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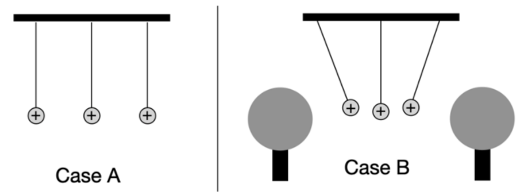
I. Lecture multiple choice [45 points]

Choose only one answer for each question and fill it out on your scantron.

1. (5 points) Three small positively charged conducting spheres hang from strings far enough apart from each other that they do not exert strong forces on each other, as shown in Case A. In Case B, two much larger spherical shells, with much more net charge, are brought near the suspended spheres. Which one of the following statements is completely TRUE for Case B? For this question, assume all electrostatic forces are horizontal.



A. The electric field is zero at the midpoint between the shells, and both shells are positively charged.

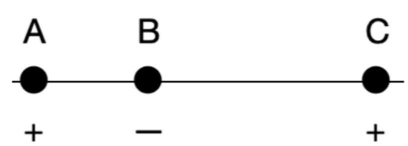
B. The electric field is zero at the midpoint between the shells, and both shells are negatively charged.

C. The electric field is zero at the midpoint between the shells, and the shells are oppositely charged.

D. The electric field points to the right at the midpoint between the shells, and the shells are oppositely charged

E. The electric field points to the left at the midpoint between the shells, and both shells are positively charged.

2. (5 points) Two small conducting spheres, A and C, are fixed in place along a line and charge B is free to move. Charge C is a distance d_o from charge B, and charge A is $d_o/2$ from B. Both A and C are positively charged and B is negatively charged. The net force on B is zero. Which one of the following statements is completely TRUE?



A. $q_A > |q_B|$ and $q_C > q_A$

B. $q_C > |q_B|$ and $q_C > q_A$

C. $q_A > |q_B|$ and $q_A > q_C$

D. $|q_B|$ could have any value and $q_C > q_A$

E. $|q_B|$ could have any value and $q_A > q_C$

3. (5 points) A positive charge is in a uniform electric field, and the charge experiences a net force to the right. Assuming there are no other forces acting, which one of the following statements could be TRUE?

   A. The electric field is to the right and the charge is moving at a constant velocity.

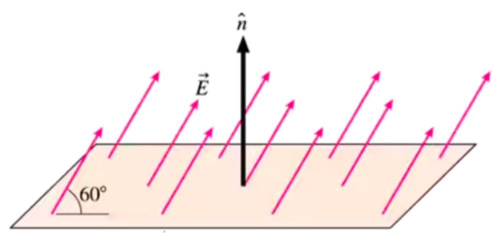
   B. The electric field is to the left and the charge is slowing down.

   C. The electric field is to the right and the charge is speeding up.

   D. The electric field is to the left and the charge is speeding up.

   E. The electric field is uniform, so the charge is moving at a constant velocity.

4. (5 points) The electric flux through the surface shown is $25\ \mathrm{N \cdot m^2/C}$, and the surface area of the rectangle is $0.40\ \mathrm{m^2}$. Which of the following is closest to the magnitude of the electric field, $\vec{E}$?



   A. 540 N/C

   B. 72 N/C

   C. 130 N/C

   D. 630 N/C

   E. 36 N/C

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5. (5 points) A rectangular surface area, represented by the perpendicular vector $A\hat{n}$, is positioned in a constant electric field, $\vec{E}_o$. Which one of the following choices represents a possible combination of the quantities associated with the flux through the surface, Φ?

A. $\vec{E}_o = -10\ \mathrm{N/C}\ \hat{\imath}$, $A\hat{n} = +5\ \mathrm{m}^2\ \hat{\jmath}$, $\Phi = -50\ \mathrm{m^2N/C}$

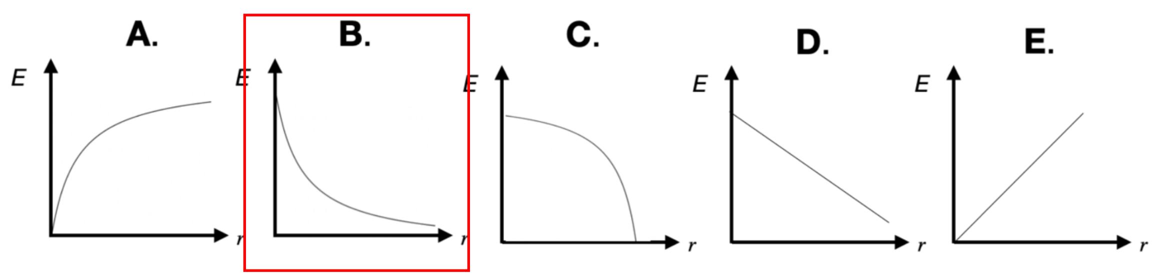
B. $\vec{E}_o = (-10\hat{\imath} + -5\hat{\jmath})\ \mathrm{N/C}$, $A\hat{n} = -2\ \mathrm{m}^2\ \hat{\imath}$, $\Phi = -20\ \mathrm{m^2N/C}$

