
AP[®] AP Physics C: Electricity & Magnetism

Sample Student Responses and Scoring Commentary

Question #2

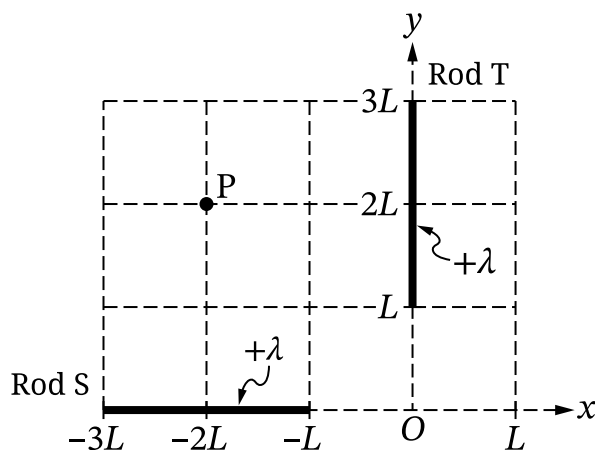
DRAFT

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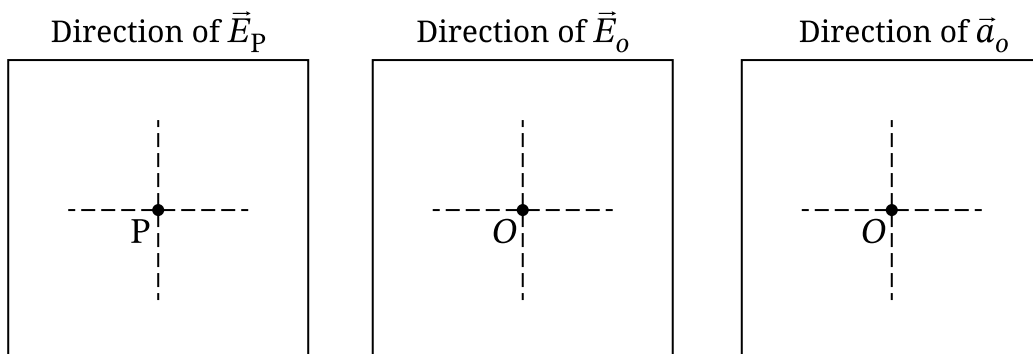
Question 2: Version J

2. Thin, nonconducting, charged Rods S and T are held fixed in the xy -plane, as shown in Figure 1. Rod S is oriented along the x -axis in the region $-3L \leq x \leq -L$. Rod T is oriented along the y -axis in the region $L \leq y \leq 3L$. Each rod has uniform, positive linear charge density $+\lambda$. Point P is located at $(-2L, 2L)$.

Figure 1**Part A**

Complete the following tasks in Figure 2.

- **Draw** an arrow starting on the dot that indicates the direction of the net electric field $\vec{E}_P$ at Point P due to Rods S and T.
- **Draw** an arrow starting on the dot that indicates the direction of the net electric field $\vec{E}_O$ at the origin O due to Rods S and T.
- **Draw** an arrow starting on the dot that indicates the direction of the net acceleration $\vec{a}_O$ of a small, negatively charged sphere (not shown) immediately after the sphere is released from rest at the origin O.

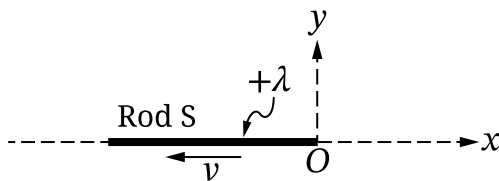
Figure 2

Part B

Derive an expression for the magnitude E_O of the net electric field at the origin O due to Rods S and T in terms of L , λ , and physical constants, as appropriate. Begin your derivation by writing a fundamental physics principle or an equation from the reference information.

Part C

Rod T is removed. Rod S is then moved such that the right end of Rod S is at the origin O . Rod S is then moved with speed v in the $-x$ -direction, as shown in Figure 3.

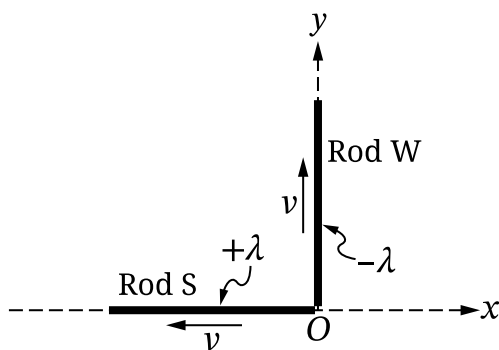
Figure 3

On the axes shown in Figure 4, **sketch** a graph of the electric potential V_O at the origin O due to Rod S as a function of the distance r between the origin and the right end of Rod S.

Figure 4

Part D

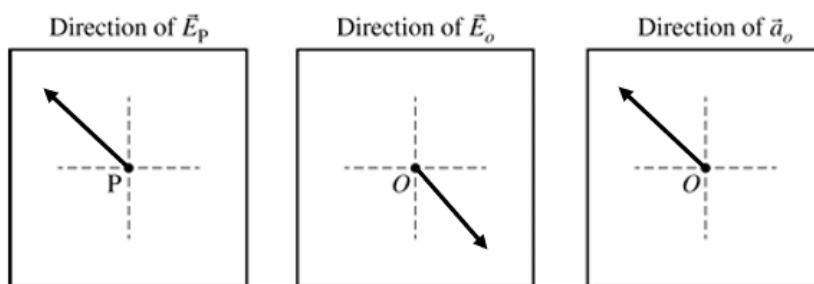
A new thin, nonconducting, charged Rod W has the same length as Rod S. Rod W has uniform, negative linear charge density $-\lambda$ and is oriented along the y -axis. Rods S and W are initially held fixed with one end at the origin. Starting at the same time, Rod S is moved with speed v in the $-x$ -direction and Rod W is moved with speed v in the $+y$ -direction, as shown in Figure 5.

Figure 5

Indicate how a sketch of V_O at the origin O due to both Rods S and W as a function of r would be different from the sketch made in part C. Briefly **justify** your answer.

