2021

AP® Physics C: Electricity and Magnetism

Sample Student Responses and Scoring Commentary

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Free Response Question 2

- ☑ **Scoring Guideline**
- ☑ **Student Samples**
- ☑ **Scoring Commentary**

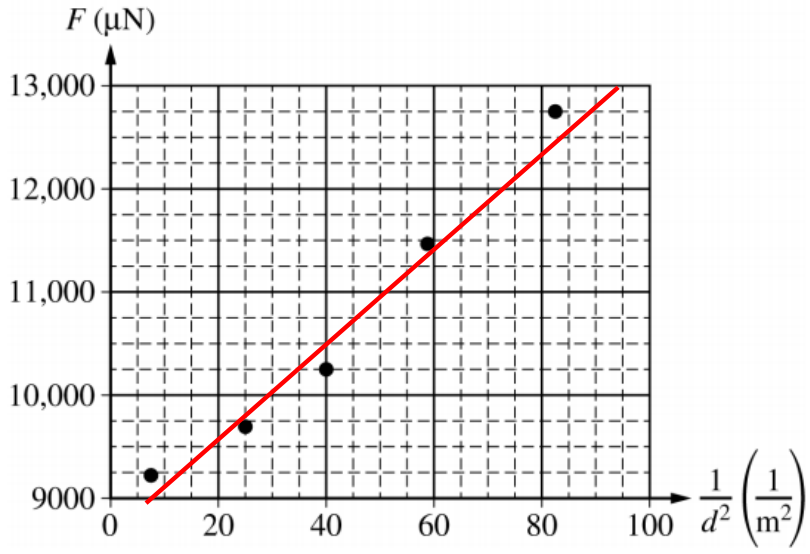
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Question 2: Free-Response Question — 15 points

(a) i. For drawing an appropriate best-fit line **1 point**

Example response for part (a)(i)



ii. For calculating the slope using two points from the best-fit line **1 point**

$$slope = m = \frac{\Delta y}{\Delta x} = \frac{(12{,}000 - 10{,}500)\ \mu\text{N}}{(72 - 40)\ \text{m}^{-2}} = 4.7 \times 10^{-5}\ \text{N•m}^2$$

For correctly relating the slope to the charge **1 point**

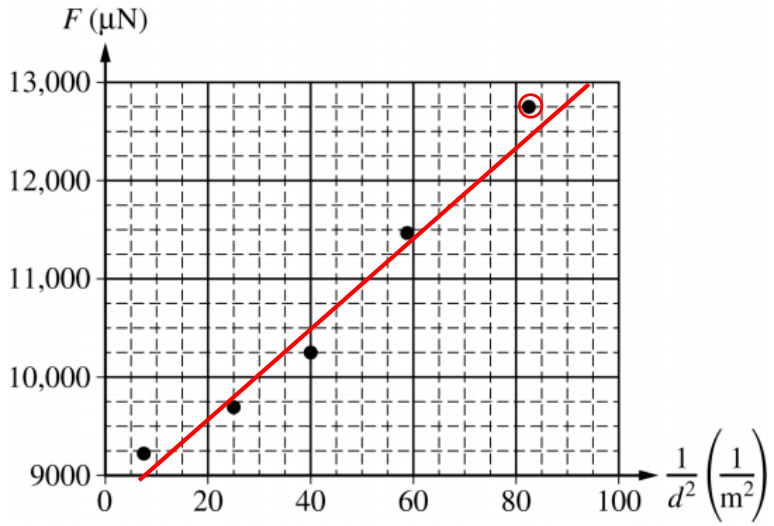
$$F = \frac{kQ^2}{r^2} \therefore \text{slope} = kQ^2$$

For correctly calculating the charge consistent with the slope from the best-fit line **1 point**

$$Q = \sqrt{\frac{\text{slope}}{k}} = \sqrt{\frac{\left(4.7 \times 10^{-5}\ \text{N•m}^2\right)}{\left(9 \times 10^{9}\ \text{N•m}^2/\text{C}^2\right)}} = 7.2 \times 10^{-8}\ \text{C}$$

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(a)	**iii.**	For drawing a circle around the appropriate data point	**1 point**



	iv.	For a correct answer From the graph, $\frac{1}{d^2} = 82.5\ \text{m}^{-2}$ $d = 0.11\ \text{m}$	**1 point**
	v.	For indicating that the *y*-intercept should be the weight of the conducting sphere and insulating rod	**1 point**
		For a correct justification	**1 point**

Example responses for part (a)(v).

