2024

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 using a correct equation for electric flux — **1 point**

Example Response

$$\Phi_E = \frac{Q}{\varepsilon_0}$$

For the correct numerical answer — **1 point**

Scoring Note: This point can be earned if a negative sign is included in the final answer or if units are missing and/or the units are incorrect.

Example Response

$$|\Phi_E| = 226\,\frac{\mathrm{N \cdot m^2}}{\mathrm{C}}$$

Example Solution

$$\oint \vec{E} \cdot d\vec{A} = \frac{Q}{\varepsilon_0}$$

$$\Phi_E = \frac{Q}{\varepsilon_0}$$

$$\Phi_E = \frac{-2.0 \times 10^{-9}\ \mathrm{C}}{8.85 \times 10^{-12}\ \dfrac{\mathrm{C^2}}{\mathrm{N \cdot m^2}}}$$

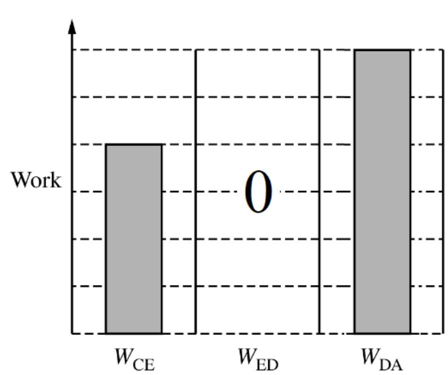
$$|\Phi_E| = 226\,\frac{\mathrm{N \cdot m^2}}{\mathrm{C}}$$

Total for part (a) — 2 points

(b)(i) For indicating that $W_{\mathrm{ED}} = 0$ — **1 point**

For drawing a bar representing W_{DA} that has a height of six units — **1 point**

Example Response



(b)(ii)	For using an equation that relates the electric field to potential difference	**1 point**

Scoring Note: This point can be earned if the response begins with a correct relationship between electric field and potential difference in which numerical values are already substituted.

Example Responses

$$E_x = -\frac{dV}{dx} \quad \textbf{OR} \quad |E_x| = \left|-\frac{dV}{dx}\right| \quad \textbf{OR} \quad |E_x| = \left|-\frac{\Delta V}{\Delta x}\right| \quad \textbf{OR} \quad \Delta V = -\int \vec{E} \cdot d\vec{r}$$

For correct substitutions of values of electric potential and the distance between equipotential lines that can be used to calculate the approximate magnitude of the electric field at Position B	**1 point**

Example Response

$$|E_x| = \left|-\frac{20.0\text{ V} - 0.0\text{ V}}{0.65\text{ m}}\right|$$

Example Solution

$$E_x = -\frac{dV}{dx}$$

$$|E_x| = \left|-\frac{dV}{dx}\right|$$

$$|E_x| = \left|-\frac{\Delta V}{\Delta x}\right|$$

$$|E_x| = \left|-\frac{20.0\text{ V} - 0.0\text{ V}}{0.65\text{ m}}\right|$$

$$|E_x| = 31\,\frac{\text{V}}{\text{m}}$$

Total for part (b) 4 points

(c)	For selecting only $+y$ with an attempt at a relevant justification	**1 point**
	For indicating that the direction of the electric field vector is perpendicular to a line that is tangent to the equipotential line at Position D	**1 point**
	For indicating one of the following: • The test charge moves from a higher electric potential to a lower electric potential. • The test charge and the sphere have charges of opposite sign. • The test charge moves in the direction of the electric field, which is directed upward.	**1 point**

Example Response

$+y$. *The direction of an electric field vector is perpendicular to an equipotential line. Because the test charge has a positive charge, the test charge would move from a position of higher electric potential to a position of lower electric potential when an electric force is exerted on the test charge. Therefore, at Position* D , *the electric force is upward because that is the direction that is perpendicular to the equipotential line and in the direction of decreasing electric potential.*

Total for part (c) 3 points

(d)(i)	For using an appropriate equation for determining the electric potential from a line of uniform charge	**1 point**

Example Responses

$$V = \frac{1}{4\pi\varepsilon_0}\sum\frac{q_i}{r_i} \quad \textbf{OR} \quad V = \frac{1}{4\pi\varepsilon_0}\int\frac{dq}{r} \quad \textbf{OR} \quad \Delta V = -\int \vec{E}\cdot d\vec{r}$$

For a correct determination of r , the distance between Point P and a point on the line of uniform charge **1 point**

Example Responses

$$V_{\text{P}} = k\sum\frac{Q}{x_{\text{P}} - x} \quad \textbf{OR} \quad V_{\text{P}} = k\int\left(\frac{1}{x_{\text{P}} - x}\right)dq$$

