cos\theta}{4\pi\varepsilon_0 Mg\sin\theta}$$
$$d = \sqrt{\frac{Qq}{4\pi\varepsilon_0 Mg\tan\theta}}$$

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

**(c)** For applying Coulomb's law to determine tension **1 point**

**Scoring Note**: This point may be earned if the student used the vertical component of tension.

**Example Response**

$$F_E = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{d^2} = F_T \sin(\theta)$$

For correct substitution into an expression for tension consistent with part (b) or a correct expression for tension **1 point**

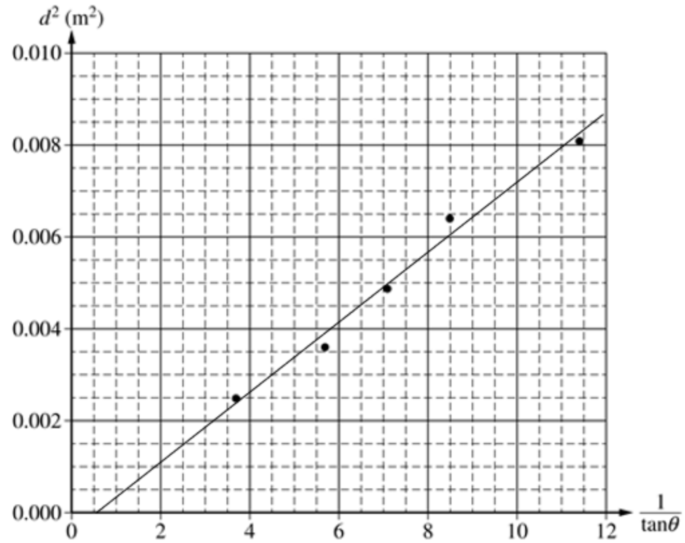
**Example Solution**

$$\Sigma F = 0$$
$$F_E - F_{Tx} = 0$$
$$F_E = F_{Tx}$$
$$\frac{1}{4\pi\varepsilon_0}\frac{Qq}{d^2} = F_T \sin(\theta)$$
$$F_T = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{d^2 \sin(\theta)}$$
$$F_T = \frac{1}{4\pi\left(8.85\times 10^{-12}\ \frac{\text{C}^2}{\text{N}\bullet\text{m}^2}\right)}\frac{\left(6.0\times 10^{-8}\ \text{C}\right)^2}{(0.057\ \text{m})^2 \sin\left(12^\circ\right)}$$
$$F_T = 0.048\ \text{N}$$

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

| | | |
|---|---|---|
| **(d)(i)** | For a line that approximates the trend of the data | **1 point** |

**Example Response**



**(d)(ii)** For using two points from the trend line drawn by the student to calculate the slope **1 point**

**Scoring Note:** Points of data may be used only if points of data are located directly on the line.

**Example Response**

$$\text{Slope} = \frac{\Delta y}{\Delta x}$$

$$\text{Slope} = \frac{\Delta(d^2)}{\Delta\left(\frac{1}{\tan(\theta)}\right)}$$

$$\text{Slope} = \frac{\left(0.0075\ \text{m}^2 - 0.001\ \text{m}^2\right)}{(10.5 - 2)}$$

$$\text{Slope} = 7.647 \times 10^{-4}\ \text{m}^2$$

For correctly relating the slope of the graph to the equation $d = \sqrt{\frac{Qq}{4\pi\varepsilon_0 Mg \tan\theta}}$ **1 point**

**Example Response**

$$d = \sqrt{\frac{Qq}{4\pi\varepsilon_0 Mg \tan\theta}}$$

$$d^2 = \frac{Qq}{4\pi\varepsilon_0 Mg \tan\theta}$$

$$d^2 = \left(\frac{Qq}{4\pi\varepsilon_0 Mg}\right)\frac{1}{\tan\theta}$$

$$\text{slope} = \left(\frac{Qq}{4\pi\varepsilon_0 Mg}\right)$$

For substituting the value of the slope of the graph into the equation $\varepsilon_0 = \frac{Qq}{4\pi Mg(\text{slope})}$ to calculate an experimental value of $\varepsilon_0$ **1 point**