When the spheres are infinitely far apart, there is no electric force between them. The only force recorded by the balance must be the weight of the lower sphere and insulating rod.

OR

The scale is zeroed before the insulating rod, and lower sphere are placed on it, so the nonzero y-intercept is their weight.

	Total for part (a)	**8 points**
(b)	For selecting "Yes" and providing a correct justification	**1 point**

Example response for part (b)

Because the later force measurements are lower than the expected values on the best-fit line, then a decrease in charge could explain the discrepancy seen in the data.

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(c)	**i.**	For correctly indicating the position of the excess positive charges	**1 point**
		For correctly indicating that the net charge is positive	**1 point**

Example response for part (c)(i)





	ii.	For a correct justification	**1 point**

Example response for part (c)(ii)

On a conductor, excess charges are free to move and will repel each other. The excess charges in the sphere will rearrange themselves until they are as far apart from each other as possible; thus, the repelling force decreases.

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

(d)	**i.**	For appropriately indicating the position of the excess charges on both spheres	**1 point**





	ii.	For selecting "Less than" and attempting a relevant justification	**1 point**
		For a correct justification	**1 point**

Example response for part (d)

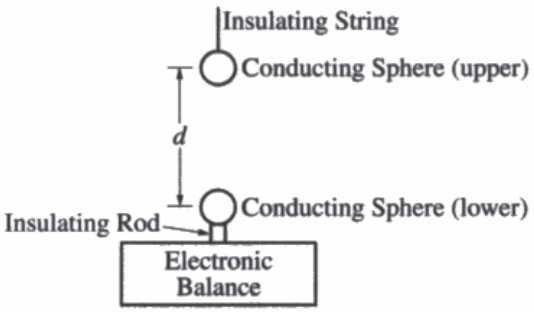
Because the opposite charged spheres will attract each other, this will decrease the upward normal force exerted by the scale on the lower sphere; thus, the reading on the scale will be less than when the spheres had the same charge.

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

Total for question 2 **15 points**

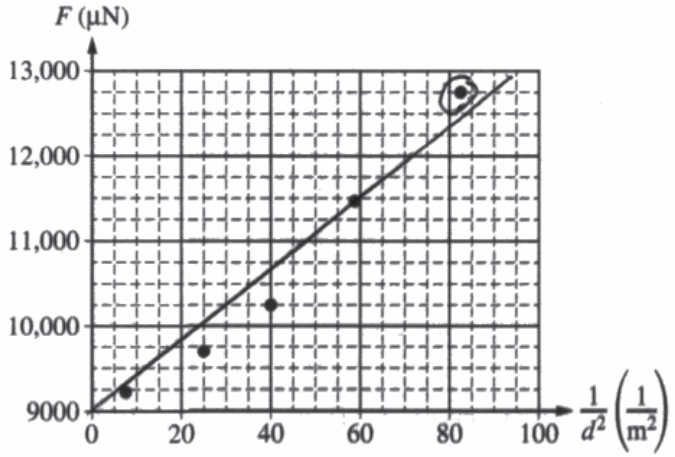
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Begin your response to **QUESTION 2** on this page.



2. Students perform an experiment to study the force between two charged objects using the apparatus shown above, which contains two identical conducting spheres. The upper sphere is attached to an insulating string, which can be used to move the sphere downward. The lower sphere sits on an insulating rod, which is on an electronic balance. The electronic balance is zeroed before the lower sphere and insulating rod are in place.

For the first trial, a charge of Q is placed on each sphere and then the upper sphere is slowly moved downward. The students measure the distance d between the centers of the spheres and the magnitude F of the force that appears on the electronic balance. The recorded data are shown on the graph of F as a function of $\frac{1}{d^2}$ shown below.



(a)

i. Draw a line that represents the best fit to the points shown.

ii. Use the graph to calculate the charge Q.

$\text{slope} = \frac{11,500\ \mu N}{60\ \frac{1}{m^2}} = 0.59\ N \cdot m^2$

$Q = \sqrt{\frac{Fd^2}{k}} = \sqrt{\frac{\text{slope}}{k}} = 8.76\ \mu C$

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iii. On the graph on the previous page, draw a circle around the data point that was taken when the distance between the centers of the spheres was the least.

iv. Determine the distance between the centers of the spheres for the data point indicated above.

