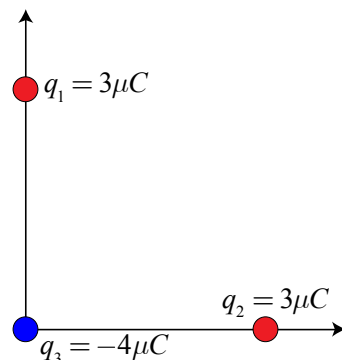


# AP2 Electrostatics

Three point charges are located at the corners of a right triangle as shown, where  $q_1 = q_2 = 3 \mu\text{C}$  and  $q_3 = -4 \mu\text{C}$ . If  $q_1$  and  $q_2$  are each 1 cm from  $q_3$ , what is the magnitude of the net force on  $q_3$ ?

- (A) 10.8 N
- (B) 1080 N
- (C) 1530 N
- (D) 2160 N



**Answer:** (C) 1530 N

Besides utilizing Coulomb's Law correctly, the key to success in this problem is recognizing that the forces on  $q_3$  are at right angles to each other. Therefore, to find the total, you must add them vectorially, finding their magnitude using the Pythagorean Theorem as they are at right angles to each other.

$$|\vec{F}_{1,3}| = \frac{kq_1q_2}{r^2} = \frac{(9 \times 10^9)(3 \times 10^{-6})(4 \times 10^{-6})}{(.01)^2} = 1080 \text{ N up}$$

$$|\vec{F}_{2,3}| = \frac{kq_1q_2}{r^2} = \frac{(9 \times 10^9)(3 \times 10^{-6})(4 \times 10^{-6})}{(.01)^2} = 1080 \text{ N right}$$

$$|\vec{F}_{total}| = \sqrt{(1080)^2 + (1080)^2} = 1530 \text{ N up and to the right}$$

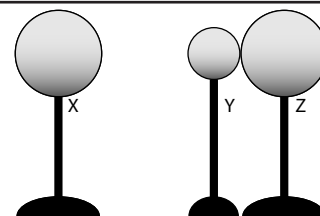
**EK:** 3.C.2 Electric force results from the interaction of one object that has an electric charge with another object that has an electric charge.

**SP:** 1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

**LO:** 3.C.2.3 The student is able to use mathematics to describe the electric force that results from the interaction of several separated point charges (generally 2 to 4 point charges, though more are permitted in situations of high symmetry).

# AP2 Electrostatics

Three metal spheres rest on insulating stands as shown in the diagram at right. Sphere Y is smaller than Spheres X and Z, which are the same size. Spheres Y and Z are initially neutral, and Sphere X is charged positively. Spheres Y and Z are placed in contact near Sphere X, though Sphere X does not touch the other spheres.



(a) Does sphere Y have a positive, negative, or neutral charge? Explain.

(b) Does sphere Z have a positive, negative, or neutral charge? Explain.

Spheres Y and Z are now separated.

(c) Compare the magnitude of the charge on Spheres Y and Z.

Sphere Y is now moved so that it touches Sphere X.

(d) What happens to the magnitude of the charge on Sphere X? Explain.

---

## Answers:

- (a) Y has a negative charge. The force of attraction from Sphere X pulls electrons from Sphere Z into Sphere Y, giving it a net negative charge.
- (b) Z has a positive charge. Z gives up excess electrons to Sphere Y, leaving it with a net positive charge.
- (c) The magnitude of the charge on Spheres Y and Z is equal due to conservation of charge.
- (d) The magnitude of the charge on Sphere X decreases due to a net flow of electrons from Y to X.

**EK:** 1.B.2 There are only two kinds of electric charge. Neutral objects or systems contain equal quantities of positive and negative charge, with the exception of some fundamental particles that have no electric charge. 4.E.3 The charge distribution in a system can be altered by the effects of electric forces produced by a charged object. 5.C.2 The exchange of electric charges among a set of objects in a system conserves electric charge.

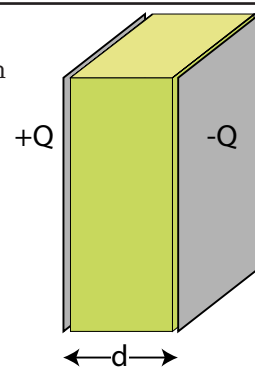
**SP:** 1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively.