For a correct integral with λdx substituted for dq **1 point**

Example Response

$$V_{\text{P}} = k\lambda\int\left(\frac{1}{x_{\text{P}} - x}\right)dx$$

For the correct limits of integration **1 point**

Example Response

$$V_{\text{P}} = k\lambda\int_0^{4L}\left(\frac{1}{x_{\text{P}} - x}\right)dx$$

Example Solutions

$$V = \frac{1}{4\pi\varepsilon_0}\sum\frac{q_i}{r_i}$$

$$V_\text{P} = k\int\left(\frac{1}{x_\text{P} - x}\right)dq$$

$$dq = \lambda\, dx$$

$$V_\text{P} = k\lambda\int\left(\frac{1}{x_\text{P} - x}\right)dx$$

$$V_\text{P} = k\lambda\int_0^{4L}\left(\frac{1}{x_\text{P} - x}\right)dx$$

$$V_\text{P} = -k\lambda\ln(x_\text{P} - x)\,\Big|_0^{4L} = k\lambda\ln(x_\text{P} - x)\,\Big|_{4L}^{0}$$

$$V_\text{P} = k\lambda\ln\left(\frac{x_\text{P}}{x_\text{P} - 4L}\right)$$

OR

$$\Delta V = -\int\vec{E}\cdot d\vec{r}$$

$$E(x) = \int\frac{k}{r^2}\,dq$$

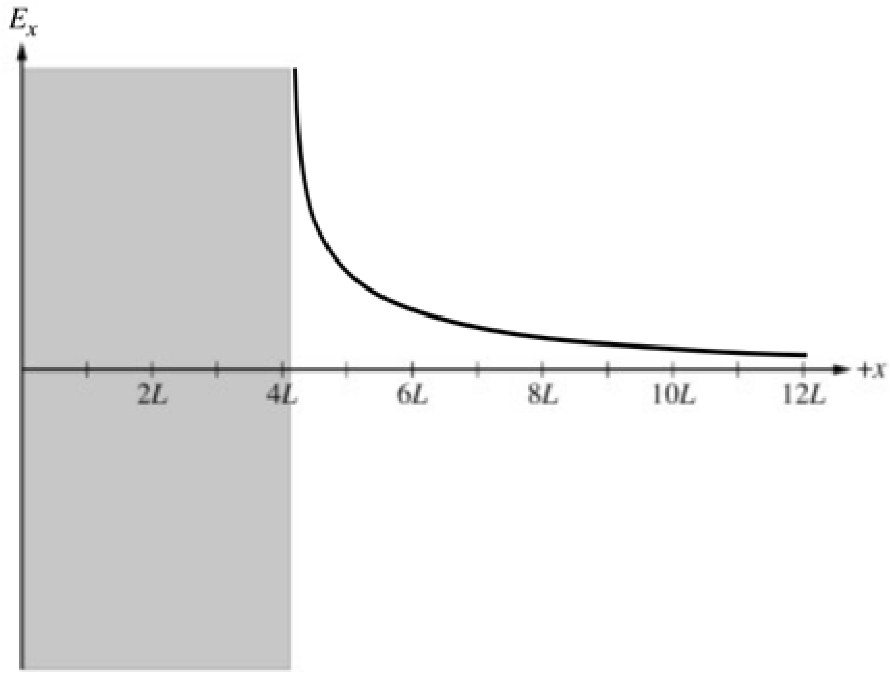
$$E(x) = \int_0^{4L}\frac{k\lambda}{(x - x')^2}\,dx' = k\lambda\left(\frac{1}{x - 4L} - \frac{1}{x}\right)$$

$$V_\text{P} = -\int_\infty^{x_\text{P}}E(x)\,dx = -k\lambda\int_\infty^{x_\text{P}}\left(\frac{1}{x - 4L} - \frac{1}{x}\right)dx$$

$$V_\text{P} = k\lambda\ln\left(\frac{x_\text{P}}{x_\text{P} - 4L}\right)$$

(d)(ii)	For sketching a curve or line that continually approaches the horizontal axis as position increases	**1 point**
	For sketching a concave up curve that is always positive	**1 point**

Example Response



Total for part (d) 6 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.