**Example Solution**

$$\text{slope} = \frac{Qq}{4\pi\varepsilon_0 Mg}$$

$$\varepsilon_0 = \frac{Qq}{4\pi Mg(\text{slope})}$$

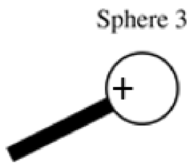
$$\varepsilon_0 = \frac{\left(6.0 \times 10^{-8}\ \text{C}\right)^2}{4\pi(0.005\ \text{kg})\left(9.8\ \text{m/s}^2\right)\left(7.647 \times 10^{-4}\ \text{m}^2\right)}$$

$$\varepsilon_0 = 7.6 \times 10^{-12}\ \frac{\text{C}^2}{\text{N}\bullet\text{m}^2}$$

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

**(e)(i)** For a "+" drawn on the left side of the sphere **1 point**

**Example Response**




**(e)(ii)** For a statement that indicates correct charge rearrangement on Sphere 3 due to the electric forces from the charges on Sphere 2 **1 point**

**Example Response**

*The negative charges on Sphere* 3 *move to the right due to the attractive forces from the positive charges on Sphere* 2*, leaving a net positive charge on the left side of Sphere* 3*.*

**(e)(iii)** For selecting "$\theta_2 < \theta_1$" with an attempt at a relevant justification **1 point**

For statement that indicates **one** of the following: **1 point**

- The average distance between the repulsive charges is greater.
- The electrostatic or repulsive force is less.

**Scoring Note:** Points 1 and 2 of part (e)(iii) can be earned with an answer that is consistent with the location of the excess positive charges drawn in part (e)(i).

**Example Response**

*Excess charges on Sphere* 3 *are now free to move, so excess like charges will be concentrated on the far ends of Sphere* 3 *when the spheres are in static equilibrium. The excess like charges, located on opposite sides of Sphere* 3*, repel with less force than if the excess charges were located at the centers of Sphere* 3*. Thus, the downward force due to gravity on Sphere* 2 *causes the center of Sphere* 2 *to hang closer to the center of Sphere* 3*.*

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

**Total for question 1 15 points**

## Question 1

Begin your response to **QUESTION 1** on this page.

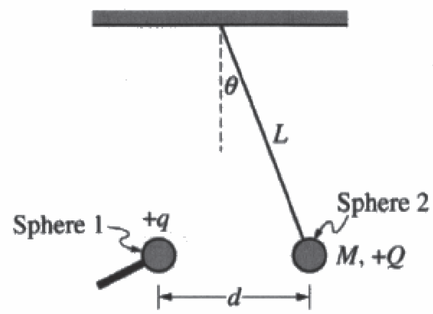
**PHYSICS C: ELECTRICITY AND MAGNETISM**

**SECTION II**

**Time—45 minutes**

**3 Questions**

**Directions:** Answer all three questions. The suggested time is about 15 minutes for answering each of the questions, which are worth 15 points each. The parts within a question may not have equal weight. Show all your work in this booklet in the spaces provided after each part.

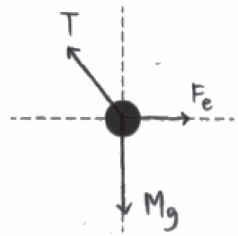



1. Students perform an experiment to determine the value of vacuum permittivity $\varepsilon_0$. Sphere 1 is nonconducting with charge $+q$ and is attached to an insulating rod. Sphere 2 is nonconducting with charge $+Q$ and has mass $M$. Sphere 2 is hung from a string of negligible mass and length $L$. Sphere 1 is brought near, without touching, Sphere 2, as shown. Equilibrium is established when the centers of the two spheres have the same vertical position, are a horizontal distance $d$ apart, and the string is at an angle $\theta$ from the vertical.

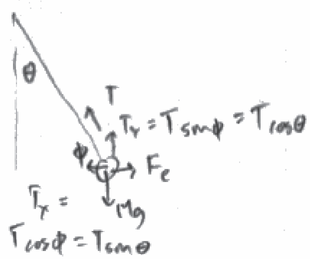
## Question 1

**Continue your response to QUESTION 1 on this page.**

**(a) On the following dot that represents Sphere 2 at the position shown in the previous figure, draw and label the forces (not components) that act on Sphere 2. Each force must be represented by a distinct arrow starting on, and pointing away from, the dot.**




**(b) Derive the relationship between the distance $d$ and the angle $\theta$ to show that $d = \sqrt{\dfrac{Qq}{4\pi\varepsilon_0 Mg\tan\theta}}$.**