**LO:** 1.B.2.2 The student is able to make a qualitative prediction about the distribution of positive and negative electric charges within neutral systems as they undergo various processes. 4.E.3.1 The student is able to make predictions about the redistribution of charge during charging by friction, conduction, and induction. 5.C.2.1 The student is able to predict electric charges on objects within a system by application of the principle of charge conservation within a system.

## AP2 Electrostatics

A capacitor is formed from two identical conducting parallel plates separated by a distance  $d$ . One plate is charged  $+Q$ , the other plate is charged  $-Q$ . A dielectric slab fills the space between the two plates. Where is the energy stored in this capacitor?

- (A) On the outsides of the metal plates.
- (B) On the insides of the metal plates.
- (C) On the outside surface of the dielectric slab.
- (D) Inside the dielectric slab.



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**Answer:** (D) Inside the dielectric slab.

The energy stored in a capacitor is actually stored in the form of electric field between the charged plates.

**EK:** 2.C.5 Between two oppositely charged parallel plates with uniformly distributed electric charge, at points far from the edges of the plates, the electric field is perpendicular to the plates and is constant in both magnitude and direction. 5.B.9 Kirchhoff's loop rule describes conservation of energy in electrical circuits. Energy conservation can be applied to combinations of resistors and capacitors in series and parallel circuits. 4.E.4 The resistance of a resistor, and the capacitance of a capacitor, can be understood from the basic properties of electric fields and forces, as well as the properties of materials and their geometry.

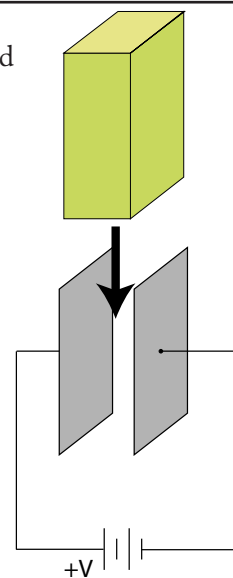
**SP:** 1.2 The student can describe representations and models of natural or man-made phenomena and systems in the domain. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

**LO:** 2.C.5.1 The student is able to create representations of the magnitude and direction of the electric field at various distances (small compared to plate size) from two electrically charged plates of equal magnitude and opposite signs, and is able to recognize that the assumption of uniform field is not appropriate near edges of plates. 5.B.9.5 The student is able to use conservation of energy principles (Kirchhoff's loop rule) to describe and make predictions regarding electrical potential difference, charge, and current in steady-state circuits composed of various combinations of resistors and capacitors. 4.E.4.1 The student is able to make predictions about the properties of resistors and/or capacitors when placed in a simple circuit, based on the geometry of the circuit element and supported by scientific theories and mathematical relationships.

## AP2 Electrostatics

An air-gap parallel plate capacitor is attached to a source of constant potential difference as shown in the diagram at right. Which of the following statements is true if a dielectric is inserted between the plates?

- (A) Energy stored in the capacitor is reduced.
- (B) Work must be done to insert the dielectric.
- (C) Capacitance of the device is reduced.
- (D) Electric field between the plates increases.



**Answer:** (B) Work must be done to insert the dielectric.

The insertion of the dielectric increases the capacitance of the device. The potential difference between the plates remains constant due to the voltage source; therefore the electric field between the plates must remain constant as reflected by  $E=V/d$ . The energy stored in the capacitor must therefore increase, as reflected by the formula  $U=0.5CV^2$ . The additional energy comes from the work done to insert the dielectric.

**EK:** 1.E.4 Matter has a property called electric permittivity. Free space has a constant value of the permittivity that appears in physical relationships. The permittivity of matter has a value different from that of free space. 2.C.5 Between two oppositely charged parallel plates with uniformly distributed electric charge, at points far from the edges of the plates, the electric field is perpendicular to the plates and is constant in both magnitude and direction. 2.E.3 The average value of the electric field in a region equals the change in electric potential across that region divided by the change in position (displacement) in the relevant direction.

