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I. [60 pts] Multiple Choice: Mark your answer on BOTH the bubble sheet and this page.

1. [5 pts] A positively charged rod (net charge $+Q$) attracts a neutral insulator without the rod and the insulator touching each other. Choose the correct explanation for this observation.

   A. A total charge of $-Q$ is induced in the insulator, causing an attractive force.

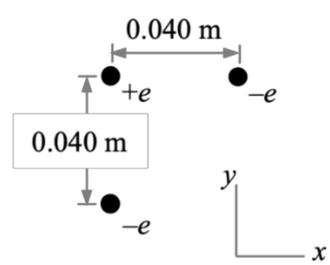
   B. All the negative charge of the insulator is pulled to the edge of the insulator that is closest to the rod, causing an attractive force.

   C. Objects with excess charge always repels electrically neutral objects even if the charge in the insulator cannot move.

   D. The atoms of the insulator get polarized in such a way that slightly more negative than positive charge is closer to the rod, causing an attractive force.

   The atoms or molecules themselves in the insulator have a slight dipole moment induced due to the nearby positive charge. For example, the electrons of the insulator, on average, move slightly closer to the rod. This effect leaves the closer (and thus stronger) negative charges to produce a greater attraction to the rod than the relatively farther (and thus weaker) positive charges that produce a repulsive force.

2. [5 pts] A proton and two electrons are fixed in place as shown. What is the ***x*-component** of the electric force on the **top-right electron?** A coordinate system is defined in the diagram.



   A. $2.5 \times 10^{-25}\,\mathrm{N}$

   B. $-4.2 \times 10^{-26}\,\mathrm{N}$

   C. $-7.2 \times 10^{-26}\,\mathrm{N}$

   D. $-9.3 \times 10^{-26}\,\mathrm{N}$

   E. None of these

   The positive charge exerts an attractive force to the left (negative x-direction) while the negative charge produces exerts a repulsive force up-and-right (positive x-component of force). We need to add these two x-components of the force.

   The magnitude of the force exerted by the positive charge is $K|e(-e)|/(r^2) = 1.44 \times 10^{-25}\,\mathrm{N}$*, so the x-component is* $-1.44 \times 10^{-25}\,\mathrm{N}$*. The magnitude of the force exerted by the negative charge is* $K|e(-e)|/(r^2) = 7.2 \times 10^{-25}\,\mathrm{N}$*, so the x-component is* $+(7.2 \times 10^{-25}\,\mathrm{N})\cos(45°) = 5.1 \times 10^{-26}\,\mathrm{N}$*. The addition of these results in a net x-component of* $-9.3 \times 10^{-26}\,\mathrm{N}$*.*

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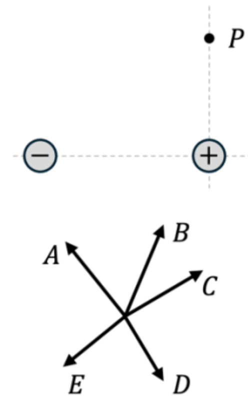
3. [5 pts] An electric dipole is illustrated at right. Which of the vectors $A - E$ in the diagram below best represents the direction of the electric field at point P?



A. Vector A

B. Vector B

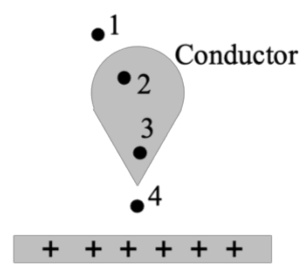
C. Vector C

D. Vector D

E. Vector E

We can use superposition of the two contributions to the electric field to find the net electric field. The electric field points award from positive charges (and toward negatives) and is stronger when closer to a charge. At point P, the field by the positive charge is directly upward, while the field by the negative charge is diagonally down-and-left but with smaller magnitude since the negative charge is farther away (and has an equal absolute value of charge as the positive charge). The addition of these two vectors results in a net field that has an upward and leftward component. Only choice A satisfies this condition.

4. [5 pts] A neutral conductor is placed near a large positively charged plate. Rank, from greatest to least, the four points according to the magnitude of the electric field.