Question 2 Translation Between Representations (TBR)**12 points****General Scoring Notes****NR (No Response):** A score of NR is only assigned to responses that are blank.

A	For drawing an arrow that is up and to the left above the horizontal axis for the direction of $\vec{E}_p$	Point A1
	For drawing an arrow that is down and to the right below the horizontal axis for the direction of $\vec{E}_o$	Point A2
	For drawing an arrow for $\vec{a}_o$ that is directed opposite the arrow drawn for the direction of $\vec{E}_o$	Point A3

Example Response/ Solution

B	For a multistep derivation that includes the equation $\vec{E} = k \int \frac{dq}{r^2} \hat{r}$	Point B1
	Scoring Note: Vector notation and unit vector notation are not required for this point to be earned.	
	For a substitution of a correct expression for dq that includes λ (e.g., $dq = \lambda dx$ or $dq = \lambda dy$)	Point B2
	For an attempt to solve the integral for a component of the net electric field that includes correct limits	Point B3
	For a correct vector addition of the derived electric fields for both rods resulting in an expression in terms of L , λ , and physical constants	Point B4

Example Response

Determine magnitude E_T of the electric field due to Rod T at the origin.

$$\vec{E} = \frac{1}{4\pi\epsilon_0} \int \frac{dq}{r^2} \hat{r}$$

$$E_T = -k \int \left(\frac{1}{y^2} \right) dq$$

$$dq = \lambda dy$$

$$E_T = -k\lambda \int_L^{3L} \frac{dy}{y^2}$$

$$E_T = k\lambda \left(\frac{1}{y} \right) \Big|_L^{3L}$$

$$E_T = k\lambda \left(\frac{1}{3L} \right) - k\lambda \left(\frac{1}{L} \right) = -\frac{2}{3} \frac{k\lambda}{L}$$

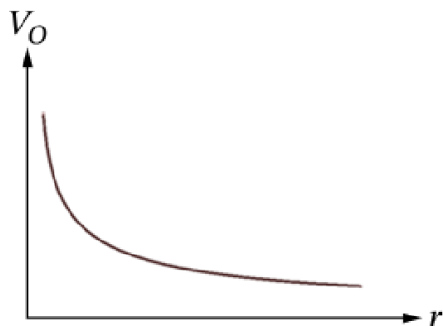
Magnitude E_S of the electric field due to Rod S is equal to E_T .

$$E_O = \sqrt{(E_S)^2 + (E_T)^2} = \sqrt{2(E_T)^2}$$

$$E_O = \sqrt{2 \left(\frac{2}{3} \frac{k\lambda}{L} \right)^2}$$

$$\therefore E_O = \frac{2\sqrt{2}}{3} \frac{k\lambda}{L}$$

C	For a curve that always decreases as r increases	Point C1
	For a curve with a slope whose absolute value always decreases as r increases	Point C2
	For a curve that approaches zero as r increases and approaches infinity as r decreases	Point C3

Example Response

D	For indicating that V_o is zero for all values of r	Point D1
	For a justification that indicates that the linear charge densities are equal in magnitude but opposite in sign and the rods are always the same distance from the origin	Point D2
	Example Response <i>The rods are identical in length but have equal and opposite linear charge densities. Electric potential is a scalar, and the electric potentials at the origin from the rods cancel because the rods are always the same distance from the origin. Therefore, $V_o = 0$.</i>	

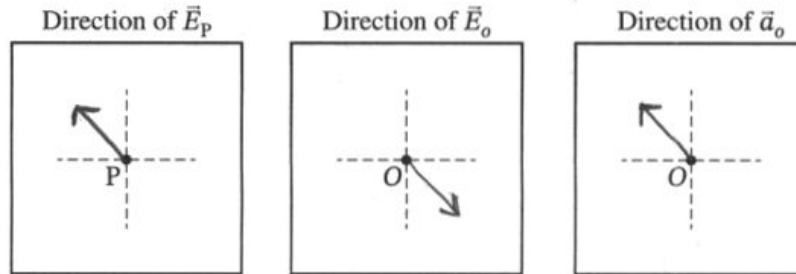
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Question 2: Version J

PART A

$$\lambda = \frac{\text{charges}}{\text{length}}$$

Figure 2



PART B

$$r^{-2} \quad -\frac{1}{r}$$

$$dE = \frac{k \, da}{r^2}$$

$$da = \lambda \, dr$$

$$E_T = k\lambda \int_{-L}^{3L} \frac{dr}{r^2}$$

$$dE = \frac{k \lambda \, dr}{r^2}$$

$$E_T = \frac{-k\lambda}{r} \Big|_{-L}^{3L}$$

$$E_T = \frac{-k\lambda}{3L} + \frac{k\lambda}{L} = \frac{2k\lambda}{3L}$$

$$E_S = k\lambda \int_{-L}^{-3L} \frac{dr}{r^2}$$

$$E_O = \sqrt{E_S^2 + E_T^2}$$

$$E_S = \frac{-k\lambda}{r} \Big|_{-L}^{-3L}$$

$$E_O = \sqrt{\left(\frac{-2k\lambda}{3L}\right)^2 + \left(\frac{2k\lambda}{3L}\right)^2}$$

$$E_S = \left(\frac{-k\lambda}{-3L}\right) - \left(\frac{-k\lambda}{-L}\right)$$

$$E_S = \frac{-k\lambda}{3L} + \frac{k\lambda}{L} = \frac{-2k\lambda}{3L}$$

Page 8

Question 2: Version J continues on the next page.

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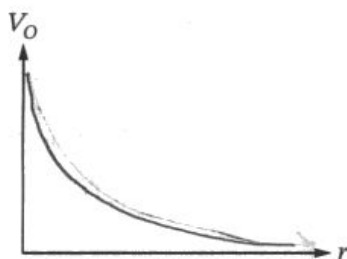
Use a pencil or a pen with black or dark blue ink. Do NOT write your name. Do NOT write outside the box.