C. $\vec{E}_o = (-10\hat{\imath} + -5\hat{\jmath})\ \mathrm{N/C}$, $A\hat{n} = +4\ \mathrm{m}^2\ \hat{\jmath}$, $\Phi = -20\ \mathrm{m^2N/C}$

D. $\vec{E}_o = (-10\hat{\imath} + -5\hat{\jmath})\ \mathrm{N/C}$, $A\hat{n} = +5\ \mathrm{m}^2\ \hat{\imath}$, $\Phi = -25\ \mathrm{m^2N/C}$

E. $\vec{E}_o = (-10\hat{\imath} + -5\hat{\jmath})\ \mathrm{N/C}$, $A\hat{n} = +5\ \mathrm{m}^2\ \hat{\imath}$, $\Phi = +50\ \mathrm{m^2N/C}$

6. (5 points) Which of the following graphs best represents the magnitude of the electric field as a function of r, measured radially outward from the surface of a very long wire of length L of charge density λ? Assume r much less than L.



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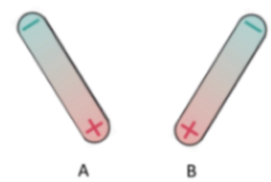
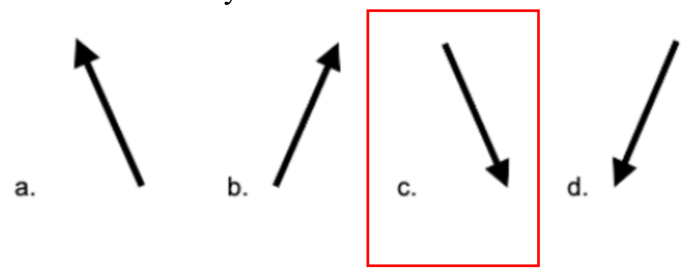
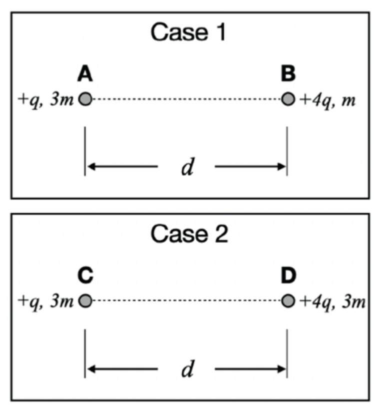
7. (5 points) Two identical polar molecules are placed in a region that has a uniform electric field. At one instant they have the orientations shown. Molecule A is experiencing no torque and molecule B is experiencing a counterclockwise torque. Which vector best represents the direction of the external electric field at this instant? You may assume the molecules are far away enough from one another that they do not affect each other's motion.





8. (5 points) In each case shown at right, a particle of charge $+q$ is placed a distance d from a particle of charge $+4q$. The masses of the particles, A, C, and D are all $3m$, the mass of particle B is m as labeled in the diagram. The particles are then released simultaneously. For which particle, if any, will the magnitude of the acceleration be the greatest after the particles are released?



A. A

B. B

C. C

D. D

E. The magnitude of the acceleration for all particles will be the same.

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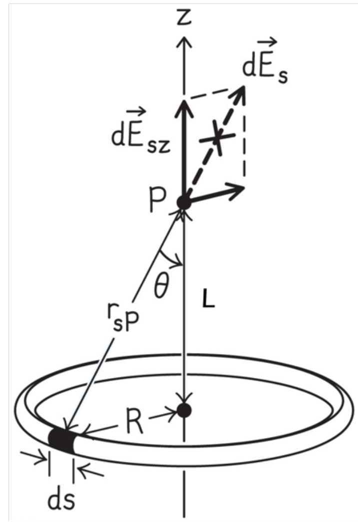
9. (5 pts) A thin ring of radius R carries a uniformly distributed charge q. The ring lays on the xy-plane with its center at the origin. What is the magnitude of the electric field at point P on the z-axis, a distance L away from the origin?