A. 4 > 3 > 2 > 1

B. 4 > 1 > 3 = 2

C. 1 > 2 > 3 > 4

D. 2 = 3 > 4 > 1

E. 4 > 2 > 3 > 1

The electric field is zero inside conductors in electrostatic, so the field at 2 and 3 is zero. Outside of conductors, the field is stronger near sharp points, so the field at 4 will be greater than the field at 1. Thus, the final ranking is 4 > 1 > 3 = 2.

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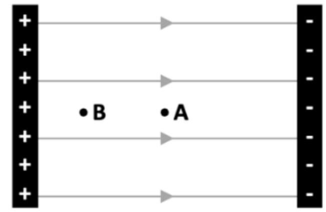
5. [5 pts] A positive charge is moved at constant speed from point A to point B in a uniform electric field as shown at right. Choose the correct statement for the work W done by the external force moving the charge and the change of the electric potential energy of the charge configuration, ΔU.



A. $W > 0,\ \Delta U < 0$

B. $W > 0,\ \Delta U > 0$

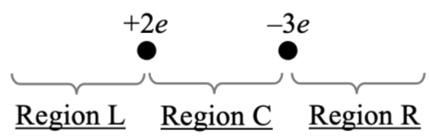
C. $W = 0,\ \Delta U = 0$

D. $W < 0,\ \Delta U < 0$

E. $W < 0,\ \Delta U > 0$

The electric force on the positive particle is to the right (same direction as the field), so the external force must exert a force to the left. A leftward external force and leftward displacement result in a positive external work, so $W > 0$. To determine the sign of ΔU, we can use the work-energy theorem $W_{net,ext} = \Delta K = \Delta U$ along with $\Delta K = 0$ (constant speed) which implies $\Delta U > 0$.

6. [5 pts] Two point charges are fixed in place, as shown. Three regions are defined; regions L and R are large but do not extend to infinity. In which regions could the electric potential be zero?



A. Only region L

B. Only region C

C. Only region R

D. Both regions L and R

E. Both regions L and C

Since a single point charge produces a potential $V = Kq/r$, the only way to have a net potential of zero is to be closer to the smaller charge so that the two absolute values of the potentials are the same. This is only possible in regions L and C.

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7. [5 pts] Along the *x*-axis, the electric potential depends on *x*, the distance from the origin, as $V(x) = Cx$, where *C* is a constant. What is the magnitude of the electric field on the *x*-axis?

   A. $E(x) = C$

   B. $E(x) = Cx^2$

   C. $E(x) = C/x$

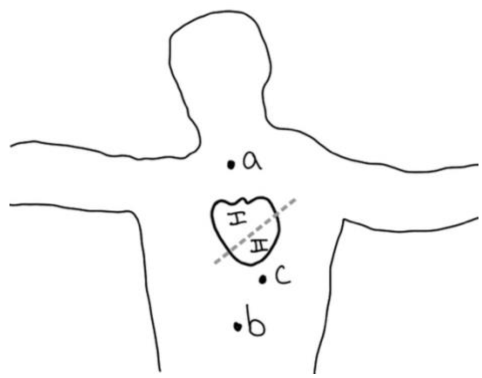
   D. $E(x) = Cx$

   E. $E(x) = 0$

   The SI units of electric field (V/m) demand that only choice A is correct. (Note that the SI units of C must be V/m since x has SI units of m and Cx must have SI units of V.)

   Alternatively, we see that the potential is linear in the position x from the reference point. We know that parallel plate capacitors are capable of producing linear electric potentials like this, which must be matched by a uniform electric field. Only choice A is uniform.

8. [5 pts] At the instant shown in the diagram, the heart can be modeled as an electric dipole. The dashed line represents a small portion of a much larger equipotential line.



   Suppose that at the instant shown, electrodes placed at locations c and a are measured to have voltage $V_a - V_c > 0$.

   What can be said about the sign of the voltage $V_b - V_a$ between electrodes a and b?

   A. $V_b - V_a > 0$

   B. $V_b - V_a < 0$

   C. $V_b - V_a = 0$

   D. More information is needed.

   Based on $V_a - V_c > 0$, side I of the heart must be positively charge and side II be negatively charged (i.e., the effective dipole of the heart is such that the positive charge is on side I). This means that point a is at positive potential and b is at negative potential, so choice B must be correct.