Question 2: Version J

PART C

Figure 4

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



PART D

A sketch of V_0 at the origin due to both rods S and W as a function of r would be different than the sketch in Part C because in Part C, V_0 is positive, but in this situation, $V_0 = 0$. Therefore, the graph of V_0 vs. r would be a line: $y = 0$. $V_0 = 0$ in this scenario because voltage is a scalar and equals $\frac{kQ}{r}$. The total charges of rods S and W are equal and opposite (same length and λ), and the rods both start at the origin and move away with velocity v , so at any given time, they are the same distance from the origin.

Page 9

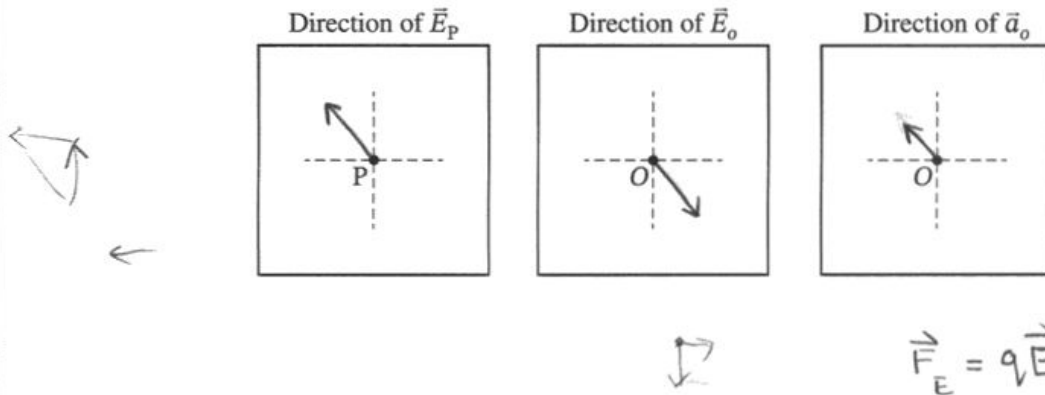
Go to Question 3 when you're done with this question.

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

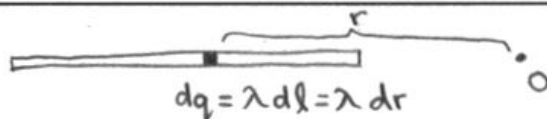
Question 2: Version J

PART A

Figure 2



PART B



$$E_O = k\lambda \left(\frac{1}{L} - \frac{1}{3L} \right) \sqrt{2}$$



$$E = k \int \frac{dq}{r^2} \hat{r}$$

$$E = k \int_L^{3L} \frac{\lambda dr}{r^2}$$

$$E = k\lambda \left[-\frac{1}{r} \right]_L^{3L}$$

$$E = k\lambda \left(-\frac{1}{3L} - \left(-\frac{1}{L} \right) \right)$$

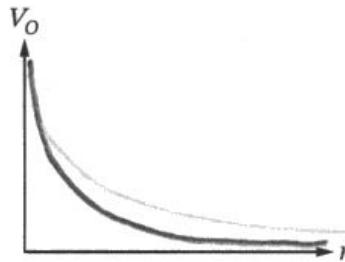
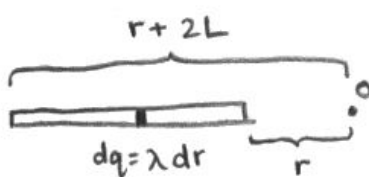
$$E = k\lambda \left(\frac{1}{L} - \frac{1}{3L} \right)$$

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

Question 2: Version J

PART C

Figure 4



$$V_o = k \int \frac{dq}{r}$$

$$V_o = k \int \frac{\lambda dr}{r} = k\lambda \int_r^{r+2L} \frac{1}{r} dr = k\lambda \ln\left(\frac{r+2L}{r}\right)$$

PART D



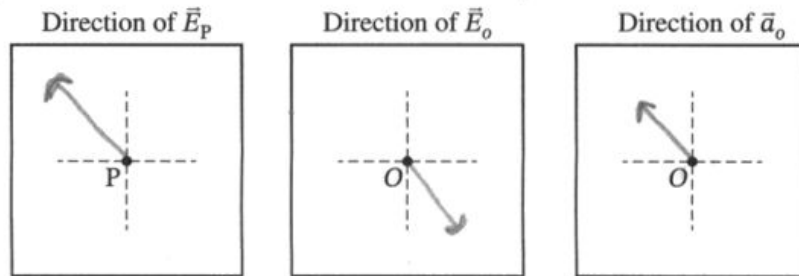
The V_0 at origin will always be 0, since the positive charge from rod S cancels out the negative charge from rod W.

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Question 2: Version J

PART A

Figure 2



PART B

$$\begin{aligned}
 E_{\text{trans}} &= k \int \frac{dq}{r^2} \hat{r} \\
 &= k \int_L^{3L} \frac{dq}{x^2} \cdot \hat{i} = k \int_L^{3L} \frac{dx}{x^2} \cdot \hat{i} \quad (dq = \lambda dx) \\
 &= k\lambda \cdot \left[-\frac{1}{x} \right]_L^{3L} \\
 &= k\lambda \cdot \left(-\frac{1}{3L} + \frac{1}{L} \right) = k\lambda \left(\frac{2}{3L} \right) \hat{i} \\
 E_{\text{trans}} &= \frac{2k\lambda}{3L} \hat{i}
 \end{aligned}$$