$\sum F_x = 0$

$F_e - T_x = 0$

$\dfrac{kqQ}{d^2} = T\sin\theta$

$\sum F_Y = 0$

$T_Y - Mg = 0$

$T\cos\theta = Mg$

$T = \dfrac{Mg}{\cos\theta}$

$\dfrac{kqQ}{d^2} = \dfrac{Mg\sin\theta}{\cos\theta} = Mg\tan\theta$

$d^2 = \dfrac{kqQ}{Mg\tan\theta} \Rightarrow d = \sqrt{\dfrac{Qq}{4\pi\varepsilon_0 Mg\tan\theta}}$

**(c) These values are collected in one trial: $Q = q = 6.0 \times 10^{-8}$ C, $\theta = 12°$, and $d = 0.057$ m. Calculate the expected force of tension exerted on Sphere 2 by the string.**

$\dfrac{kqQ}{d^2} = T\sin\theta$

$T = \dfrac{kqQ}{d^2\sin\theta} = \dfrac{9\cdot10^9\cdot(6\cdot10^{-8})^2}{0.057^2\cdot\sin 12°} = 0.0480$ N



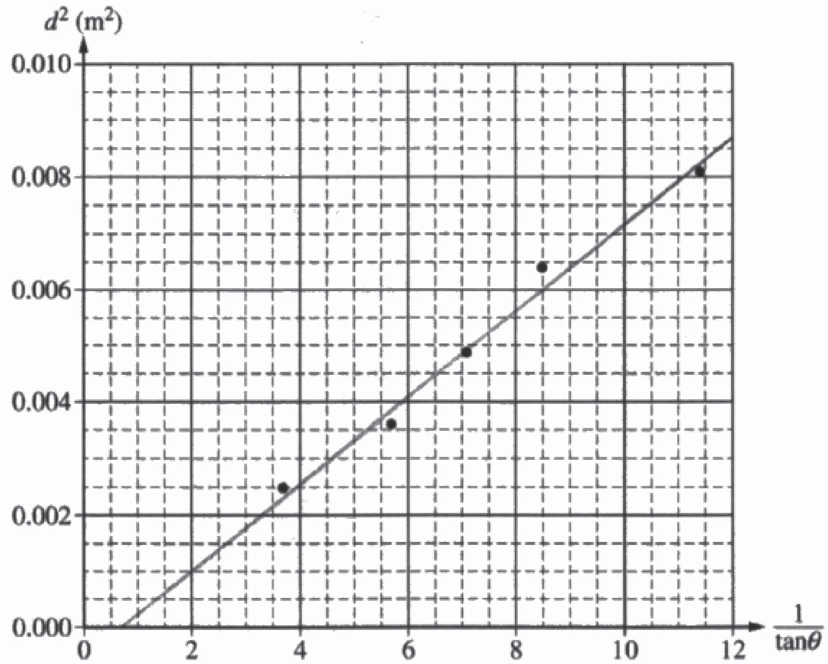
**GO ON TO THE NEXT PAGE.**

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

## Question 1

Continue your response to **QUESTION 1** on this page.

(d) The students vary $d$ and measure $\theta$ after equilibrium is reached. The students use the collected data to plot the following graph of $d^2$ vs. $\frac{1}{\tan\theta}$.




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

ii. Using the best-fit line, calculate an experimental value for the vacuum permittivity $\varepsilon_0$ when $M = 0.0050$ kg and $Q = q = 6.0 \times 10^{-8}$ C.

$$d^2 = \frac{kqQ}{Mg} \cdot \frac{1}{\tan\theta} = \frac{qQ}{4\pi\varepsilon_0 Mg} \cdot \frac{1}{\tan\theta}$$

$$m \approx \frac{0.006 - 0.0025}{8.5 - 4} = 7.778 \cdot 10^{-4}$$

$$\frac{qQ}{4\pi\varepsilon_0 Mg} = m$$

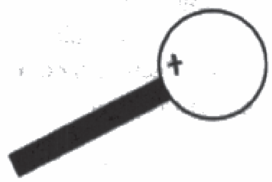
$$\varepsilon_0 = \frac{qQ}{4\pi m Mg} = \frac{(6 \cdot 10^{-8})^2}{4\pi \cdot 7.778 \cdot 10^{-4} \cdot 0.005 \cdot 9.8} = 7.517 \cdot 10^{-12} \ \frac{C^2}{Nm^2}$$

Continue your response to **QUESTION 1** on this page.