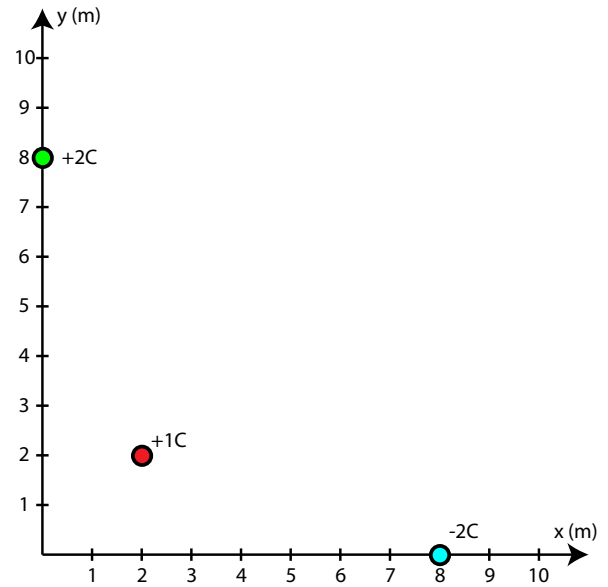
**SP:** 1.5 The student can reexpress key elements of natural phenomena across multiple representations in the domain. 7.2 The student can connect concepts in and across domain(s) to generalize or extrapolate in and/or across enduring understandings and/or big ideas.

**LO:** 2.C.5.1 The student is able to create representations of the magnitude and direction of the electric field at various distances (small compared to plate size) from two electrically charged plates of equal magnitude and opposite signs, and is able to recognize that the assumption of uniform field is not appropriate near edges of plates. 2.E.3.1 The student is able to apply mathematical routines to calculate the average value of the magnitude of the electric field in a region from a description of the electric potential in that region using the displacement along the line on which the difference in potential is evaluated.

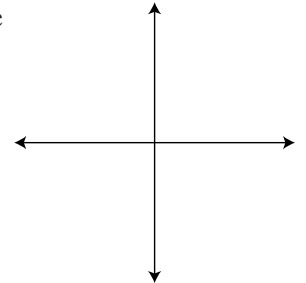
# AP2 Electrostatics

Three point charges are situated as shown in the diagram at right.

- (a) Find the magnitude of the electric field at the origin due to the three charges shown.



- (b) On the diagram at right, draw an arrow to represent the net electric field vector at the origin. Label angle theta in your diagram.  
(c) Determine the angle theta in your diagram, in degrees.



- (d) Calculate the electric potential at the origin.

- (e) If an electron is placed at the origin, what electric potential energy does it possess? Answer in units of electron-volts.

# AP2 Electrostatics

**Answer:**

- (a) First find the electric field due to each of the individual charges in terms of their vector components, then add those vectors to find the total electric field vector. You can then find the magnitude of the total electric field due to the three charges.

$$\vec{E}_{(0,8)} = \frac{kq}{r^2} = -\frac{(9 \times 10^9)(2)}{8^2} \hat{j} = -2.81 \times 10^8 \hat{j} \text{ N/C}$$

$$\vec{E}_{(8,0)} = \frac{kq}{r^2} = -\frac{(9 \times 10^9)(2)}{8^2} \hat{i} = 2.81 \times 10^8 \hat{i} \text{ N/C}$$

$$|\vec{E}_{(2,2)}| = \frac{kq}{r^2} = -\frac{(9 \times 10^9)(1)}{(\sqrt{2^2 + 2^2})^2} = 1.13 \times 10^9 \text{ N/C} \rightarrow \vec{E}_{(2,2)} = -7.95 \times 10^8 \hat{i} \text{ N/C} - 7.95 \times 10^8 \hat{j} \text{ N/C}$$

$$\vec{E}_{\text{Total}} = -5.14 \times 10^8 \hat{i} \text{ N/C} - 1.08 \times 10^9 \hat{j} \text{ N/C}$$

$$|\vec{E}_{\text{Total}}| = \sqrt{(-5.14 \times 10^8)^2 + (-1.08 \times 10^9)^2} = 1.20 \times 10^9 \text{ N/C}$$