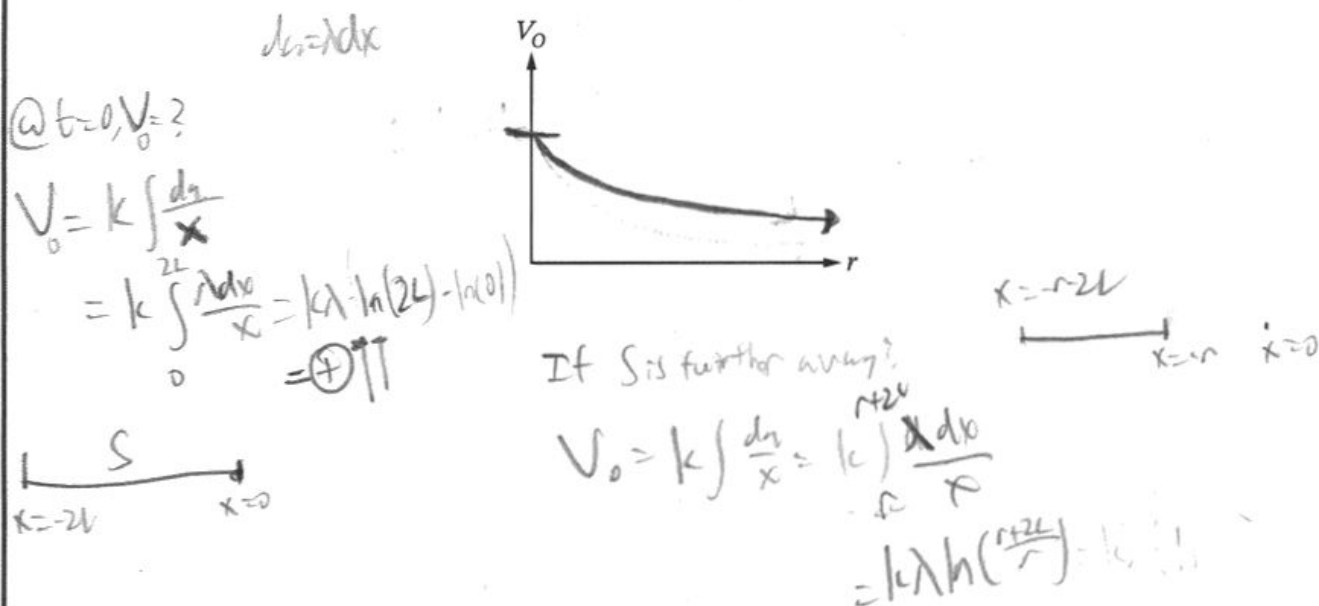
$$\begin{aligned}
 E_0 &= E_{\text{trans}} + E_{\text{trans}} \\
 \text{Likewise, } E_{\text{trans}} &= \frac{2k\lambda}{3L} \cdot \hat{j} \\
 |E_0| &= \sqrt{E_s^2 + E_T^2} = \boxed{\frac{\sqrt{2} k\lambda}{3L}} \quad \frac{\text{Newtons}}{\text{Coulombs}}
 \end{aligned}$$

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Question 2: Version J

PART C

Figure 4



PART D

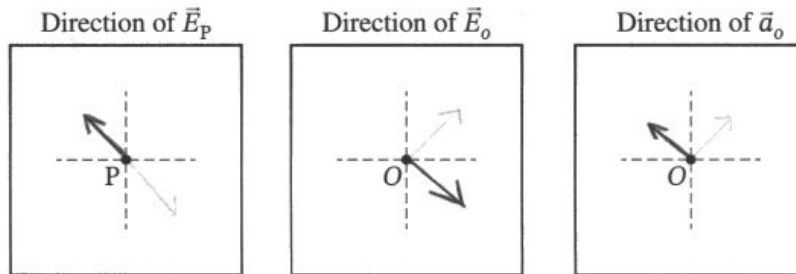
A sketch of V_0 at the origin would look different because the graph would be zero at all values of r . The negative electric potential from Rod W would cancel out that of the positive electric potential from Rod S.

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Question 2: Version J

PART A

Figure 2



PART B

$$E = \frac{1}{4\pi\epsilon_0} \int \frac{1}{r^2} dq \quad \lambda = \frac{q}{L} = \frac{dq}{dr}$$

$$E_T = \frac{1}{4\pi\epsilon_0} \int_L^{4L} \frac{\lambda}{r^2} dr \quad \lambda dr = dq$$

$$= \frac{\lambda}{4\pi\epsilon_0} \left[-\frac{1}{r} \right]_L^{4L}$$

$$= \frac{\lambda}{4\pi\epsilon_0} \left(-\frac{1}{4L} + \frac{1}{L} \right) = \frac{\lambda}{4\pi\epsilon_0} \left(\frac{3}{4L} \right)$$

$$E_S = \frac{1}{4\pi\epsilon_0} \int_L^{4L} \frac{\lambda}{r^2} dr$$

$$= \frac{\lambda}{4\pi\epsilon_0} \left(-\frac{1}{4L} + \frac{1}{L} \right) = \frac{\lambda}{4\pi\epsilon_0} \left(\frac{3}{4L} \right)$$

$$E_O = \sqrt{E_T^2 + E_S^2}$$

$$E_O = \sqrt{\left(\frac{3\lambda}{16\pi\epsilon_0 L} \right)^2 + \left(\frac{3\lambda}{16\pi\epsilon_0 L} \right)^2}$$

$$E_O = \sqrt{\frac{9\lambda^2}{128\pi^2\epsilon_0^2 L^2}}$$

$$= \frac{3\lambda}{\pi\epsilon_0 L} \cdot \sqrt{\frac{1}{128}}$$

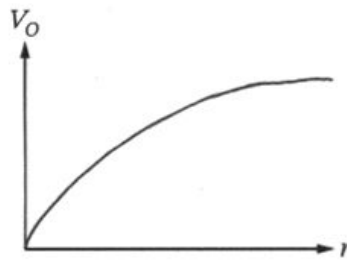
$$= \frac{3\lambda}{8\sqrt{2}\pi\epsilon_0 L} = \frac{3\lambda}{8\sqrt{2}\pi\epsilon_0 L}$$

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Question 2: Version J

PART C

Figure 4



$$V = \frac{1}{4\pi\epsilon_0} \int \frac{1}{r} dq$$

$$V = \frac{1}{4\pi\epsilon_0} \int \frac{\lambda}{r} dr$$

$$= \frac{\lambda}{4\pi\epsilon_0} \ln|r| \rightarrow \text{produces an ln graph}$$

PART D

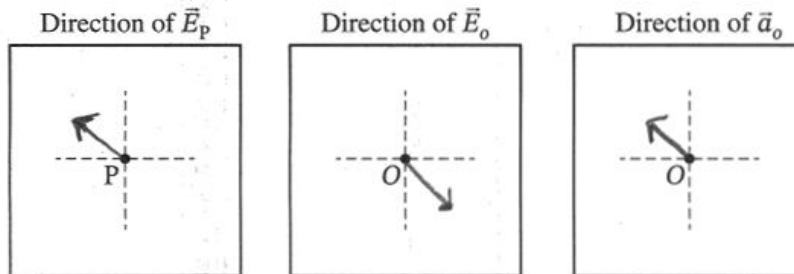
It would be constantly zero. Since V is a scalar value, the direction of movement does not matter so long as the separation distances are of the same magnitude. Thus, since both Rod S and W move at the same speed, and $V = V_S + V_W$, there will be no net potential at the origin, giving V_W will be negative and equal in magnitude to V_S .