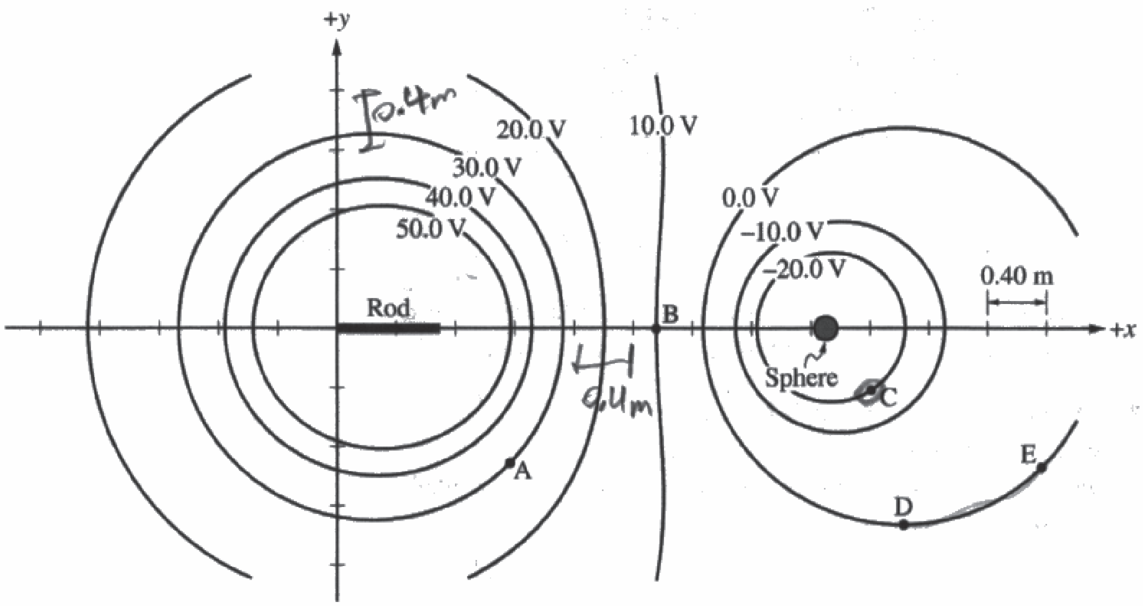


Figure 1

1. A nonconducting rod of uniform positive linear charge density is near a sphere with charge −2.0 nC. The rod and sphere are held at rest on the x-axis, as shown in Figure 1. Equipotential lines and positions A, B, C, D, and E are labeled. Adjacent tick marks on the x-axis and the y-axis are 0.40 m apart.

   (a) **Calculate** the absolute value of the electric flux through the Gaussian surface whose cross section is the −20.0 V equipotential line.

$$\Phi = \frac{Q_{in}}{\epsilon_0} = \frac{-2E-9C}{8.85E-12} = 225.99\ Nm^2/C$$

Q5271/2

Question 1

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

A positive test charge (not shown) is placed and held at rest at Position C. An external force is applied to the test charge to move the test charge to different positions in the order of C→E→D→A. The test charge is momentarily held at rest at each position.

(b) The bar shown in Figure 2 represents the absolute value of the work W_{CE} done by the external force on the test charge to move the test charge from Position C to Position E.

i. Complete the following tasks on Figure 2.

- Draw a bar to represent the relative absolute value of the work W_{ED} done by the external force on the test charge to move the test charge from Position E to Position D.
- Draw a bar to represent the relative absolute value of the work W_{DA} done by the external force on the test charge to move the test charge from Position D to Position A.
- The height of each bar should be proportional to the value of W_{CE}. If $W_{ED} = 0$ and/or $W_{DA} = 0$, write a "0" in the corresponding columns, as appropriate.

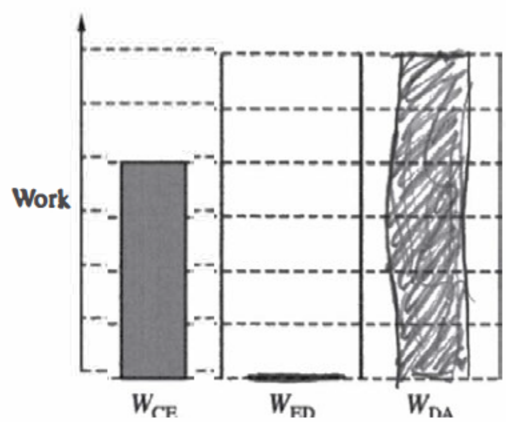


Figure 2

ii. Calculate the approximate magnitude of the x-component of the electric field at Position B.

$E_B = ?$

$E = -\frac{dV}{dx} = \frac{20\,V}{0.7\,m} = 28.57\ \text{J/C}$

Use a pencil or a pen with black

Question 1

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

The positive test charge is placed at Position D. The test charge is then released from rest.

(c) **Indicate** the direction (not components) of the net electric force exerted on the test charge immediately after the test charge is released from rest.

____ $+x$ __X__ $+y$ ____ Directly away from the sphere

____ $-x$ ____ $-y$ ____ Directly toward the sphere

Without using equations, **justify** your answer using physics principles.