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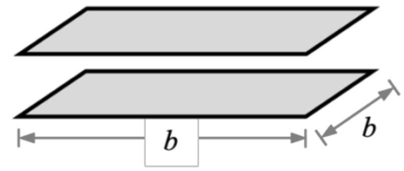
9. [5 pts] A vacuum parallel plate capacitor is composed of two identical square conductors (plates) that are separated by 0.01 m. When a 100-volt battery is attached to the plates, the charge stored on the positive plate is measured to be $4.0\ \mu\text{C} = 4.0 \times 10^{-6}$ C. What is the **area** of each plate?



A. 0.45 m^2

B. 6.7 m^2

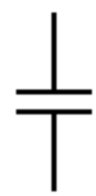
C. 45 m^2

D. 67 m^2

E. None of these

We can equate the definition of capacitance to the geometric expression for capacitance: $Q/\Delta V = \varepsilon_0 A/d$. *Solving for A yields* $Q/\Delta V = \varepsilon_0 A/d = 45\,\mathrm{m}^2$

10. [5 pts] A capacitor is initially connected to a battery to charge its plates. It is then disconnected from the battery, as shown.



Suppose a dielectric slab with dielectric constant 5 is inserted into the capacitor while it is disconnected from the battery. How does the energy stored in the capacitors change due to the dielectric?

A. Energy increases by a factor of 5

B. Energy decreases by a factor of 5

C. Energy increases by a factor of 25

D. Energy decreases by a factor of 25

E. Energy remains the same.

Dielectrics always increase capacitance (which is why we use them!) in a proportional manner, so the capacitance would increase by a factor of 5. Since charge is constant (and not voltage) due to the battery being disconnected, we can write the energy stored in a capacitor as $U_{\text{cap}} = \frac{1}{2}C(\Delta V)^2 = \frac{1}{2}C(Q/C)^2$ *which simplifies to* $U_{\text{cap}} = \frac{1}{2}Q^2/C$. *Thus, energy decreases by a factor of 5.*

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11. [5 pts] An experiment is conducted on an unknown electrical device. The voltage between its two terminals is varied and the resulting current is measured. The data is shown at right.

I (amps)	|Δ*V*| (volts)
2	6
3	8
4	10
5	12

Based on this data, can the device be considered ohmic?

A. Yes, the device is ohmic because equal changes in voltage result in equal changes in current.

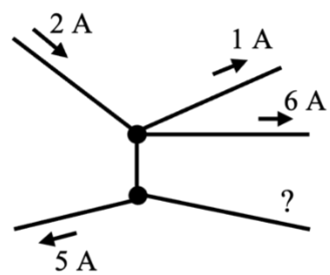
B. Yes, the devices is ohmic because only whole numbers are measured.

C. No, the device is not ohmic because only whole numbers are measured.

D. No, the device is not ohmic because the resistance is different for each data point.

The resistance $R = |\Delta V|/I$ is different for each data point. For example, the resistance is 3 ohms for the first one and 2.4 ohms for the last.

12. [5 pts] A portion of a circuit is shown in the diagram. Determine the current in the unknown wire, including its direction.



A. 0 A (no current)

B. 1 A, rightward

C. 5 A, leftward

D. 10 A, leftward

E. 11 A, rightward

One way to proceed is to focus first on the upper junction. A total of 7 amps is flowing out of the junction but only 2 amp is flowing in. By Kirchhoff's junction law, the unlabeled vertical wire must have an additional 5 amps flowing into the junction (upward). Now apply Kirchhoff's junction law to the lower junction. There are 10 amps flowing out of the junction, so the unknown wire on the right must have 10 amps flowing into the junction (leftward)