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

Question 2: Version J

PART A

Figure 2



PART B

$$E = \frac{1}{4\pi\epsilon_0} \int \frac{dq}{r^2} \hat{r}$$

$$E = k \int \frac{\lambda 2L}{r^2}$$

$$E = k\lambda 2L \int \frac{1}{r^2}$$

$$E = k\lambda 2L \left[-\frac{1}{r} \right]_{\frac{L}{2}}^{\frac{3L}{2}}$$

Sum for other

$$E_0 = \sqrt{E_s^2 + E_T^2}$$

$$E_0 = \sqrt{\left(\frac{1}{2}k\lambda 2L\sqrt{2}\right)^2 + \left(\frac{1}{2}k\lambda 2L\sqrt{2}\right)^2}$$

$$\lambda = \frac{q}{L} \rightarrow 2L$$

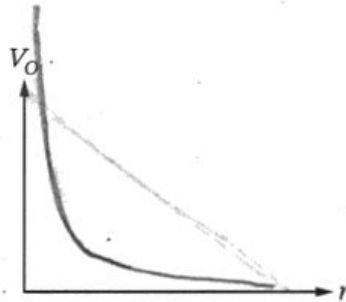


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Question 2: Version J

PART C

Figure 4



PART D

the new sketch of V_0 as a
result of r would be different
due to a V_0 now being affected
by sources increasing with V

$$\text{Similar to } V_0 = C \frac{1}{r}$$

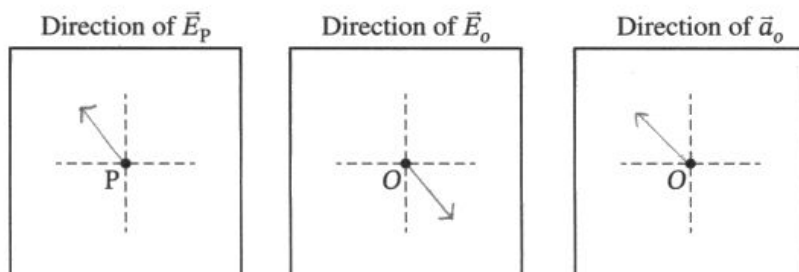
with C being a constant number

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Question 2: Version J

PART A

Figure 2



PART B

$$E_o = E_s + E_T$$

$$E = k \int \frac{dq}{r^2} \hat{r}$$

$$E_T = k \int_{-L}^{3L} \frac{dq}{(L+y)^2} = k \int_{-L}^{3L} \frac{\lambda dy}{(L+y)^2} = k \left(\frac{-\lambda}{L+y} \right) \Big|_{-L}^{3L} \\ = k \left(\frac{-\lambda}{4L} + \frac{\lambda}{2L} \right) \\ = \frac{k\lambda}{4L} \text{ (in the } -y \text{ direction)} \rightarrow E_T = \frac{k\lambda}{4L} \hat{j}$$

(k = coulomb constant)

$$E_s = k \int_{-L}^{-3L} \frac{dq}{(L-x)^2} = k \int_{-L}^{-3L} \frac{\lambda dx}{(L-x)^2} = k \left(\frac{\lambda}{L-x} \right) \Big|_{-L}^{-3L} \\ = k \left(\frac{\lambda}{-4L} - \frac{\lambda}{-2L} \right) \\ = \frac{k\lambda}{4L} \text{ (in the } +x \text{ direction)} \rightarrow E_s = \frac{k\lambda}{4L} \hat{i}$$

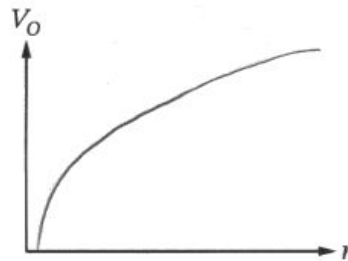
$$E_o = \frac{k\lambda}{4L} \hat{i} - \frac{k\lambda}{4L} \hat{j} \\ |E_o| = \sqrt{\left(\frac{k\lambda}{4L}\right)^2 + \left(-\frac{k\lambda}{4L}\right)^2} \\ |E_o| = \sqrt{2} \left(\frac{k\lambda}{4L}\right)$$

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Question 2: Version J

PART C

Figure 4



PART D

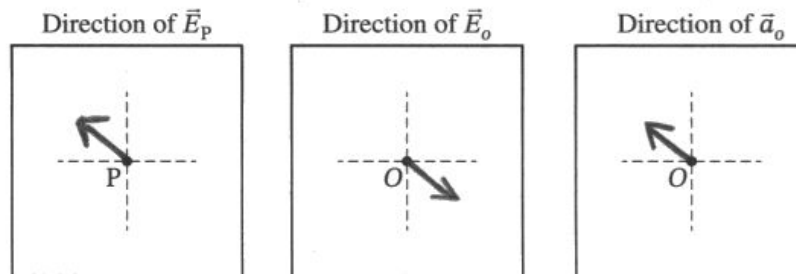
A sketch of V_0 as a function of r would have a less steep slope / increase at a slower rate. Since $E_x = -\frac{dV}{dx}$ & the total electric field at the origin is stronger when rod W is added, E would decrease at a slower rate with respect to r , & so V_0 's slope would become less steep.