E points in the direction of Decreasing potential, and is always perpendicular to lines of equivalent potential. Thus, E points up and exerts a force on the positive charge in the same direction

Question 1

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

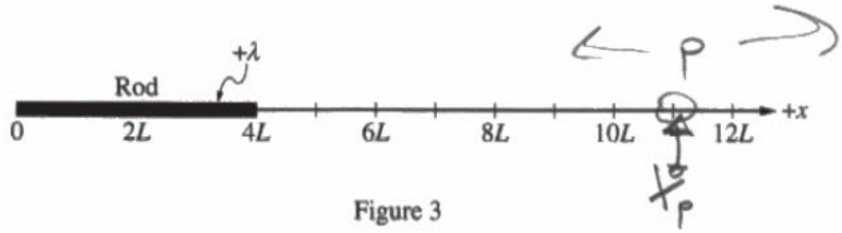


Figure 3

The sphere and the test charge are removed. The rod has length $4L$ and uniform positive linear charge density $+\lambda$. The rod is held at rest on the x-axis in the orientation shown in Figure 3. Position P (not shown) is located on the x-axis a distance x_P from the origin, where $x_P > 4L$.

(d) The electric potential V_P at x_P is $V_P = k\lambda \ln\left(\dfrac{x_P}{x_P - 4L}\right)$.

i. Using integral calculus, **derive** the expression for V_P provided.

$$V_P = ? = \frac{kq_i}{r_i} = \int \frac{k\,dq}{r} = k\lambda \int_{x_P-4L}^{x_P} \frac{dr}{r} = k\lambda \left[\ln(r)\right]_{x_P-4L}^{x_P}$$

$$\lambda = \frac{dq}{dr}$$

$$dq = \lambda\, dr$$

$$V_P = k\lambda\left[\ln(x_P) - \ln(x_P - 4L)\right]$$

$$V_P = k\lambda \ln\left(\frac{x_P}{x_P - 4L}\right)$$

Question 1

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

ii. On Figure 4, **sketch** a graph of the x-component E_x of the electric field from the rod as a function of x in the region $4L < x < 12L$.

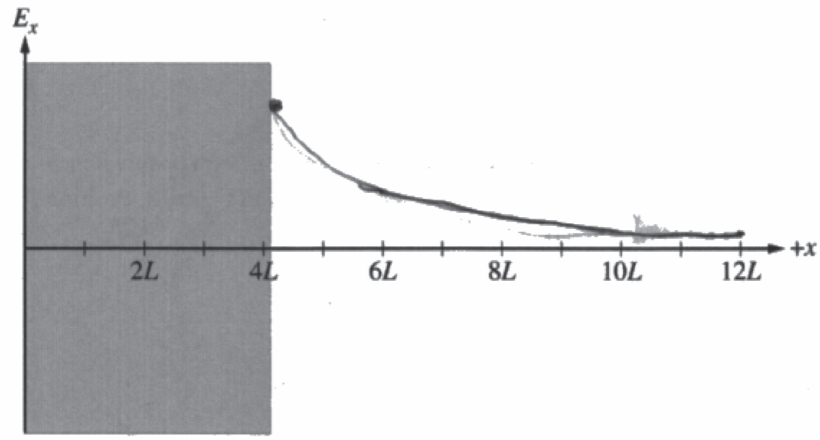


Figure 4

Hi :)

$$E = \frac{dV}{dx} = \frac{-d\,k\lambda \ln\left(\frac{x_p}{x_p - 4x}\right)}{dx}$$

$$\frac{-k\lambda}{}$$

Question 1

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

PHYSICS C: ELECTRICITY AND MAGNETISM

SECTION II

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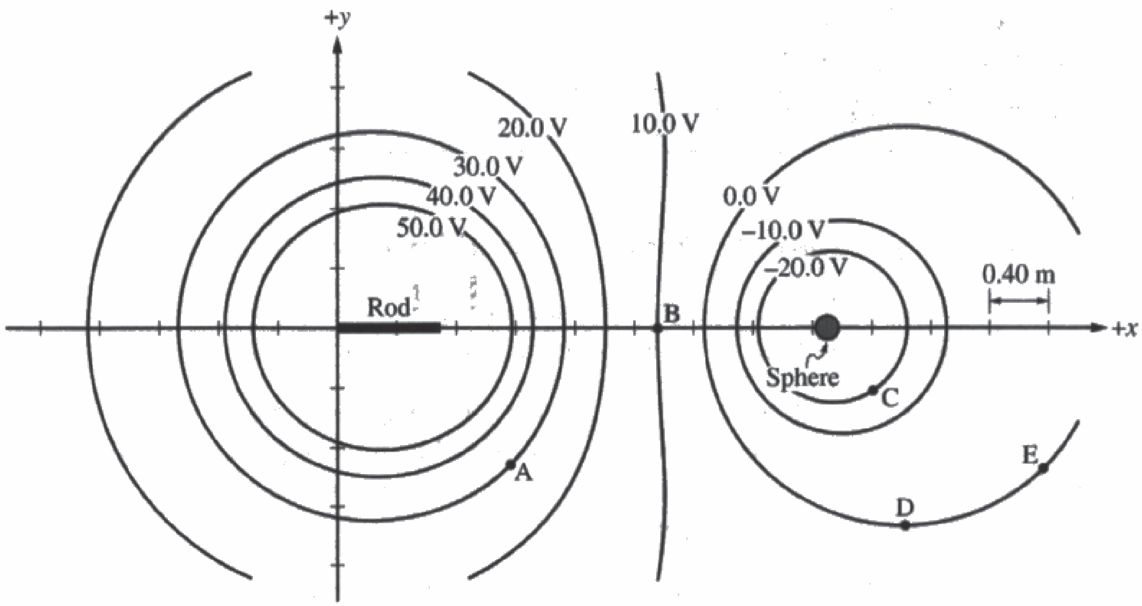