(e) The students modify the experiment by replacing Sphere 1 with a conducting Sphere 3 that has the same size and charge $+q$. The experiment is repeated.

i. The circle in the following figure represents Sphere 3 when spheres 2 and 3 are at equilibrium. On the circle, draw a single "+" sign to represent the location of highest concentration of the excess positive charges.

Sphere 3




ii. Briefly explain your reasoning for the sketch drawn in part (e)(i).

the positive charges are free to move in a conductor and will be repelled by the other positively charged sphere to the farthest point possible which is on the left

iii. In the original experiment, when the centers of the two spheres are a horizontal distance $d_1$ apart, the string makes an angle $\theta_1$ from the vertical. In the modified experiment, when the centers of the two spheres are a horizontal distance $d_1$ apart, the string makes an angle $\theta_2$ from the vertical.

Is $\theta_2$ greater than, less than, or equal to $\theta_1$ ?

____ $\theta_2 > \theta_1$    _✓_ $\theta_2 < \theta_1$    ____ $\theta_2 = \theta_1$

**Briefly justify your answer.**

the positive charges will be slightly farther away in the second experiment so there will be a slightly smaller repulsive force and smaller angle





**GO ON TO THE NEXT PAGE.**

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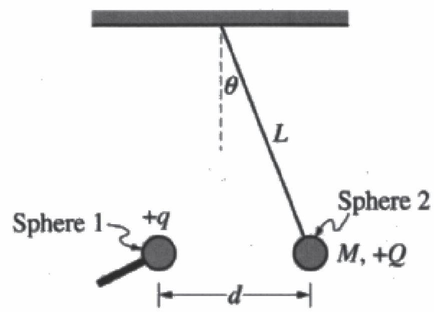


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## Question 1

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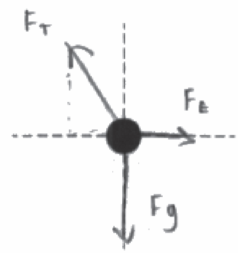


(b) Derive the relationship between the distance $d$ and the angle $\theta$ to show that $d = \sqrt{\frac{Qq}{4\pi\varepsilon_0 Mg \tan\theta}}$.

Coulomb's law

$|\vec{F_E}| = \frac{1}{4\pi\varepsilon_0}\left|\frac{q_1 q_2}{r^2}\right|$

$= \frac{1}{4\pi\varepsilon_0}\left|\frac{Q \cdot q}{(2L\sin\theta)^2}\right|$

$= \frac{1}{4\pi\varepsilon_0}\left|\frac{Qq}{4L^2\sin^2\theta}\right|$

$\frac{1}{2}d = L\sin\theta$

$d = 2L\sin\theta$

(c) These values are collected in one trial: $Q = q = 6.0 \times 10^{-8}$ C, $\theta = 12°$, and $d = 0.057$ m. Calculate the expected force of tension exerted on Sphere 2 by the string.

x-component:
Coulomb's law

$|\vec{F_E}| = \frac{1}{4\pi\varepsilon_0}\left|\frac{q_1 q_2}{r^2}\right|$

$= \frac{1}{4\pi(8.85 \cdot 10^{-12})}\left|\frac{(6.0 \cdot 10^{-8})(6.0 \cdot 10^{-8})}{(0.057)^2}\right|$

$= \frac{1}{1.112 \cdot 10^{-10}}\left|\frac{3.6 \cdot 10^{-15}}{0.003249}\right|$