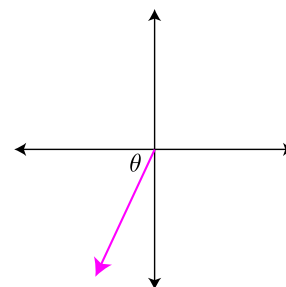
- (b) See diagram at right.

$$(c) \theta = \tan^{-1}\left(\frac{\text{opp}}{\text{adj}}\right) = \tan^{-1}\left(\frac{1.08 \times 10^9}{5.14 \times 10^8}\right) = 65^\circ$$

$$(d) V = \sum \frac{kq}{r} = \frac{(9 \times 10^9)(2)}{8} + \frac{(9 \times 10^9)(-2)}{8} + \frac{(9 \times 10^9)(1)}{\sqrt{2^2 + 2^2}} = 3.18 \times 10^9 \text{ V}$$

$$(e) U = qV = (-1.6 \times 10^{-19} \text{ C})(3.18 \times 10^9 \text{ V}) = -5.1 \times 10^{-10} \text{ J}$$

$$-5.1 \times 10^{-10} \text{ J} \times \frac{1 \text{ eV}}{1.6 \times 10^{-19} \text{ J}} = -3.18 \times 10^9 \text{ eV}$$



**EK:** 2.A.2 A scalar field gives, as a function of position (and perhaps time), the value of a physical quantity that is described by a scalar, such as electric potential. 2.C.4 The electric field around dipoles and other systems of electrically charged objects (that can be modeled as point objects) is found by vector addition of the field of each individual object.

**SP:** 1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 3.3 The student can evaluate scientific questions.

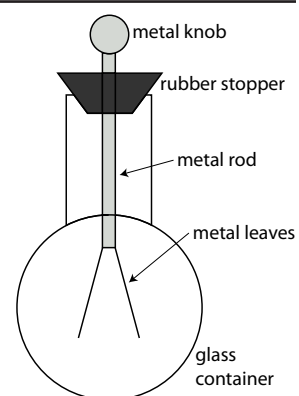
**LO:** 2.A.2.b A scalar field gives, as a function of position (and perhaps time), the value of a physical quantity that is described by a scalar, such as electric potential. When more than one source object with mass or charge is present, the scalar field value can be determined by scalar addition. 2.C.4.2 The student is able to apply mathematical routines to determine the magnitude and direction of the electric field at specified points in the vicinity of a small set (2–4) of point charges, and express the results in terms of magnitude and direction of the field in a visual representation by drawing field vectors of appropriate length and direction at the specified points.

# AP2 Electrostatics

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A student investigates how a negatively charged ebonite rod influences an uncharged electroscope as shown in the diagram at right.

- (a) Write a step-by-step procedure of how the negatively charged ebonite rod could produce a positive charge on the electroscope. Other materials can be used, but none can be charged, and none can alter the charge of the ebonite rod.



- (b) Referring to each step your procedure in part (a), describe or illustrate the movement of any relevant charge in the ebonite rod, electroscope and/or other materials used.

- (c) Assume the student charges the electroscope. Describe how the negatively charged ebonite rod could be used to test whether the electroscope is positively charged. Also explain what the student should expect to observe and why.

# AP2 Electrostatics

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**Answer:**

- (a)
  - 1. Bring ebonite rod near, but do not touch, the knob of the electroscope.
  - 2. While keeping rod near, ground the electroscope with a finger or grounding wire.
  - 3. While keeping rod near, remove finger or grounding wire.
  - 4. Remove ebonite rod.
- (b)
  - 1. No change in ebonite rod, electrons repelled to the leaves of the electroscope.
  - 2. Electrons exit the electroscope into the ground/earth.
  - 3. No charge movement in either device.
  - 4. Positive and negative charges in electroscope redistribute such that the electroscope has a net positive charge.
- (c) Bring the negatively charged rod near the electroscope and look for attraction between the leaves; the positively charged leaves are attracted to the opposite charge.

**EK:** 1.B.2 There are only two kinds of electric charge. Neutral objects or systems contain equal quantities of positive and negative charge, with the exception of some fundamental particles that have no electric charge. 4.E.3 The charge distribution in a system can be altered by the effects of electric forces produced by a charged object.