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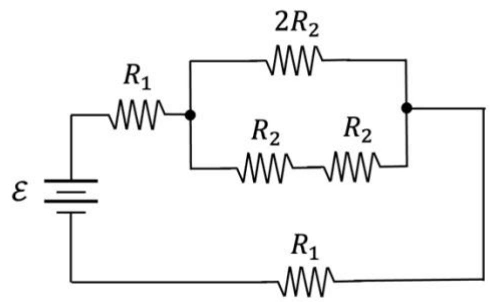
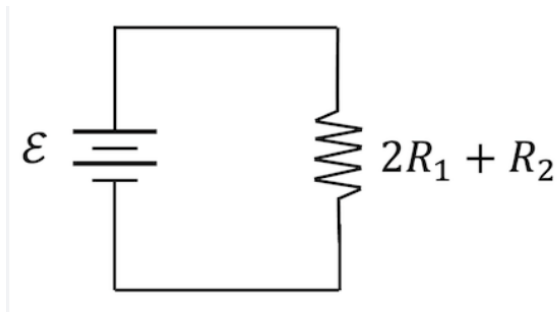
II. Lecture long-answer questions (20 points total)

Consider the circuit shown at right for the next two questions.

13. [5 pts] Draw an equivalent circuit containing only one resistor and express the equivalent resistance with the quantities given in the original circuit. Explain how you determined the equivalent resistance.



First, we will calculate the equivalent resistance for the parallel resistors: $\left(\frac{1}{2R_2}+\frac{1}{R_2+R_2}\right)^{-1} = R_2$*. Now, we have resistances* R_1, R_2*, and* R_1 *in series. So, the total equivalent resistance is* $R_{eq} = R_1 + R_2 + R_1 = 2R_1 + R_2$.



14. [5 pts] Express Kirchhoff's loop law for the equivalent circuit and determine the current through the battery.

Kirchhoff's loop law reads $\mathcal{E} - IR_{eq} = 0 \Rightarrow \mathcal{E} = IR_{eq}$*. This is a single loop, so the current is the same everywhere along the circuit, and the current through the battery is then* $I = \mathcal{E}/R_{eq} = \mathcal{E}/(2R_1 + R_2)$*.*

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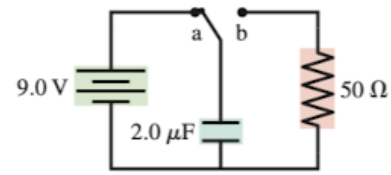
Consider the circuit shown at right for the next two questions.



15. [4 pts] What are the charge Q on the capacitor and the current I through the resistor when the switch has been in position a for a long time? Show your work.

When the switch has been in position a for a long time, the capacitor is fully charged and at the same potential with the battery. Thus, $Q = CV = (2.0 \cdot 10^{-6}\text{ F}) \cdot (9.0\text{ V}) = 1.8 \cdot 10^{-5}\text{ C}$. *On the other hand, the right side of the circuit is open (no conducting pathway) and there is no current flowing through the resistor.*

16. The switch is changed to position b at $t = 0$ s.

i. [3 pts] What is the current I through the resistor immediately after the switch is changed? Show your work.

Immediately after the switch is closed, the capacitor is still fully charged and has the same potential as the battery. The resistor is connected in parallel with the capacitor, which at this time could be considered the battery of the circuit, and according to Kirchhoff's loop law, the current at this moment reads $I_0 = \frac{9.0\text{ V}}{50\ \Omega} = 0.18\text{ A}$.

ii. [3 pts] What is the current I through the resistor at $t = 50\ \mu s$? Show your work.

This is an RC circuit and the current will decay as a function of time according to the equation $I(t) = I_0 e^{-t/\tau}$, *where the time constant* $\tau = RC = (50\ \Omega) \cdot 2.0 \cdot 10^{-6}\text{ F} = 100\ \mu s$. *Thus* $I(50\ \mu\text{s}) = I_0 e^{-1/2} = \frac{I_0}{\sqrt{e}} \approx 0.11\ A$.

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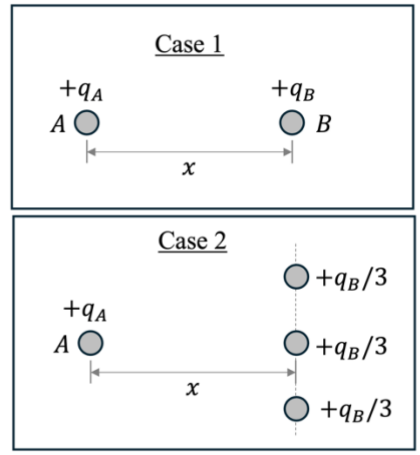
III. Tutorial and lab long answer questions (20 points total)

Use this context for questions 17 and 18.