$= 0.00996$

$F_T \sin 12° = 0.00996$

$F_T(0.2079) = 0.00996$

$F_T = 0.04793$ N

$\boxed{F_T = 0.048 \text{ N}}$



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## Question 1

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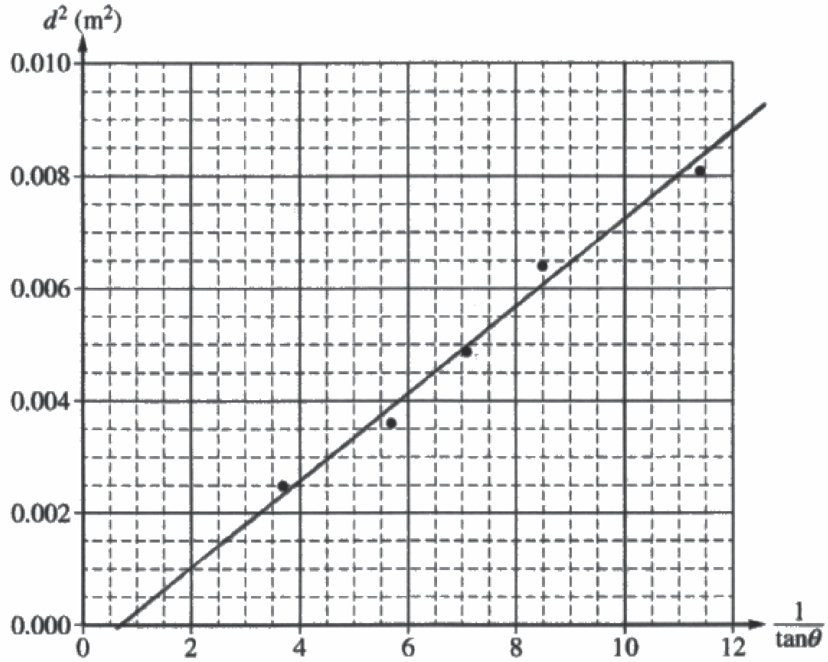


i. Draw the best-fit line for the data.

ii. Using the best-fit line, calculate an experimental value for the vacuum permittivity $\varepsilon_0$ when $M = 0.0050$ kg and $Q = q = 6.0 \times 10^{-8}$ C.

Coulomb's law

$|\vec{F}_E| = \frac{1}{4\pi\varepsilon_0}\left|\frac{q_1 q_2}{r^2}\right|$

$C = \frac{k\varepsilon_0 A}{d}$

## Question 1

Continue your response to **QUESTION 1** on this page.

(e) The students modify the experiment by replacing Sphere 1 with a conducting Sphere 3 that has the same size and charge $+q$. The experiment is repeated.

i. The circle in the following figure represents Sphere 3 when spheres 2 and 3 are at equilibrium. On the circle, draw a single "+" sign to represent the location of highest concentration of the excess positive charges.

Sphere 3


ii. Briefly explain your reasoning for the sketch drawn in part (e)(i).

Opposites attract and likes repel. Since sphere 2 is also positive, it would repel and get repelled by sphere 3, which is positive. Since they are both positive, the positive charges would end up on opposite ends, so in this case the positive would be on the far left. This happens because the electrons move within the object, moving to the right toward the positive sphere 2.

iii. In the original experiment, when the centers of the two spheres are a horizontal distance $d_1$ apart, the string makes an angle $\theta_1$ from the vertical. In the modified experiment, when the centers of the two spheres are a horizontal distance $d_1$ apart, the string makes an angle $\theta_2$ from the vertical.

Is $\theta_2$ greater than, less than, or equal to $\theta_1$ ?

✓ $\theta_2 > \theta_1$ ____ $\theta_2 < \theta_1$ ✓ $\theta_2 = \theta_1$

Briefly justify your answer.

~~Since sphere 3 is conducting and sphere 1 was not conducting, sphere 3 is able to have a greater~~

Even though sphere 3 is conducting and sphere 1 was not conducting, they still have equal charges, they are both +q, and they also have the same size. Thus, according to Coulomb's law, they would still have equal repelling force since they have the same charge and distance between the centers of mass.

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## Question 1

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**PHYSICS C: ELECTRICITY AND MAGNETISM**

**SECTION II**

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**3 Questions**

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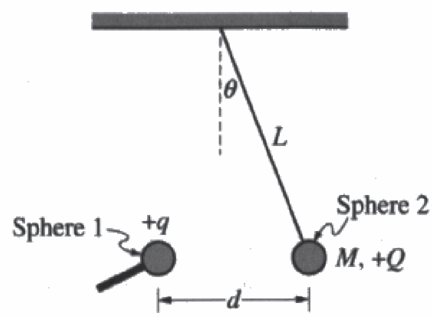


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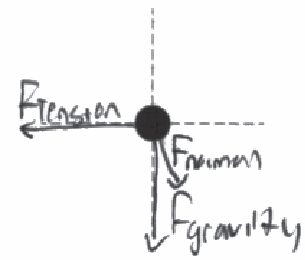


(b) Derive the relationship between the distance $d$ and the angle $\theta$ to show that $d = \sqrt{\dfrac{Qq}{4\pi\varepsilon_0 Mg\tan\theta}}$.

$F = \dfrac{kq_1q_2}{r^2}$ $\quad a^2+b^2=c^2$

(c) These values are collected in one trial: $Q = q = 6.0 \times 10^{-8}$ C, $\theta = 12°$, and $d = 0.057$ m. Calculate the expected force of tension exerted on Sphere 2 by the string.