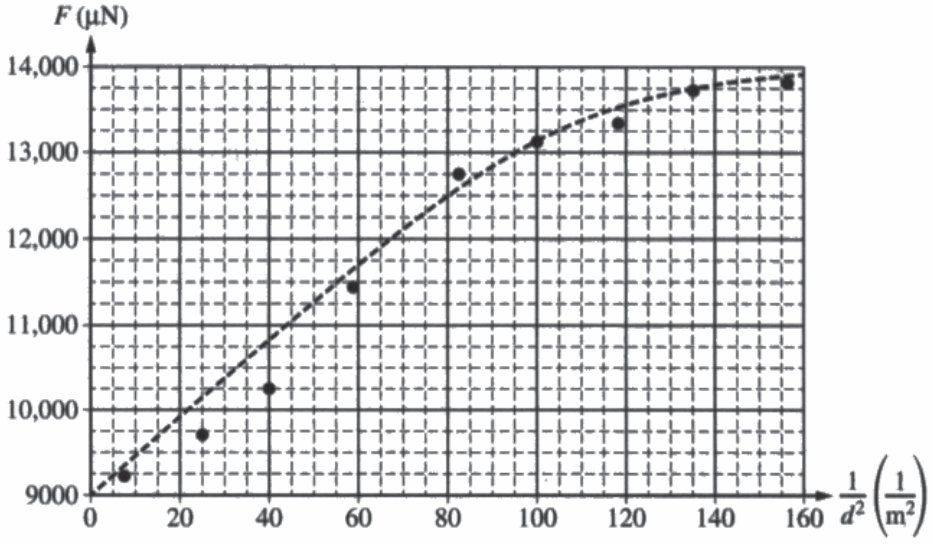
$\frac{1}{d^2} = 81 \frac{1}{m^2}$ $d = 0.11$ m

v. What physical quantity does the vertical intercept represent?

the weight of the lower sphere and insulating rod

Justify your answer.

The vertical intercept represents the force when the top sphere is infinitely far away, so the only force acting on the scale is the weight of the lower sphere and insulating rod.



The experiment is extended by collecting additional data points, which appear on the right side of the graph shown above. The new data points do not follow the linear pattern seen with the first points. The group of students tries to explain this discrepancy.

(b) One student suspects that charge is slowly leaking off the top sphere. Could this explain the discrepancy?

X Yes ____ No

Justify your answer.

If the top sphere's charge decreases, then the force also decreases, as seen in the graph because of the curve of best fit falling below a straight line. Therefore, leaking charge could explain the discrepancy.

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(c) A second student suspects that the excess charges have rearranged themselves, polarizing the spheres.

i. On the circles representing the spheres below, use a single "+" sign on each sphere to represent the locations of highest concentration of the excess positive charges.



ii. Explain how this rearrangement could be responsible for the discrepancy.

Because the positive charges are farther away, the force between them decreases, which explains the discrepancy.

(d) A third student suggests that the experiment be modified so that the top sphere is given a negative charge that is equal in magnitude to the positive charge given to the bottom sphere.

i. On the circles representing the spheres below, use a single "+" sign on the bottom sphere to represent the location of highest concentration of the excess positive charges. Use a single "–" sign on the top sphere to represent the location of the highest concentration of the excess negative charges.



ii. For a separation distance equal to that of the data point indicated in part (a)(iii), would the magnitude of the force reading with spheres of opposite charges be greater than, less than, or equal to the magnitude of the force reading with spheres of the same charges?

____ Greater than X Less than ____ Equal to

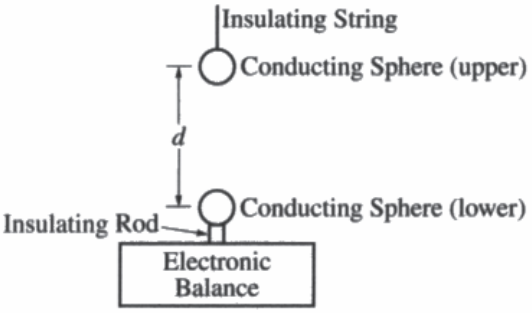
Justify your answer.