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Question 2: Version J

PART A

Figure 2



PART B

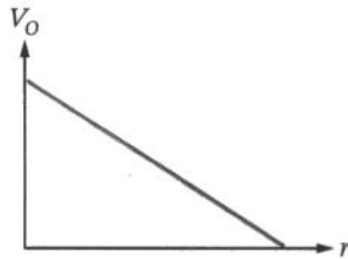
$$E = \frac{1}{4\pi\epsilon_0} \int \frac{dq}{r^2} \hat{r}$$

$$E_S = k \int_{-L}^{L+2L} \frac{\lambda}{L^2} dl$$

$$E_T = k \int_L^{L+2L} \frac{\lambda}{L^2} dl$$

$$E_S + E_T$$

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Question 2: Version J**PART C****Figure 4****PART D**

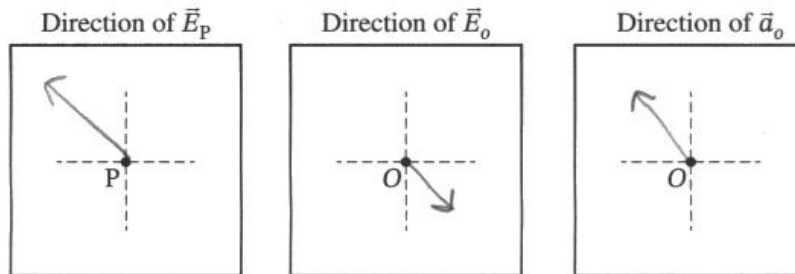
Because a rod of opposite charge is now included, because as a negative charge gets farther away the V_0 increases the graph wouldn't be a decreasing linear and would instead be flat as the rate at which V_0 increases due to rod W and decreases due to rod S would cancel each other out

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Question 2: Version J

PART A

Figure 2



PART B

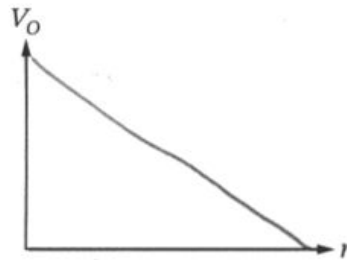
$$Q = \lambda L$$

$$E = \frac{kQ}{r^2}$$

$$\vec{E} = \left(\frac{k\lambda 2L}{L^2} \right) \hat{x} + \left(\frac{k\lambda 2L}{L^2} \right) \hat{y}$$

$$|\vec{E}| = \sqrt{\frac{4k^2\lambda^2}{L^2} + \frac{4k^2\lambda^2}{L^2}} = \sqrt{\frac{8k^2\lambda^2}{L^2}}$$

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Question 2: Version J**PART C****Figure 4****PART D**

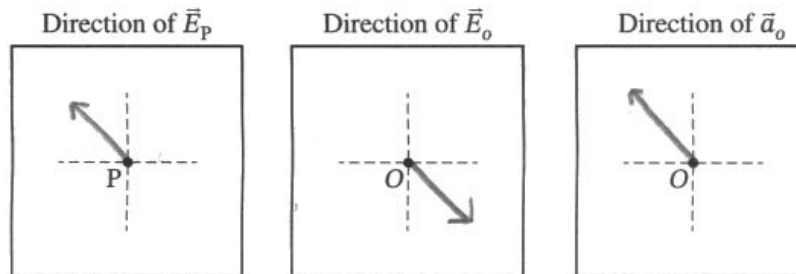
A sketch of V_0 at the origin 0 would be different because the V_0 would always be zero. Since electric potential is a scalar, a negative and positive quantity of the same magnitude would cancel out. Therefore, V_0 would be a straight line at 0.

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

Question 2: Version J

PART A

Figure 2



PART B

$$|\vec{F}_E| = \frac{1}{4\pi\epsilon_0} \frac{|q_1 q_2|}{r^2}$$

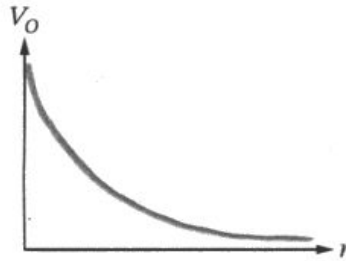
$$F_E = k \frac{q^2}{L^2}$$

$$E = \frac{F_E}{q}$$

$$E = \frac{k \frac{q^2}{L^2}}{q}$$

$$E_0 = k \frac{\lambda}{L^2}$$

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Question 2: Version J**PART C****Figure 4****PART D**

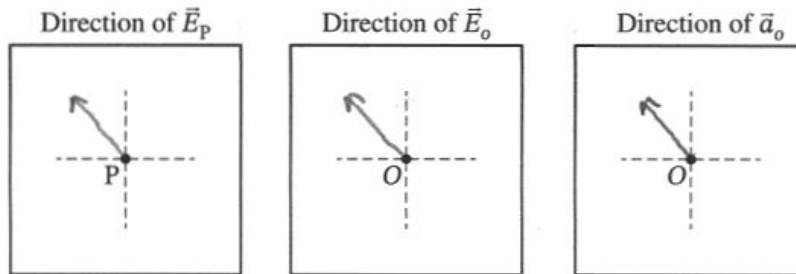
The sketch of V_0 at the origin would begin at a much higher V_0 at $r=0$. Due to an introduction of another wire, the amount of total charge and electric field at the origin increases; thus, increasing V_0 at $r=0$.

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Question 2: Version J

PART A

Figure 2



PART B

$$\vec{E} = \frac{1}{4\pi\epsilon_0} \int \frac{dq}{r^2} \hat{r}$$

$$E_o = \frac{kQ}{L^2} + \frac{kQ}{L^2}$$

$$\lambda = \frac{Q}{2L}; Q = 2\lambda L$$

$$E_o = \frac{2\lambda L k}{L^2} + \frac{2\lambda L k}{L^2}$$

$$E_o = \frac{4\lambda k}{L}$$

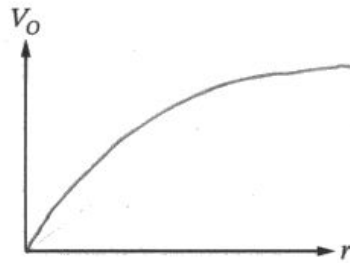
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Question 2: Version J

PART C

$$E = -\frac{\partial V}{\partial x}$$

Figure 4



PART D

A sketch of V_0 at the origin 0 due to both Rods S and W as a function of r would be different than the sketch made in part C because the net electric field changes. This is because since the rods are moving, the distance between them and the origin increases, causing E to change. E changing alters the shape of $V_0(r)$ because $E = -\frac{\partial V}{\partial x}$.