$F = \dfrac{kq_1q_2}{r}$ $\quad F=ma$



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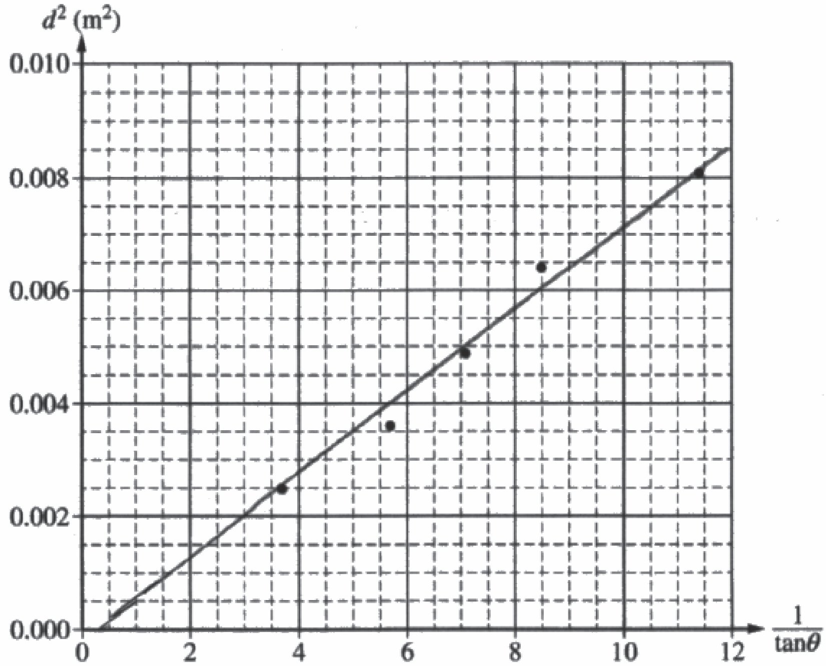
## Question 1

Continue your response to **QUESTION 1** on this page.

(d) The students vary $d$ and measure $\theta$ after equilibrium is reached. The students use the collected data to plot the following graph of $d^2$ vs. $\frac{1}{\tan\theta}$.




i. Draw the best-fit line for the data. E2

ii. Using the best-fit line, calculate an experimental value for the vacuum permittivity $\varepsilon_0$ when $M = 0.0050$ kg and $Q = q = 6.0 \times 10^{-8}$ C.

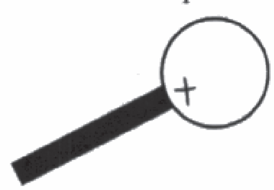
$F = \frac{kq_1q_2}{r}$

## Question 1

Continue your response to **QUESTION 1** on this page.

(e) The students modify the experiment by replacing Sphere 1 with a conducting Sphere 3 that has the same size and charge $+q$. The experiment is repeated.

i. The circle in the following figure represents Sphere 3 when spheres 2 and 3 are at equilibrium. On the circle, draw a single "+" sign to represent the location of highest concentration of the excess positive charges.




ii. Briefly explain your reasoning for the sketch drawn in part (e)(i).

The positive charge in the sphere is attracted to the negative charge on the rod.

iii. In the original experiment, when the centers of the two spheres are a horizontal distance $d_1$ apart, the string makes an angle $\theta_1$ from the vertical. In the modified experiment, when the centers of the two spheres are a horizontal distance $d_1$ apart, the string makes an angle $\theta_2$ from the vertical.

Is $\theta_2$ greater than, less than, or equal to $\theta_1$ ?

____ $\theta_2 > \theta_1$ ____ $\theta_2 < \theta_1$ ✓ $\theta_2 = \theta_1$

Briefly justify your answer.

The angles will equal since the centers of the two circles in each expirement are a distance $d_1$ apart.

## Question 1

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

### Overview

The responses were expected to demonstrate the ability to:

- Draw a free-body diagram indicating the forces exerted on a nonconducting, positively charged sphere hanging from a string near another positively charged sphere.
- Derive the relationship between the distance between two charged spheres and the angle $\theta$ of the string to validate a given expression for distance in terms of $\theta$, requiring the application of Newton's second law in two dimensions.
- Calculate the tension in the string using an appropriate application of Coulomb's law.
- Draw a best-fit line that shows the trend of given data.
- Calculate the slope of the best-fit line and use the slope to find an experimental value of permittivity.
- Draw a representation of polarization on a sphere.
- Explain how charges move on a conducting sphere when near another charged sphere.
- Describe the motion of a charged conducting sphere when near another charged sphere.