With opposite charges, the electric force and weight force oppose each other, which decreases the magnitude of the force when compared to the same charges.

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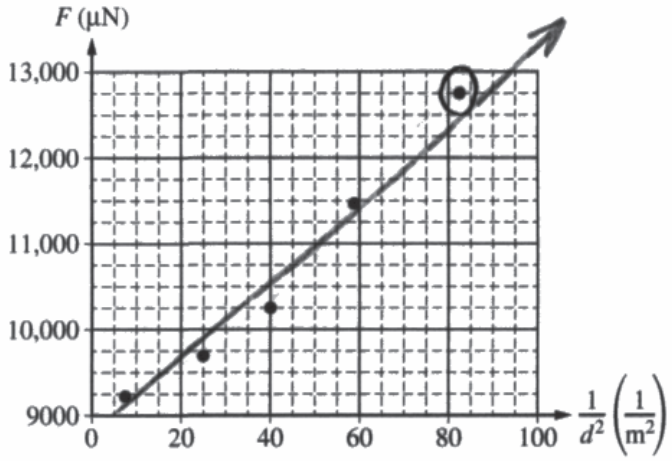
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2. Students perform an experiment to study the force between two charged objects using the apparatus shown above, which contains two identical conducting spheres. The upper sphere is attached to an insulating string, which can be used to move the sphere downward. The lower sphere sits on an insulating rod, which is on an electronic balance. The electronic balance is zeroed before the lower sphere and insulating rod are in place.

For the first trial, a charge of Q is placed on each sphere and then the upper sphere is slowly moved downward. The students measure the distance d between the centers of the spheres and the magnitude F of the force that appears on the electronic balance. The recorded data are shown on the graph of F as a function of $\frac{1}{d^2}$ shown below.



(a)

i. Draw a line that represents the best fit to the points shown.

ii. Use the graph to calculate the charge Q.

$F = k\frac{Q^2}{d^2}$

$\frac{1}{d^2} \approx 60$

$k = 9 \cdot 10^9$

$F_{\mu N} \approx 11,500\,\mu N$

$11500\,\mu N = k(60)(Q^2)$

$Q = 1.46 \cdot 10^{-7}\,C$

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iii. On the graph on the previous page, draw a circle around the data point that was taken when the distance between the centers of the spheres was the least.

iv. Determine the distance between the centers of the spheres for the data point indicated above.

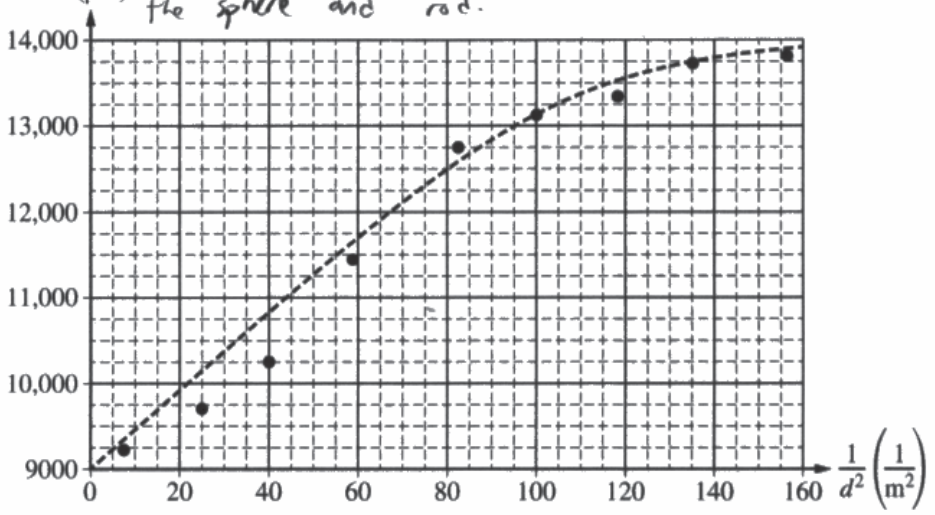
$\frac{1}{d^2} \approx 83 \quad d = \frac{1}{\sqrt{83}} \approx$ (0.11m)

v. What physical quantity does the vertical intercept represent?

The weight of the lower sphere and insulating rod.

Justify your answer.