Two experiments involve charged particles: In case 1, two positively charged particles, A and B are held a distance x apart as shown. The magnitude of the charge on particle A is *greater than* the magnitude of the charge on particle B ($|q_A| > |q_B|$).

In case 2, particle B is replaced by three identical particles of charge $q_{\mathrm{B}}/3$ that lie along a line as shown.



17. [5 pts] In case 1, is the magnitude of the electric force on particle A *greater than*, *less than*, or *equal to* the magnitude of the electric force on particle B? Explain.

    The force exerted by particle A by particle B and the force exerted by particle B on particle A 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.

$$\left|\vec{F}_{AB}\right| = \left|\vec{F}_{BA}\right| = k\frac{q_A q_B}{x^2}$$

    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.

18. [5 pts] Is the magnitude of the net electric force on particle A in case 2 *greater than*, *less than*, or *equal to* the magnitude of the electric force on particle A in case 1? Explain.

    Greater than. Suppose that the $+q_B$ charge in case 1 exerts a force of magnitude F_0 on the $+q_A$ charge in case 1. By Coulomb's law, the $+q_B/3$ charge directly to the right of the $+q_A$ charge in case 2 exerts a force $F_0/3$ on the $+q_A$ charge. The other two $+q_B/3$ charges in case 2 exert forces with magnitude less than $F_0/3$ on the $+q_A$ charge since they are located a distance greater than x from the $+q_A$ charge. Additionally, the y-components of the forces exerted by the upper and lower $+q_B/3$ charges in case 2 cancel due to symmetry. Due to the decreased forces and the cancelation of the y-components, the magnitude of the electric force on particle A greater than, less than, or equal to the magnitude of the electric force on particle B.

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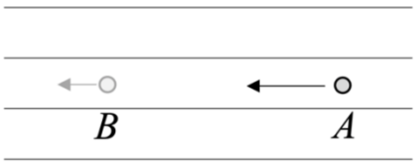
19. [5 pts] An electron is present in a uniform horizontal electric field (the direction of the field is not shown). At point *A*, the electron has a speed *v* and is moving to the left. At point *B*, the electron has a speed *v*/2.



Does the electric field point to the right or the left? Explain.

To the left.

Reasoning method 1: Since the electron slows down, we can conclude that the kinetic energy of the electron decreases as it moves to the left. This means that the work done on the electron is negative. Since the displacement is to the left, the force on the electron must be pointing to the right. Electrons experience forces in the opposite direction to the electric field, so the electric field must point to the left.

Reasoning method 2: Since the electron slows down as it moves to the left, the electron's acceleration must be to the right (acceleration direction opposes the velocity for an object that is slowing down.) For the acceleration to be to the right, the force on the electron must also be pointing to the right. Electrons experience forces in the opposite direction to the electric field, so the electric field must point to the left.

20. [5 pts] A capacitor is connected to an ideal battery of voltage V_0. The distance between the two plates is then increased, while the capacitor remains connected to the battery. Will the magnitude of the charge on the plates *increase, decrease* or *remain the same* as a result of increasing the distance between the plates? Explain.

Decrease. *Since the capacitor is connected to the battery, the voltage across the capacitor is always equal to the battery voltage which keeps a constant voltage V_0. Increasing the distance between the plates decreases the capacitance of the capacitor ($C = \varepsilon_0 A/d$).*

The charge on the plates is given as: $Q = CV$. Since the voltage across the plates remains the same, but the capacitance decreases, the charge on the plates must also decrease.

Alternative reasoning: The magnitude of the electric field between the plates of the capacitor is given as:

$$\left|\vec{E}\right| = \frac{Q}{\varepsilon_0 A} = \frac{|\Delta V|}{d}$$

Since the voltage remains the same and the distance between the plates is increased, the magnitude of the electric field between the plates decreases. Since the magnitude of the electric field is proportional to the charge on the plates, it can be reasoned that the charge on the plates must decrease.