A. $\int_0^{2\pi R} k \frac{Lq}{2\pi R(L^2+R^2)} ds$

B. $\int_0^{2\pi R} k \frac{q}{2\pi R(L^2+R^2)} ds$

C. $\int_0^{2\pi R} k \frac{q}{2\pi R(L^2+R^2)^{3/2}} ds$

D. $\int_0^{2\pi R} k \frac{q}{2\pi (L^2+R^2)^{3/2}} ds$

E. $\int_0^{2\pi R} k \frac{Lq}{2\pi R(L^2+R^2)^{3/2}} ds$

II. Lab multiple choice [15 points]

Choose only one answer for each question, and fill it out on your scantron.

10. (5 pts) In Lab A2, a group places two charges 0.50 m apart and measures the force on one of the charges. They repeat the experiment three times and tabulate their data as shown. Which of the values below correctly reports the best estimate and the associated uncertainty according to the rules introduced in these labs?

Trial	Force (N)
1	4.51
2	4.64
3	4.73

A. (4.63 ± 0.1) N

B. (4.63 ± 0.11) N

C. (4.6 ± 0.1) N

D. (4.6 ± 0.2) N

E. More than one of these choices correctly reports the best estimate and its uncertainty.

The average of the data can be found as follows:

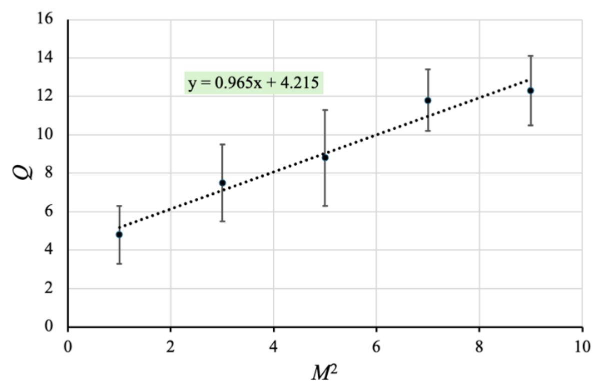
$$avg = \frac{4.51\text{ N} + 4.64\text{ N} + 4.73\text{ N}}{3} = 4.63\text{ N}$$

And the standard deviation as:

$$\sigma = \sqrt{\frac{(4.51\ \mathrm{N} - 4.63\ \mathrm{N})^2 + (4.64\ \mathrm{N} - 4.63\ \mathrm{N})^2 + (4.73\ \mathrm{N} - 4.63\ \mathrm{N})^2}{2}} = 0.11\ \mathrm{N}$$

If the students wanted to use two significant figures in the error (as calculated by the standard deviation), they could report the value as (4.63 ± 0.11) N *or if they wanted to use one significant figure in the error, they could report the value as* (4.6 ± 0.1) N. *This means that choice E is correct as both choices B and C represent a correct reporting of the best estimate and the uncertainty.*

11. (5 pts) A student has formed the graph of quantity Q versus the square of quantity M (M^2). They have also drawn the best-fit line on the graph. Which of the following is true?



A. Quantity Q is proportional to quantity M.

B. Quantity Q is proportional to quantity M^2.

C. Quantity Q is linearly related to quantity M.

D. Quantity Q is linearly related to quantity M^2.

A proportional relationship between two variables, x and y, is given by the equation: $y = mx$. *A plot of a proportional relationship is a straight line that* ***goes through the origin****.*

A linear relationship between two variables, x and y, is given by the equation: $y = mx + c$. *A plot of a proportional relationship is a straight line that has a non-zero intercept.*

In the plot above, the trendline is straight and has a non-zero intercept. This means that the quantity Q has a linear relationship with M^2. *The equation of the trendline is also showed, which we can write as:*

$$Q = 0.965M^2 + 4.215$$

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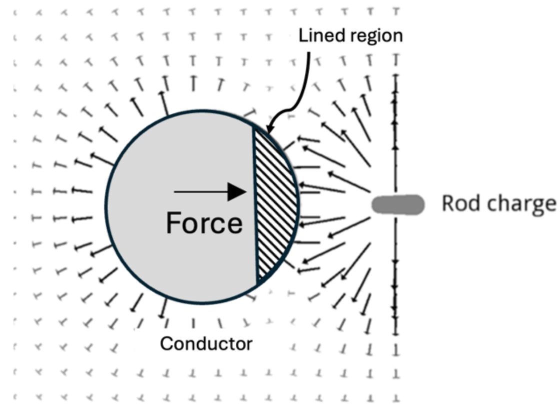
12. (5 pts) The diagram at right is a screenshot from the Lab A1 simulation. Both the rod and the conductor have excess charge. Based on the information given in the image, which of the following statements do you agree with?