The balance was zeroed before placing the sphere and insulating rod on the balance, and even if the charge is zero, the vertical intercept represents the force of the weight of the sphere and rod.



The experiment is extended by collecting additional data points, which appear on the right side of the graph shown above. The new data points do not follow the linear pattern seen with the first points. The group of students tries to explain this discrepancy.

(b) One student suspects that charge is slowly leaking off the top sphere. Could this explain the discrepancy?

___ Yes ___X___ No

Justify your answer.

The top sphere is connected with an insulating string, which does not allow charge to escape.

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(c) A second student suspects that the excess charges have rearranged themselves, polarizing the spheres.

i. On the circles representing the spheres below, use a single "+" sign on each sphere to represent the locations of highest concentration of the excess positive charges.



ii. Explain how this rearrangement could be responsible for the discrepancy.

This reduces the Force pushing these two spheres apart, reducing the experimental force on the balance.

(d) A third student suggests that the experiment be modified so that the top sphere is given a negative charge that is equal in magnitude to the positive charge given to the bottom sphere.

i. On the circles representing the spheres below, use a single "+" sign on the bottom sphere to represent the location of highest concentration of the excess positive charges. Use a single "–" sign on the top sphere to represent the location of the highest concentration of the excess negative charges.



ii. For a separation distance equal to that of the data point indicated in part (a)(iii), would the magnitude of the force reading with spheres of opposite charges be greater than, less than, or equal to the magnitude of the force reading with spheres of the same charges?

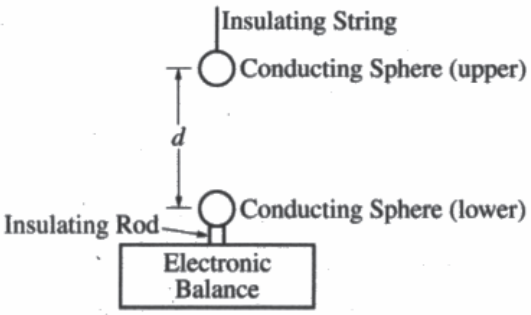
____ Greater than X Less than ____ Equal to

Justify your answer.

Instead of pushing away from each other, these two spheres would attract. This would cause a reduction in the value of F on the balance due to the lower sphere being pulled upwards by the upper sphere.

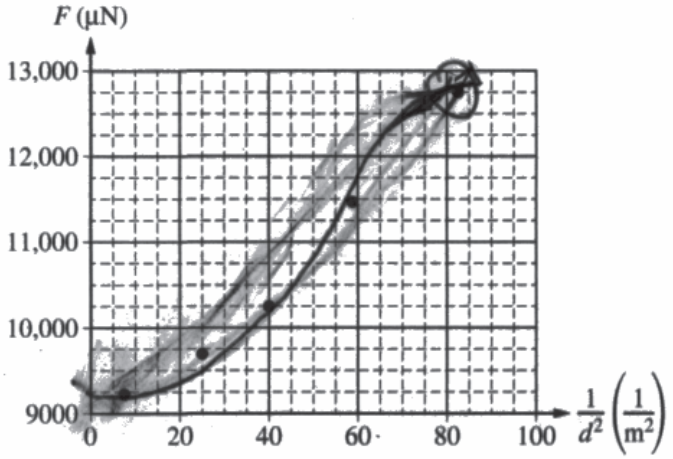
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2. Students perform an experiment to study the force between two charged objects using the apparatus shown above, which contains two identical conducting spheres. The upper sphere is attached to an insulating string, which can be used to move the sphere downward. The lower sphere sits on an insulating rod, which is on an electronic balance. The electronic balance is zeroed before the lower sphere and insulating rod are in place.

For the first trial, a charge of Q is placed on each sphere and then the upper sphere is slowly moved downward. The students measure the distance d between the centers of the spheres and the magnitude F of the force that appears on the electronic balance. The recorded data are shown on the graph of F as a function of $\frac{1}{d^2}$ shown below.



(a)

i. Draw a line that represents the best fit to the points shown.

ii. Use the graph to calculate the charge Q.

$F = k \frac{Q^2}{r^2}$

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

iii. On the graph on the previous page, draw a circle around the data point that was taken when the distance between the centers of the spheres was the least.