**Sample: 1A**
**Score: 15**

Part (a) earned 2 points. The first point was earned for correctly showing an arrow to the right labeled for the electrostatic force. The second point was earned for correctly showing a downward arrow labeled for the gravitational force and an arrow pointing up and to the left labeled for the tension force. Part (b) earned 3 points. The first point was earned for correctly equating the horizontal component of tension to the electrostatic force. The second point was earned for correctly equating the vertical component of tension to the gravitational force. The third point was earned for correctly using both horizontal and vertical force equations to find an expression for the distance $d$. Part (c) earned 2 points. The first point was earned for correctly applying Coulomb's law for the electrostatic force. The second point was earned for correctly substituting numerical values in a correct and consistent expression for tension. Part (d) earned 4 points. The first point was earned for correctly including an appropriate student drawn best-fit line that shows the trend of the data. The second point was earned for correctly calculating the slope using two points from the best-fit line. The third point was earned for correctly relating the slope and given equation. The fourth point was earned for correctly substituting the slope into a correct equation to find an experimental value of $\varepsilon_0$. Part (e) earned 4 points. The first point was earned for correctly showing a "$+$" sign on the left side of the sphere. The second point was earned for correctly explaining that the charges on Sphere $3$ move due to the repulsive force from Sphere $2$. The third point was earned for indicating a correct selection and including an attempt at a relevant justification. The fourth point was earned for correctly stating that the greater charge separation results in a smaller force, which results in a smaller angle.

## Question 1 (continued)

**Sample: 1B**
**Score: 7**

Part (a) earned 2 points. The first point was earned for correctly showing an arrow to the right labeled for the electrostatic force. The second point was earned for correctly showing a downward arrow labeled for the gravitational force and an arrow pointing up and to the left labeled for the tension force. Part (b) earned no points. The first point was not earned because the response does not equate the horizontal component of tension to the electrostatic force. The second point was not earned because the response does not equate the vertical component of tension to the gravitational force. The third point was not earned because the response does not show an attempt to solve a system of equations. Part (c) earned 2 points. The first point was earned for correctly applying Coulomb's law for the electrostatic force. The second point was earned for correctly substituting numerical values in a correct and consistent expression for tension. Part (d) earned 1 point for including an appropriate student drawn best-fit line that shows the trend of the data. The second point was not earned because the response does not include a calculation of slope using two points from the best-fit line. The third point was not earned because the response does not include showing a relationship between the slope and given equation. The fourth point was not earned because the response does not include using the slope to calculate an experimental value of $\varepsilon_0$. Part (e) earned 2 points. The first point was earned for correctly showing a "+" sign on the left side of the sphere. The second point was earned for correctly explaining that the charges on Sphere 3 move due to the repulsive force from Sphere 2. The third point was not earned because the response does not include a correct selection. The fourth point was not earned because the response does not include a correct justification.

**Sample: 1C**
**Score: 2**

Part (a) earned no points. The first point was not earned because the response does not include an arrow representing the electrostatic force. The second point was not earned because the response does not draw the tension force arrow up and to the left. Part (b) earned no points. The first point was not earned because the response does not equate the horizontal component of tension to the electrostatic force. The second point was not earned because the response does not equate the vertical component of tension to the gravitational force. The fourth point was not earned because the response does not show an attempt to solve a system of equations. Part (c) earned no points. The first point was not earned because the response does not indicate an application of Coulomb's law. The second point was not earned because the response does not include an expression for tension. Part (d) earned 1 point for correctly including an appropriate student drawn best-fit line that shows the trend of the data. The second point was not earned because the response does not include a calculation of slope using two points from the best-fit line. The third point was not earned because the response does not include showing a relationship between the slope and given equation. The fourth point was not earned because the response does not include using the slope to calculate an experimental value of $\varepsilon_0$. Part (e) earned 1 point for correctly showing a "+" sign on the left side of the sphere. The second point was not earned because the response does not include an explanation that the charges on Sphere 3 move due to the electrostatic force from Sphere 2. The third point was not earned because the response does not include a correct selection. The fourth point was not earned because the response does not include a correct justification.