I. The lined region on the conductor has the same sign charge as the rod.

II. The lined region on the conductor has the opposite sign charge as the rod.

III. The charge on the rod and conductor must have opposite signs since the conductor experiences an attractive force to the rod.

IV. The charge on the rod and conductor could be the same sign and the conductor is attracted to the rod due to polarization.

A. Statements I and III

B. Statements I and IV

C. Statements II and III

D. Statements II and IV

The lined region on the conductor aims to represent the polarization of the conductor. The charged rod attracts the opposite charge on the conductor and causes the right-hand side of the conductor to have a partial charge that is opposite to that of the conductor. The polarization of the conductor can cause the conductor to be attracted to the rod. It is not necessary for the rod and conductor to have opposite charge to be attracted, making statement III incorrect.

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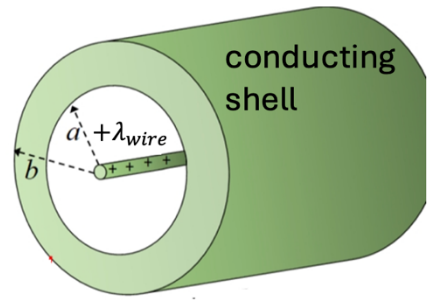
III. Lecture Free Response [25 points]



$Q13 – Q17$ refer to this context: An infinite wire with charge density $+\lambda_{wire}$ is surrounded by an infinitely long cylindrical conducting shell that has zero excess charge. The shell and wire share the same axis.

13. [6 pts] What is the surface charge density, λ_{inner}, on the **inner surface** of the conducting shell (at $r = a$ from the axis)? Answer in terms of the given variables. Be sure to include the sign and explicitly state if λ_{inner} is zero. Explain your reasoning.

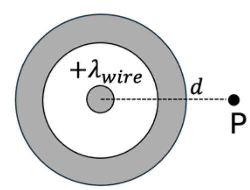
Choose a cylindrical Gaussian surface with a curved portion that lies inside the conducting shell and with an axis aligned with the wire. Since the electric field is zero inside the conductor, the flux through the curved part is zero. Since electric field for r < a must point in the radial direction by symmetry, the flux through the endcaps of the Gaussian surface is also zero. The net flux is zero through the surface, so by Gauss' Law the net charged enclosed must also be zero. Therefore, $\lambda_{inner} + \lambda_{wire} = 0$, *and so* $\lambda_{inner} = -\lambda_{wire}$.

14. [5 pts] What is the surface charge density, λ_{outer}, on the **outer surface** of the large conducting shell? Answer in terms of the given variables. Be sure to include the sign and explicitly state if λ_{outer} is zero. Explain your reasoning.

Charge is conserved and the conducting shell has zero excess charge overall.

Therefore $\lambda_{inner} + \lambda_{outer} = 0$, *and so* $\lambda_{outer} = -\lambda_{inner} = +\lambda_{wire}$.

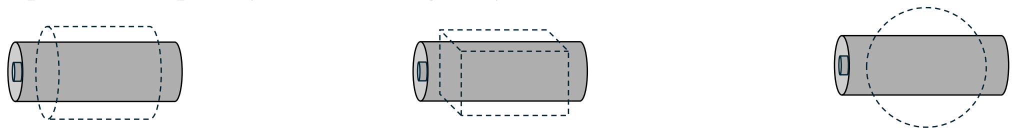
15. [3 pts] A cross section of the setup is shown at right. On the diagram, sketch the direction of the electric field at point P. If the electric field is zero, state so explicitly. No explanation required.



The electric field at point P is to the right. No explanation is required, but one could argue it this way:

Due to the cylindrical symmetry in the problem, the electric field could only have radial components. To determine whether $\vec{E}$ *points radially inward, outward, or is zero at point P, choose a cylindrical Gaussian surface with radius d centered on the wire. This surface encloses net positive charge, so flux through the curved part of the surface must be positive—which corresponds to an outward electric field.*

16. [5 pts] Which of the following Gaussian surfaces would allow you to determine the electric field strength at point P? Explain your reasoning for your choice.



*The **cylindrical** surface would allow us to determine the electric field. The symmetry of this surface matches the symmetry of the wire and shell. At all points on the surface, the magnitude of the electric field is constant and the angle between the field and the area vector $d\vec{A}$ is constant, which allows us to simplify the flux integral.*

17. [6 pts] Use the Gaussian surface you chose in the previous question to write an expression for the electric field at point P in terms of the variables given and any constants. If you choose to use any additional variables, be sure to define them. Show your work.