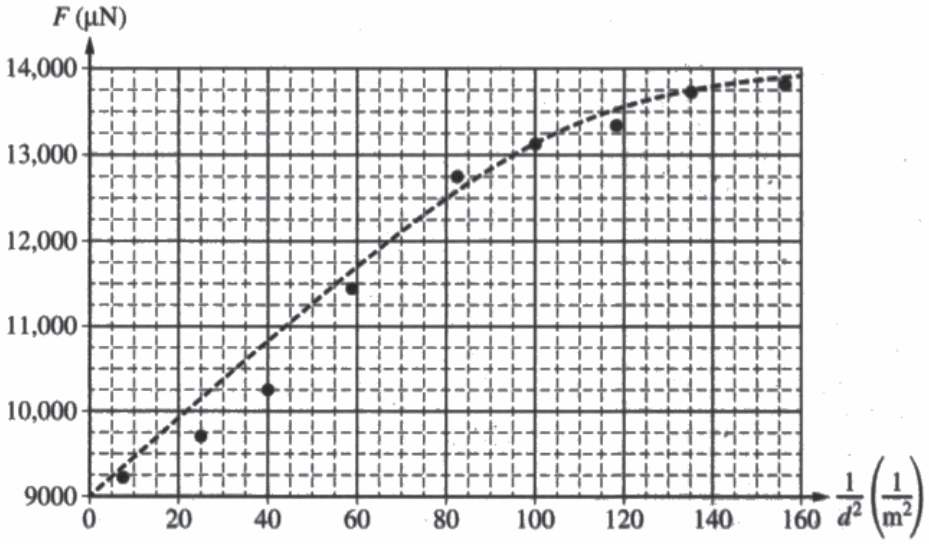
iv. Determine the distance between the centers of the spheres for the data point indicated above.

$\frac{1}{(B_0)^2} = 1.5625 \times 10^{-4}$

v. What physical quantity does the vertical intercept represent?

The point where both spheres meet

Justify your answer.



The experiment is extended by collecting additional data points, which appear on the right side of the graph shown above. The new data points do not follow the linear pattern seen with the first points. The group of students tries to explain this discrepancy.

(b) One student suspects that charge is slowly leaking off the top sphere. Could this explain the discrepancy?

___ Yes ✓ No

Justify your answer.

charge couldn't leave in given situation

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(c) A second student suspects that the excess charges have rearranged themselves, polarizing the spheres.

i. On the circles representing the spheres below, use a single "+" sign on each sphere to represent the locations of highest concentration of the excess positive charges.



ii. Explain how this rearrangement could be responsible for the discrepancy.

with positive charge on both spheres facing eachother the spheres would push against eachother via electric field

(d) A third student suggests that the experiment be modified so that the top sphere is given a negative charge that is equal in magnitude to the positive charge given to the bottom sphere.

i. On the circles representing the spheres below, use a single "+" sign on the bottom sphere to represent the location of highest concentration of the excess positive charges. Use a single "–" sign on the top sphere to represent the location of the highest concentration of the excess negative charges.



ii. For a separation distance equal to that of the data point indicated in part (a)(iii), would the magnitude of the force reading with spheres of opposite charges be greater than, less than, or equal to the magnitude of the force reading with spheres of the same charges?

✓ Greater than _____ Less than _____ Equal to

Justify your answer.

opposite charges would provide greater force

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:

- Construct an appropriate best-fit line for experimental data provided in graphical form.
- Utilize math skills to calculate a slope, interpret a graph containing inverse quantities, and correctly use the units given for experimental data to calculate an unknown quantity.
- Relate the slope of a linearized graph to appropriate physical quantities.
- Relate a mathematical representation (e.g., best fit line's vertical intercept) to a physical quantity stemming from the experimental design.
- Recognize how nonideal experimental behavior that occurs in a laboratory setting and is manifested in graphs of experimental data.
- Analyze experimental evidence to see if it is consistent with a proposed claim.
- Construct and justify a physical representation of the location of excess charge in polarized conductors that is consistent with a proposed claim.
- Use Coulomb's Law to relate electric force to distance between charges and magnitude of charges.
- Recognize net force as a vector sum of gravitational and electric forces.
- Demonstrate an understanding of the vector nature (attraction or repulsion) of electric charge interactions.
- Understand the resulting location of excess charge in polarized objects.