Figure 1

1. A nonconducting rod of uniform positive linear charge density is near a sphere with charge −2.0 nC. The rod and sphere are held at rest on the x-axis, as shown in Figure 1. Equipotential lines and positions A, B, C, D, and E are labeled. Adjacent tick marks on the x-axis and the y-axis are 0.40 m apart.

   (a) **Calculate** the absolute value of the electric flux through the Gaussian surface whose cross section is the −20.0 V equipotential line.

$$\oint E \cdot dA = \frac{Q}{\varepsilon_0} = \phi_E = \left|\frac{-2\times10^{-9}}{\varepsilon_0}\right| = 225.989 \ \frac{Nm^2}{C}$$

Question 1

Continue your response to QUESTION 1 on this page.

A positive test charge (not shown) is placed and held at rest at Position C. An external force is applied to the test charge to move the test charge to different positions in the order of C→E→D→A. The test charge is momentarily held at rest at each position.

(b) The bar shown in Figure 2 represents the absolute value of the work W_{CE} done by the external force on the test charge to move the test charge from Position C to Position E.

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- The height of each bar should be proportional to the value of W_{CE}. If $W_{ED} = 0$ and/or $W_{DA} = 0$, write a "0" in the corresponding columns, as appropriate.

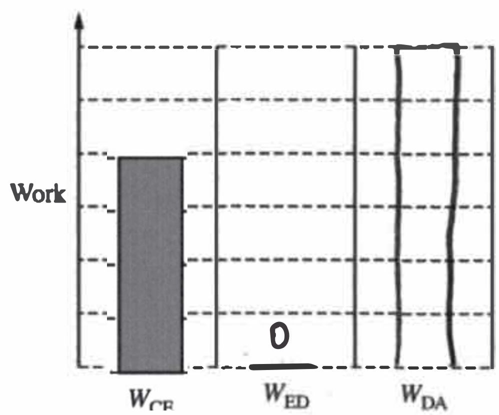

Figure 2

ii. **Calculate** the approximate magnitude of the x-component of the electric field at Position B.

$$E = \frac{+dV}{dx} = \frac{+\Delta V}{\Delta x} = \frac{+(20-0)}{0.4+0.2+0.1} = +28.571 \frac{N}{C}$$

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.

Q5271/3

Question 1

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

The positive test charge is placed at Position D. The test charge is then released from rest.

(c) **Indicate** the direction (not components) of the net electric force exerted on the test charge immediately after the test charge is released from rest.

____ $+x$ ____ $+y$ ____ Directly away from the sphere

____ $-x$ ____ $-y$ _X_ Directly toward the sphere

Without using equations, **justify** your answer using physics principles.

The positive test charge is attracted to the negatively charged sphere.

positive charges move towards decreasing potential and the E-field is pointed towards decreasing potential (charge moves in direction of field

5:05

Question 1

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

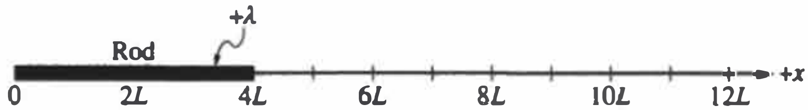

Figure 3

The sphere and the test charge are removed. The rod has length $4L$ and uniform positive linear charge density $+\lambda$. The rod is held at rest on the x-axis in the orientation shown in Figure 3. Position P (not shown) is located on the x-axis a distance x_P from the origin, where $x_P > 4L$.

(d) The electric potential V_P at x_P is $V_P = k\lambda \ln\left(\frac{x_P}{x_P - 4L}\right)$.

i. Using integral calculus, derive the expression for V_P provided.