**SP:** 1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 4.2 The student can design a plan for collecting data to answer a particular scientific question.

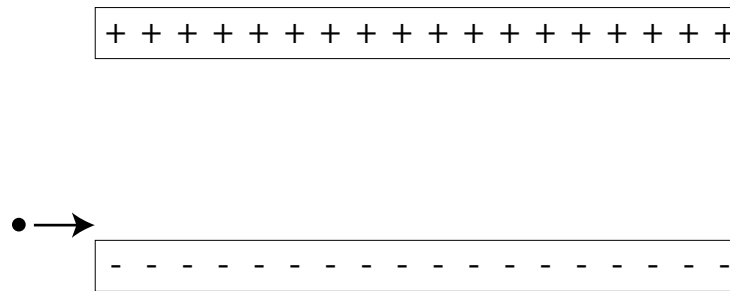
**LO:** 1.B.2.2 The student is able to make a qualitative prediction about the distribution of positive and negative electric charges within neutral systems as they undergo various processes. 4.E.3.1 The student is able to make predictions about the redistribution of charge during charging by friction, conduction, and induction. 4.E.3.4 The student is able to construct a representation of the distribution of fixed and mobile charge in insulators and conductors that predicts charge distribution in processes involving induction or conduction. 4.E.3.5 The student is able to plan and/or analyze the results of experiments in which electric charge rearrangement occurs by electrostatic induction, or is able to refine a scientific question relating to such an experiment by identifying anomalies in a data set or procedure.



# AP2 Electrostatics

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Two charged, parallel plates are separated by a distance,  $d$ . The electric field intensity,  $E$ , is  $150 \text{ N/C}$ . An electron with a speed of  $3.0 \times 10^6 \text{ m/s}$  comes in from the left just above the negatively charged plate as shown below.



- (a) Draw the field lines between the plates.  
 (b) If the plates are  $10 \text{ cm}$  in length, how far has the electron moved in the  $y$ -direction during the time it takes to travel across the plates?

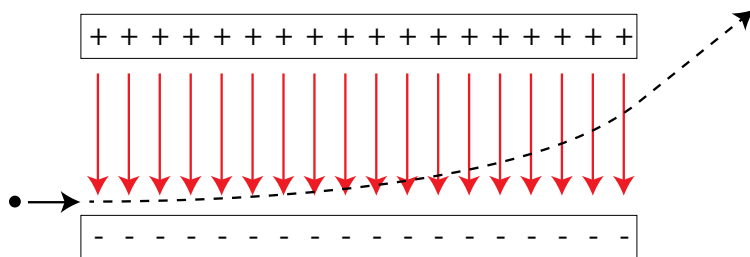
- (c) Sketch the trajectory of the electron as it moves through the plates and beyond.  
 (d) How much KE has the electron gained as it moves between the plates?

- (e) The electron is replaced by a proton moving at the same speed. How do the following change?
- |               |                 |                 |                        |
|---------------|-----------------|-----------------|------------------------|
| crossing time | _____ increases | _____ decreases | _____ remains the same |
| acceleration  | _____ increases | _____ decreases | _____ remains the same |
| $\Delta KE$   | _____ increases | _____ decreases | _____ remains the same |

# AP2 Electrostatics

Answer:

(a)



$$(b) \quad t_{cross} = \frac{d}{v} = \frac{0.1m}{3 \times 10^6 \text{ m/s}} = 3.3 \times 10^{-8} s$$

$$a_y = \frac{F_y}{m} = \frac{qE_y}{m} = \frac{(1.6 \times 10^{-19} C)(150 \text{ N/C})}{9.11 \times 10^{-31} \text{ kg}} = 2.63 \times 10^{13} \text{ m/s}^2$$

$$\Delta y = \frac{1}{2} a t^2 = \frac{1}{2} (2.63 \times 10^{13} \text{ m/s}^2) (3.3 \times 10^{-8} s)^2 = 0.014 m$$

(c) See diagram above

$$(d) \quad W = \Delta K = F \Delta y = qE_y \Delta y = (1.6 \times 10^{-19} C)(150 \text{ N/C})(0.014 m) = 3.4 \times 10^{-19} J$$

(e) crossing time                      \_\_\_\_\_ increases                      \_\_\_\_\_ decreases                        X   remains the same

acceleration                      \_\_\_\_\_ increases                        X   decreases                      \_\_\_\_\_ remains the same

$\Delta KE$                       \_\_\_\_\_ increases                        X   decreases                      \_\_\_\_\_ remains the same

Crossing time remains the same because no forces are acting in the direction of motion.