Call the length of the cylindrical Gaussian surface L. The net charge enclosed by the surface is $Q_{in} = \lambda_{wire} L$. By Gauss' Law, the net electric flux through the surface is $\Phi_e = \frac{Q_{in}}{\epsilon_o} = \lambda_{wire} L/\epsilon_o$.

The flux through the flat endcaps is zero. For the curved portion, the field has constant magnitude and is parallel to the area vector all locations, so the integral can be simplified:

$\Phi_e = \int \vec{E} \cdot d\vec{A} = E \int dA = EA = E(2\pi d L)$

This is equal to the net flux through the surface in this case. Setting this equal to our earlier expression and solving for E we get

$$E = \frac{\lambda_{wire}}{2\pi\epsilon_o d}$$

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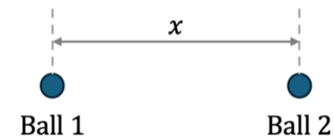
IV. Tutorial Free Response [15 points]

18. (5 pts) Two positively charged balls are placed a distance x apart as shown. The magnitude of the charge on ball 1 is larger than the magnitude of the charge on ball 2. The balls are observed to repel.



Is the magnitude of the electric force on ball 1 *greater than, less than,* or *equal to* the magnitude of the electric force on ball 2? Explain.

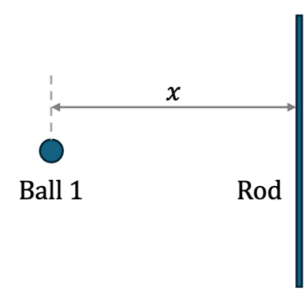
The force exerted by ball 1 on ball 2 and the force exerted by ball 2 on ball 1 form a Newton's third-law force pair. This means that the forces have equal magnitudes.

We could also consider the Coulomb's law which describes the forces on point charges.

$$\left|\vec{F}_{12}\right| = \left|\vec{F}_{21}\right| = k\frac{q_1 q_2}{x^2}$$

The magnitude of the force as determined by Coulomb's law depends on the product of both charges. This is consistent with the conclusion that the magnitude of the forces in question are equal.

19. (5 pts) Ball 2 is replaced by a rod. The rod has the same positive charge that ball 2 had (in the previous section) and is placed the same distance x from ball 1 as shown. The charge on the rod is uniformly distributed along its length.



Is the magnitude of the electric force on ball 1 by the rod (F_{1R}) *greater than, less than,* or the same as the magnitude of the electric force on ball 1 by ball 2 (F_{12}) in the previous section? Explain.

The uniformly charged rod in can be thought of as a continuous distribution of charge segments, each with a small amount of charge dQ. Each of the charge segments exerts an electric force on ball 1. For each segment on the right-half of the rod, we can pair it with a segment on the left-half of the rod such that the summation of forces exerted on ball 1 by this pair would result in the cancellation of their y-components. Additionally, as we move farther from the middle of the rod, the force exerted by each charge segment weakens, as the distance to ball 1 increases. As a result, the electric force exerted by the rod on ball 1 is smaller in magnitude than the electric force exerted by ball 2 on ball 1.

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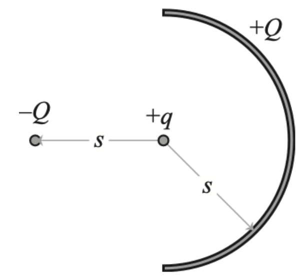
20. (5 pts) A thin, semicircular rod has a total charge $+Q$ uniformly distributed along it. A positive point charge $+q$ and a negative point charge $-Q$ are placed as shown. (The $+q$ charge is equidistant from $-Q$ and from all points on the rod.)



Let F_P and F_R represent the magnitudes of the forces on the $+q$ charge due to the $-Q$ point charge and due to the rod, respectively.

Is F_P *greater than, less than,* or *equal to* F_R? Explain.

We can apply a similar line of reasoning as that in Q19. The semicircular rod can be thought of as a continuous distribution of charge segments, each with a small amount of charge dQ. *We can pair each segment on the rod that lies above the point charge +q with a segment that lies below the point charge. The y-components of the forces exerted on the +q charge by these segments would cancel due to symmetry, leaving only a summation of the x-components. The magnitude of the total charge on the rod is the same as that of the -Q charge, and the -Q charge is the same distance from the +q charge as all points on the rod. However, since there is a cancellation of the y-components of the forces by each small dQ segment, the magnitude of the force exerted by the point charge -Q is greater than that exerted by the rod.*