$V_p = \frac{kQ}{r}$

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

Q5271/5

Question 1

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

ii. On Figure 4, **sketch** a graph of the x-component E_x of the electric field from the rod as a function of x in the region $4L < x < 12L$.

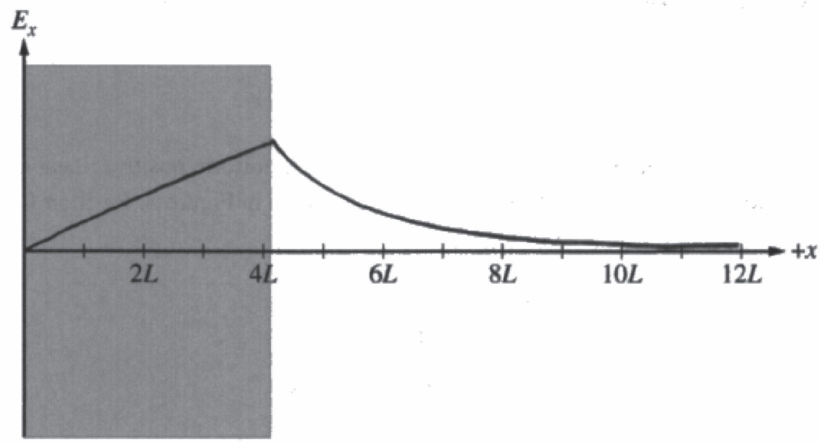

Figure 4

GO ON TO THE NEXT PAGE.

Question 1

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

PHYSICS C: ELECTRICITY AND MAGNETISM

SECTION II

Time—45 minutes

3 Questions

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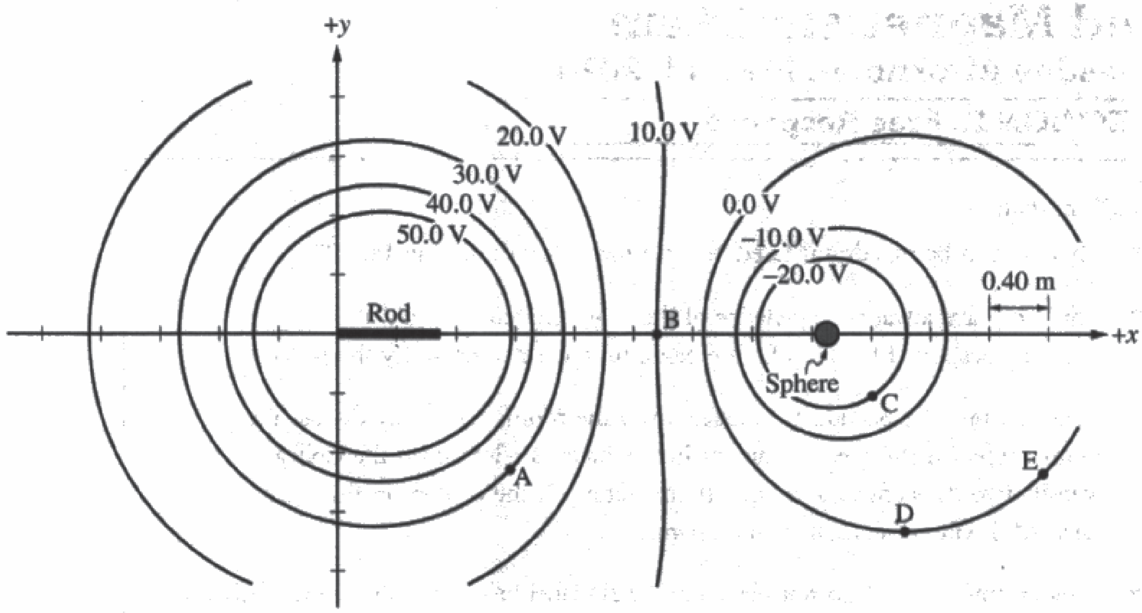

Figure 1

1. A nonconducting rod of uniform positive linear charge density is near a sphere with charge −2.0 nC. The rod and sphere are held at rest on the x-axis, as shown in Figure 1. Equipotential lines and positions A, B, C, D, and E are labeled. Adjacent tick marks on the x-axis and the y-axis are 0.40 m apart.

   (a) **Calculate** the absolute value of the electric flux through the Gaussian surface whose cross section is the −20.0 V equipotential line.

$$\mathcal{E} = \oint E \cdot d\ell = \frac{Q}{\varepsilon_0} \frac{d\Phi}{dt}$$

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.

A positive test charge (not shown) is placed and held at rest at Position C. An external force is applied to the test charge to move the test charge to different positions in the order of C→E→D→A. The test charge is momentarily held at rest at each position.