Acceleration decreases because the force remains the same and the mass increases.

Change in kinetic energy decreases because  $\Delta y$  decreases because acceleration decreases.

**EK:** 3.C.2 Electric force results from the interaction of one object that has an electric charge with another object that has an electric charge. 2.C.1 The magnitude of the electric force  $F$  exerted on an object with electric charge  $q$  by an electric field  $E$  is  $F=qE$ . The direction of the force is determined by the direction of the field and the sign of the charge, with positively charged objects accelerating in the direction of the field and negatively charged objects accelerating in the direction opposite the field. 2.C.5 Between two oppositely charged parallel plates with uniformly distributed electric charge, at points far from the edges of the plates, the electric field is perpendicular to the plates and is constant in both magnitude and direction.

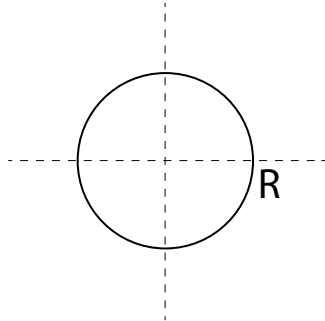
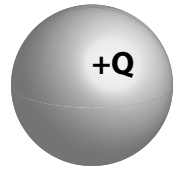
**SP:** 1.4 The student can use representations and models to analyze situations or solve problems qualitatively and quantitatively. 2.2 The student can apply mathematical routines to quantities that describe natural phenomena.

**LO:** 3.C.2.1 The student is able to use Coulomb's law qualitatively and quantitatively to make predictions about the interaction between two electric point charges. 2.C.1.1 & 2.C.2.2 The student is able to predict and calculate the direction and the magnitude of the force exerted on an object with an electric charge  $q$  placed in an electric field  $E$  using the mathematical model of the relation between an electric force and an electric field:  $F=qE$ ; a vector relation. 2.C.5.3 The student is able to represent the motion of an electrically charged particle in the uniform field between two oppositely charged plates and express the connection of this motion to projectile motion of an object with mass in the Earth's gravitational field.

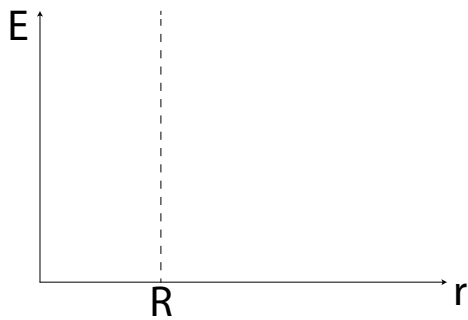
# AP2 Electrostatics

A charged conducting solid sphere of radius  $R$  has a charge of  $+Q$ .

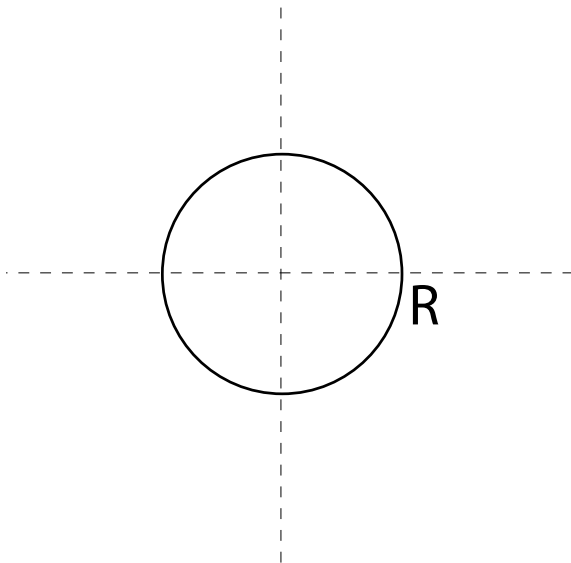
(a) Describe and draw the shape and direction of the electric field lines inside of  $R$  and beyond  $R$ .