Question 2

Sample Identifier: PCEM Sample 2A

Score: 12

- Point A1 was earned. The response indicates an arrow pointing in the correct direction of up and to the left.
- Point A2 was earned. The response indicates an arrow pointing in the correct direction, down and to the right.
- Point A3 was earned. The response indicates an arrow pointing in the opposite direction of the arrow drawn for E_O .
- Point B1 was earned. The response indicates a multistep derivation that includes a relevant equation.
- Point B2 was earned. The response substitutes a correct expression for dq .
- Point B3 was earned. The response attempts to solve the integral for the electric field.
- Point B4 was earned. The response correctly adds the electric field vectors of both rods in the given terms.
- Point C1 was earned. The response indicates a curve that always decreases as r increases.
- Point C2 was earned. The response indicates a curve with a slope whose absolute value always decreases as r increases.
- Point C3 was earned. The response indicates a curve that approaches zero as r increases and approaches infinity as r decreases.
- Point D1 was earned. The response indicates that V_O is zero for all values of r by stating that the graph would be a line at $y = 0$.
- Point D2 was earned. The response indicates that the charges of the rods are equal and opposite, and the rods are always the same distance from the origin.

Sample Identifier: PCEM Sample 2B

Score: 11

- Point A1 was earned. The response indicates an arrow pointing in the correct direction, up and to the left.
- Point A2 was earned. The response indicates an arrow pointing in the correct direction, down and to the right.
- Point A3 was earned. The response indicates an arrow pointing in the opposite direction of the arrow drawn for E_O .
- Point B1 was earned. The response indicates a multistep derivation that includes a relevant equation.
- Point B2 was earned. The response substitutes a correct expression for dq in terms of λ .
- Point B3 was earned. The response attempts to solve the integral for the electric field and uses correct limits.
- Point B4 was earned. The response shows a correct expression for E_O that is supported by a visual representation of the vector addition.
- Point C1 was earned. The response indicates a curve that always decreases as r increases.
- Point C2 was earned. The response indicates a curve with a slope whose absolute value always decreases as r increases.

- Point C3 was earned. The response indicates a curve that approaches zero as r increases and approaches infinity as r decreases.
- Point D1 was earned. The response indicates that V_O is always zero.
- Point D2 was not earned. The response does not mention the two rods being the same distance from the origin.

Sample Identifier: PCEM Sample 2C**Score: 10**

- Point A1 was earned. The response indicates an arrow pointing in the correct direction of up and to the left.
- Point A2 was earned. The response indicates an arrow pointing in the correct direction of down and to the right.
- Point A3 was earned. The response indicates an arrow pointing in the opposite direction of the arrow drawn for E_O .
- Point B1 was earned. The response indicates a multistep derivation that includes a relevant equation.
- Point B2 was earned. The response substitutes a correct expression for dq in terms of λ .
- Point B3 was earned. The response attempts to solve the integral for the electric field with correct limits.
- Point B4 was earned. The response correctly adds the electric field vectors of both rods using the given quantities.
- Point C1 was earned. The response indicates a curve that always decreases as r increases.
- Point C2 was earned. The response indicates a curve with a slope whose absolute value always decreases as r increases.
- Point C3 was not earned. The response shows a curve with a finite value at $r = 0$, rather than approaching infinity.
- Point D1 was earned. The response indicates that V_O is zero for all values of r .
- Point D2 was not earned. The response does not mention that the rods are always the same distance from the origin.

Sample Identifier: PCEM Sample 2D**Score: 9**

- Point A1 was earned. The response indicates an arrow pointing in the correct direction of up and to the left.
- Point A2 was earned. The response indicates an arrow pointing in the correct direction of down and to the right.
- Point A3 was earned. The response indicates an arrow pointing in the opposite direction of the arrow drawn for E_O .
- Point B1 was earned. The response indicates a multistep derivation that includes a relevant equation.
- Point B2 was earned. The response substitutes a correct expression for dq in terms of λ .
- Point B3 was not earned. The response attempts to solve the integral for the electric field, but the limits (L to $4L$) are not correct.

- Point B4 was earned. The response correctly adds the vectors of the derived electric fields for both rods in terms of the given quantities.
- Point C1 was not earned. The response indicates a curve that always increases as r increases.
- Point C2 was earned. The response indicates a curve with a slope whose absolute value always decreases as r increases.
- Point C3 was not earned. The response does not indicate a curve that approaches zero as r increases and approaches infinity as r decreases.
- Point D1 was earned. The response indicates that V_O is zero for all values of r .
- Point D2 was earned. The response indicates that the linear charge densities are equal in magnitude but opposite in sign and the rods are always the same distance from the origin.

Sample Identifier: PCEM Sample 2E**Score: 8**

- Point A1 was earned. The response indicates an arrow pointing in the correct direction of up and to the left.
- Point A2 was earned. The response indicates an arrow pointing in the correct direction of down and to the right.
- Point A3 was earned. The response indicates an arrow pointing in the opposite direction of the arrow drawn for E_O .
- Point B1 was earned. The response indicates a multistep derivation that includes a relevant equation.
- Point B2 was not earned. The response does not substitute a correct expression for dq .
- Point B3 was not earned. The response attempts to solve the integral for the electric field but uses incorrect limits.
- Point B4 was earned. The response correctly adds the electric field vectors of both rods using the given quantities.
- Point C1 was earned. The response indicates a curve that always decreases as r increases.
- Point C2 was earned. The response indicates a curve with a slope whose absolute value always decreases as r increases.
- Point C3 was earned. The response indicates a curve that approaches zero as r increases and approaches infinity as r decreases.
- Point D1 was not earned. The response does not indicate that V_O is zero for all values of r .
- Point D2 was not earned. The response does not mention linear charge densities or the rods' distances from the origin.