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i. Complete the following tasks on Figure 2.

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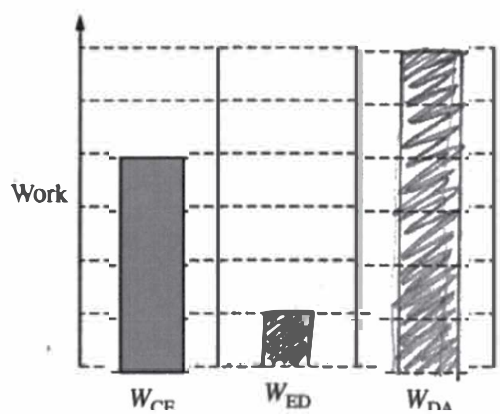
- **Draw** a bar to represent the relative absolute value of the work W_{DA} done by the external force on the test charge to move the test charge from Position D to Position A.
- The height of each bar should be proportional to the value of W_{CE}. If $W_{ED} = 0$ and/or $W_{DA} = 0$, write a "0" in the corresponding columns, as appropriate.



$W = \int_{3.8}^{4.8} F \cdot dr =$

Figure 2

ii. **Calculate** the approximate magnitude of the x-component of the electric field at Position B.

$\oint E \cdot dA = \frac{Q}{\varepsilon_0} = \frac{(2 \times 10^{-9})}{(8.85 \times 10^{-12})} = 225.989$

Question 1

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

The positive test charge is placed at Position D. The test charge is then released from rest.

(c) **Indicate** the direction (not components) of the net electric force exerted on the test charge immediately after the test charge is released from rest.

____ $+x$ _X_ $+y$ ____ Directly away from the sphere

____ $-x$ ____ $-y$ _X_ Directly toward the sphere

Without using equations, **justify** your answer using physics principles.

The charge will move towards the sphere since the sphere has negative charge, and oppositely charged objects attract.

GO ON TO THE NEXT PAGE.

Question 1

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

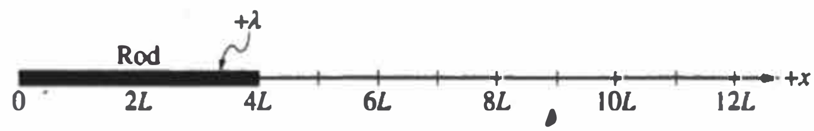


Figure 3

The sphere and the test charge are removed. The rod has length $4L$ and uniform positive linear charge density $+\lambda$. The rod is held at rest on the x-axis in the orientation shown in Figure 3. Position P (not shown) is located on the x-axis a distance x_P from the origin, where $x_P > 4L$.

(d) The electric potential V_P at x_P is $V_P = k\lambda \ln\left(\frac{x_P}{x_P - 4L}\right)$.

i. Using integral calculus, derive the expression for V_P provided.

$$V_P = k\lambda \ln\left[\frac{x_P}{x_P - 4L}\right]$$

GO ON TO THE NEXT PAGE.

Question 1

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

ii. On Figure 4, **sketch** a graph of the x-component E_x of the electric field from the rod as a function of x in the region $4L < x < 12L$.

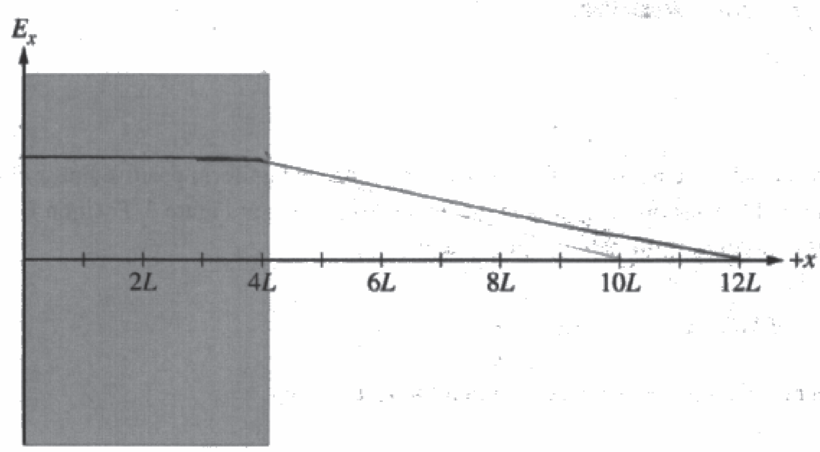


Figure 4

Question 1

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

Overview

- Responses should demonstrate comprehension of the concepts of electric flux and its relationship to charge and Gauss's law.
- Responses should demonstrate the ability to determine electric field given information about electric potential and vice versa.
- Responses should demonstrate comprehension of the connection between electric potential, charge, and energy/work.
- Responses should demonstrate comprehension of equipotential lines or surfaces and ability to interpret a diagram illustrating equipotential lines.
- Responses should demonstrate the ability to use charge density to derive an expression for the potential or electric field as a function of position relative to a charge distribution.
- Responses should be able to produce a graph of potential vs. position for a given charge distribution.
- Responses should demonstrate the ability to choose appropriate fundamental equations, derive appropriate expressions including substitutions of given variables, and calculate results with correct numerical values and units.
- Responses should demonstrate the ability to make a claim and justify using physics principles.