Sample: E Q2 A
Score: 13

Part (a)(i) earned 1 point. The response earned 1 point for drawing a straight line that accurately shows the trend of the data. Part (a)(ii) earned one point. The response did not earn the first point because the slope calculation does not use two points on the best-fit line. The response earned the second point for relating the slope to KQ^2. The response did not earn the third point because the answer for Q is not in an accepted range (10^{-8} C). Part (a)(iii) earned 1 point. The response earned 1 point for circling the correct data point and no others. Part (a)(iv) earned 1 point. The response earned 1 point for stating a correct answer. Part (a)(v) earned 2 points. The response earned the first point for identifying the weight of lower sphere and insulating rod as the physical quantity represented by the vertical intercept. The response earned the second point for stating the balance reads only the weight when the electric force is zero. Part (b) earned 1 point. The response earned 1 point for checking "Yes" and implicitly using Coulomb's Law as evidence that the force would be lower than expected if the charge was decreasing. Part (c)(i) earned 2 points. The response earned the first point for drawing both "+" signs in the correct positions. The response earned the second point for indicating that the net charge is positive by drawing only "+" signs. Part (c)(ii) earned 1 point. The response earned 1 point for stating the increased distance between the charges in the polarized configuration results in a lower electric force. Part (d)(i) earned 1 point. The response earned 1 point for drawing the "–" and "+" sign in the correct positions. Part (d)(ii) earned 2 points. The response earned the first point for correctly checking "Less than" and attempting a relevant justification. The response earned the second point for stating that the electric force is attractive and reduces the value of the force reading on the balance.

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Question 2 (continued)

Sample: E Q2 B
Score: 9

Part (a)(i) earned 1 point. The response earned 1 point for drawing a straight line that accurately shows the trend of the data. Part (a)(ii) earned no points. The response did not earn the first point because no slope calculation is shown. The response did not earn the second point because it does not relate the slope to the charge Q. The response did not earn the third point because the answer for Q is not in an appropriate range (10^{-8} C). Part (a)(iii) earned 1 point. The response earned 1 point for circling the correct data point and no others. Part (a)(iv) earned 1 point. The response earned 1 point for stating a correct answer. Part (a)(v) earned 2 points. The response earned the first point for identifying the weight of lower sphere and insulating rod as the physical quantity represented by the vertical intercept. The response earned the second point for stating the balance was initially zeroed and will read only the sphere and rod's gravitational force. Part (b) earned no points. The response earned no points because the check mark and justification are incorrect. Part (c)(i) earned 1 point. The response did not earn the first point because the "+" signs are not in the correct positions. The response earned the second point for indicating that the net charge is positive by drawing only "+" signs. Part (c)(ii) earned no points. The response earned no points because the justification is incorrect. Part (d)(i) earned 1 point. The response earned 1 point for drawing the "–" and "+" sign in the correct positions. Part (d)(ii) earned 2 points. The response earned the first point for correctly checking "Less than" and attempting a relevant justification. The response earned the second point for stating that the electric force is attractive and reduces the value of the force reading on the balance.

Sample: E Q2 C
Score: 3

Part (a)(i) earned no points. The response earned no points because a nonlinear best-fit line is drawn. Part (a)(ii) earned no points. The response did not earn the first point because no slope calculation is shown. The response did not earn the second point because it does not relate the slope to the charge Q. The response did not earn the third point because there is no calculated answer for Q. Part (a)(iii) earned 1 point. The response earned 1 point for circling the correct data point and no others. Part (a)(iv) earned no points. The response earned no points because the answer is incorrect. Part (a)(v) earned no points. The first point was not earned because the response indicates an incorrect physical quantity to represent the vertical intercept. The response did not earn the second point because no justification is attempted. Part (b) earned no points. The response earned no points because the check mark and justification are incorrect. Part (c)(i) earned 1 point. The response did not earn the first point because both "+" signs are not in the correct positions. The response earned the second point for indicating that the net charge is positive by drawing only "+" signs. Part (c)(ii) earned no points. The response earned no points because the justification is incorrect. Part (d)(i) earned 1 point. The response earned 1 point for drawing the "–" and "+" sign in the correct positions. Part (d)(ii) earned no points. The response did not earn the first point because the check mark is incorrect. The response did not earn the second point because the justification is incorrect.

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