Sample Identifier: PCEM Sample 2F**Score: 7**

- Point A1 was earned. The response indicates an arrow pointing in the correct direction of up and to the left.
- Point A2 was earned. The response indicates an arrow pointing in the correct direction of down and to the right.
- Point A3 was earned. The response indicates an arrow pointing in the opposite direction of the arrow drawn for E_O .

- Point B1 was earned. The response indicates a multistep derivation that includes a relevant equation.
- Point B2 was earned. The response replaces dq with a correct expression in terms of λ .
- Point B3 was not earned. The response attempts to solve the integral for the electric field, but the limits chosen (L and $3L$) are not consistent with the denominator $(L + y)^2$.
- Point B4 was earned. The response correctly adds the electric field vectors of both rods using the given quantities.
- Point C1 was not earned. The response indicates a curve that increases as r increases.
- Point C2 was earned. The response indicates a curve with a slope whose absolute value always decreases as r increases.
- Point C3 was not earned. The response does not indicate a curve that approaches zero as r increases and approaches infinity as r decreases.
- Point D1 was not earned. The response does not indicate that V_O is zero for all values of r .
- Point D2 was not earned. The response does not indicate that the linear charge densities are equal in magnitude and that the rods are always the same distance from the origin.

Sample Identifier: PCEM Sample 2G**Score: 7**

- Point A1 was earned. The response indicates an arrow pointing in the correct direction, up and to the left.
- Point A2 was earned. The response indicates an arrow pointing in the correct direction, down and to the right.
- Point A3 was earned. The response indicates an arrow pointing in the opposite direction of the arrow drawn for E_O .
- Point B1 was earned. The response indicates a multistep derivation that includes a relevant equation.
- Point B2 was earned. The response substitutes a correct expression for dq in terms of λ .
- Point B3 was not earned. The response has the correct limits on the integral, but does not attempt to solve the integral for E .
- Point B4 was not earned. The response does not attempt to add vectors for E in terms of the quantities given.
- Point C1 was earned. The response indicates a curve that always decreases as r increases.
- Point C2 was not earned. The response does not indicate a curve with a slope whose absolute value always decreases as r increases.
- Point C3 was not earned. The response does not indicate a curve that approaches zero as r increases nor approaches infinity as r decreases.
- Point D1 was earned. The response indicates that the V from the rods would cancel out, resulting in a V_O of zero.
- Point D2 was not earned. The response does not mention the distance from the rods to the origin.

Sample Identifier: PCEM Sample 2H**Score: 6**

- Point A1 was earned. The response indicates an arrow pointing in the correct direction of up and to the left.
- Point A2 was earned. The response indicates an arrow pointing in the correct direction of down and to the right.
- Point A3 was earned. The response indicates an arrow pointing in the opposite direction of the arrow drawn for E_O .
- Point B1 was not earned. The response indicates a multistep derivation but treats the objects as point charges rather than as charged objects with a continuous distribution.
- Point B2 was not earned. The response does not substitute a correct expression for dq .
- Point B3 was not earned. The response does not attempt to solve an integral for the electric field.
- Point B4 was earned. The response correctly adds the vectors of the derived electric fields for both rods in terms of the given quantities.
- Point C1 was earned. The response indicates a curve that always decreases as r increases.
- Point C2 was not earned. The response indicates a line with a constant slope instead of a slope whose absolute value is decreasing as r is increasing.
- Point C3 was not earned. The response does not indicate a curve that approaches zero as r increases or approaches infinity as r decreases.
- Point D1 was earned. The response indicates that V_O is zero for all values of r .
- Point D2 was not earned. The response does not mention the distance of the rods to the origin.

Sample Identifier: PCEM Sample 2I**Score: 6**

- Point A1 was earned. The response indicates an arrow pointing in the correct direction, up and to the left.
- Point A2 was earned. The response indicates an arrow pointing in the correct direction, down and to the right.
- Point A3 was earned. The response indicates an arrow pointing in the opposite direction of the arrow drawn for E_O .
- Point B1 was not earned. The response indicates a multistep derivation but does not include a relevant equation for the electric field.
- Point B2 was not earned. The response does not substitute a correct expression for dq .
- Point B3 was not earned. The response does not attempt to solve an integral for the electric field.
- Point B4 was not earned. The response does not attempt to add the vectors of the electric fields.
- Point C1 was earned. The response indicates a curve that always decreases as r increases.
- Point C2 was earned. The response indicates a curve with a slope whose absolute value always decreases as r increases.
- Point C3 was earned. The response indicates a curve that approaches zero as r increases and approaches infinity as r decreases.

- Point D1 was not earned. The response indicates that V_O is increasing, not zero, for all values of r .
- Point D2 was not earned. The response does not mention the linear charge densities or the rods' distances from the origin.

Sample Identifier: PCEM Sample 2J**Score: 3**

- Point A1 was earned. The response indicates an arrow pointing in the correct direction, up and to the left.
- Point A2 was not earned. The response indicates an arrow pointing up and to the left instead of down and to the right.
- Point A3 was not earned. The arrow drawn in the response is not in the opposite direction of the arrow drawn for E_O .
- Point B1 was earned. The response indicates a multistep derivation that includes a relevant equation.
- Point B2 was not earned. The response has no substitution for dq in terms of λ .
- Point B3 was not earned. The response does not attempt to evaluate the integral or include any limits.
- Point B4 was not earned. The response adds the electric fields together as scalars, not as vectors.
- Point C1 was not earned. The response does not indicate a curve that always decreases as r increases.
- Point C2 was earned. The response indicates a curve with a slope whose absolute value always decreases as r increases.
- Point C3 was not earned. The response does not indicate a curve that approaches zero as r increases and approaches infinity as r decreases.
- Point D1 was not earned. The response does not indicate that V_O equals zero or that the electric potentials cancel out.
- Point D2 was not earned. The response makes no mention of the linear charge densities or of the distance of the rods from the origin.