(b) Sketch a graph of electric field intensity as a function of distance from the center of the sphere,  $r$ .



(c) Draw three equipotential lines as dashed lines on the diagram below.

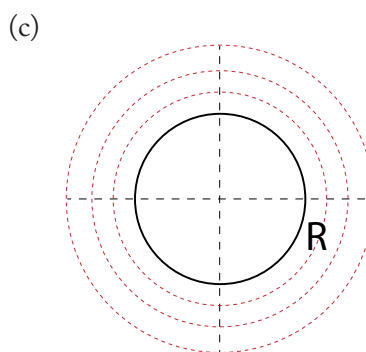
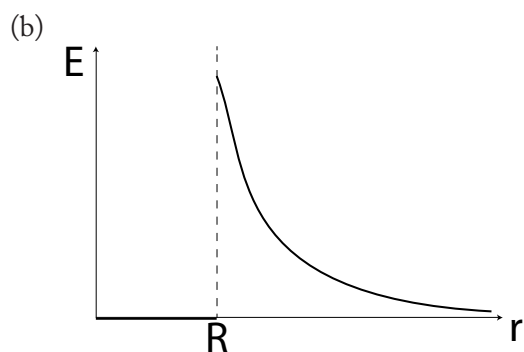
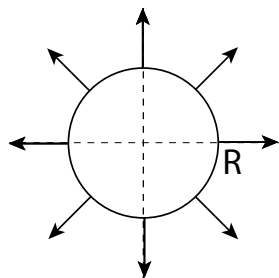


# AP2 Electrostatics

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**Answer:**

- (a)  $E=0$  inside the sphere, so no lines. Field lines radiate outward in all directions starting at the surface of the sphere.



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**EK:** 2.C.3 The electric field outside a spherically symmetric charged object is radial and its magnitude varies as the inverse square of the radial distance from the center of that object. (Electric field lines are not in the curriculum. Students will be expected to rely only on the rough intuitive sense underlying field lines, wherein the field is viewed as analogous to something emanating uniformly from a source.) 2.E.2 Isolines in a region where an electric field exists represent lines of equal electric potential, referred to as equipotential lines. An isoline map of electric potential can be constructed from an electric field vector map, using the fact that the isolines are perpendicular to the electric field vectors. Since the electric potential has the same value along an isoline, there can be no component of the electric field along the isoline.

**SP:** 1.1 The student can create representations and models of natural or man-made phenomena and systems in the domain. 1.5 The student can reexpress key elements of natural phenomena across multiple representations in the domain.

**LO:** 2.C.3.1 The student is able to explain the inverse square dependence of the electric field surrounding a spherically symmetric electrically charged object. 2.E.2.1 The student is able to determine the structure of isolines of electric potential by constructing them in a given electric field.

# AP2 Electrostatics

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Four air-gap capacitors with various dimensions and conditions are arranged as described in the table below.

Capacitor	Area of Plates	Separation Distance	Voltage Across Plates
A	A	2d	V
B	A	d	2V
C	2A	d	V/2
D	2A	d/2	V

Rank each capacitor from lowest to highest amount of charge on each plate.

- (A)  $D=C<B=A$
- (B)  $C<D=A<B$
- (C)  $C<A<D<B$
- (D)  $A<C<B<D$

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**Answer:** (D)  $A<C<B<D$ . Charge is the product of capacitance and voltage, and capacitance is proportional to area / separation distance, therefore  $Q$  is proportional to  $VA/d$ .

**EK:** 4.E.4 The resistance of a resistor, and the capacitance of a capacitor, can be understood from the basic properties of electric fields and forces, as well as the properties of materials and their geometry.

**SP:** 2.2 The student can apply mathematical routines to quantities that describe natural phenomena. 6.4 The student can make claims and predictions about natural phenomena based on scientific theories and models.

**LO:** 4.E.4.2 The student is able to design a plan for the collection of data to determine the effect of changing the geometry and/or materials on the resistance or capacitance of a circuit element and relate results to the basic properties of resistors and capacitors.