Sample: 1A
Score: 15

Part (a) earned 2 points. The first point was earned for using a correct equation for electric flux. The second point was earned for indicating the correct numerical answer. Part (b) earned 4 points. The first point was earned for indicating that $W_{\text{ED}} = 0$. The second point was earned for indicating that W_{DA} has a height of six units. The third point was earned for using an equation that relates the electric field to potential difference. The fourth point was earned because although the final answer does not have correct units, the response correctly substitutes values of electric potential and the distance between equipotential lines that can be used to calculate the approximate magnitude of the electric field at Position B. Part (c) earned 3 points. The first point was earned for selecting only $+y$ and attempting a relevant justification. The second point was earned for indicating that the direction of the electric field vector is perpendicular to a line that is tangent to the equipotential line at Position D. The third point was earned for indicating that the test charge moves from a higher electric potential to a lower electric potential. Part (d) earned 6 points. The first point was earned for using an appropriate equation for determining the electric potential from a line of uniform charge. The second point was earned for correctly determining the value of r, the distance between Point P and a point on the line of uniform charge. The third point was earned for indicating a correct integral with λdx substituted for dq. The fourth point was earned for indicating correct limits of integration. The fifth point was earned for indicating a curve or line that continually approaches the horizontal axis as position increases. The sixth point was earned for indicating a concave up curve that is always positive.

Question 1 (continued)

Sample: 1B
Score: 9

Part (a) earned 2 points. The first point was earned for using a correct equation for electric flux. The second point was earned for indicating the correct numerical answer. Part (b) earned 4 points. The first point was earned for indicating that $W_{\text{ED}} = 0$. The second point was earned for indicating that W_{DA} has a height of six units. The third point was earned for using an equation that relates the electric field to potential difference. The fourth point was earned for substituting the correct values of electric potential and the distance between equipotential lines to calculate the approximate magnitude of the electric field at Position B. Part (c) earned 1 point. The first point was not earned because the response does not select only $+y$. The second point was not earned because the response does not indicate that the direction of the electric field vector is perpendicular to a line that is tangent to the equipotential line at Position D. The third point was earned for indicating that the test charge and the sphere have charges of opposite sign and states the test charge moves from a higher electric potential to a lower electric potential. Part (d) earned 2 points. The first point was not earned because the response does not use an appropriate equation for determining the electric potential from a line of uniform charge. The second point was not earned because the response does not correctly determine the value of r, the distance between Point P and a point on the line of uniform charge. The third point was not earned because the response does not indicate a correct integral with λdx substituted for dq. The fourth point was not earned because response does not indicate correct limits of integration. The fifth point was earned for indicating a curve or line that continually approaches the horizontal axis as position increases. The sixth point was earned for indicating a concave up curve that is always positive.

Sample: 1C
Score: 3

Part (a) did not earn any points. The first point was not earned because the response does not use a correct equation for electric flux. The second point was not earned because the response does not indicate the correct numerical answer. Part (b) earned 1 point. The first point was not earned because the response does not indicate that $W_{\text{ED}} = 0$. The second point was earned for indicating that W_{DA} has a height of six units. The third point was not earned because the response does not use an equation that relates the electric field to potential difference. The fourth point was not earned because the response does not substitute correct values for electric potential and the distance between equipotential lines to calculate the approximate magnitude of the electric field at Position B. Part (c) earned 1 point. The first point was not earned because the response does not select only $+y$. The second point was not earned because the response does not indicate that the direction of the electric field vector is perpendicular to a line that is tangent to the equipotential line at Position D. The third point was earned for indicating that the test charge and the sphere have charges of opposite sign. Part (d) earned 1 point. The first point was not earned because the response does not use an appropriate equation for determining the electric potential from a line of uniform charge. The second point was not earned because the response does not correctly determine the value of r, the distance between Point P and a point on the line of uniform charge. The third point was not earned because the response does not indicate a correct integral with λdx substituted for dq. The fourth point was not earned because the response does not indicate correct limits of integration. The fifth point was earned for indicating a curve or line that continually approaches the horizontal axis as position increases. The sixth point was not earned because the response does not indicate a concave up curve.