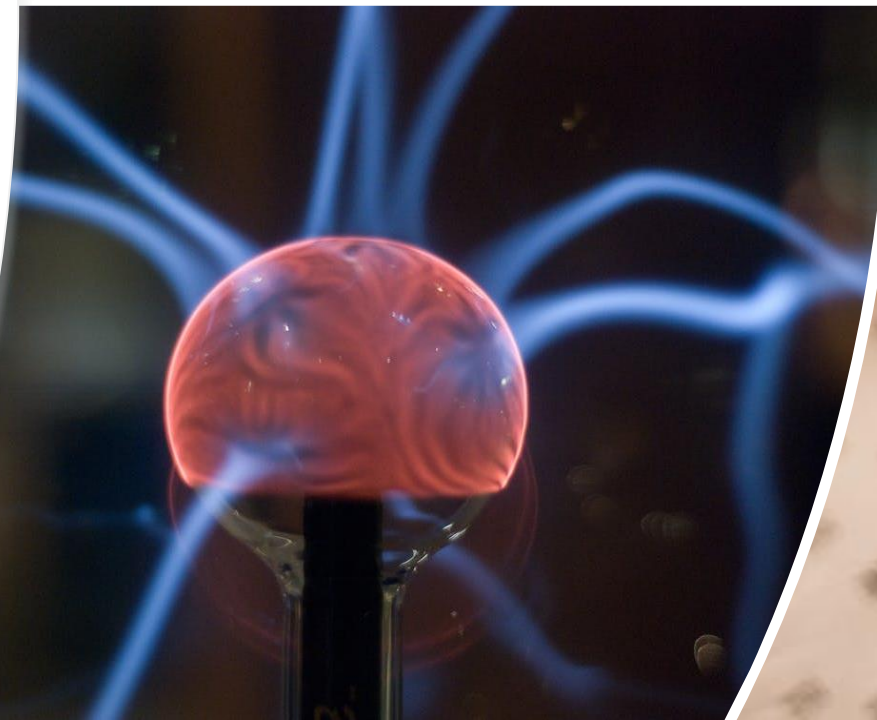


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# Electric Field

Overmugged





# Content

- Concept of an electric field
- Electric force
- Electric field strength
- Electric potential and electric potential energy
- Equipotential lines and surfaces
- Motion of charged particle in a uniform electric field



# Concept of an Electric Field

- When a charge particle is placed in the presence of another charged particle, one charge particle experiences an electric force due to the electric field setup by the other charged particle. This force may be attractive or repulsive, depending on the nature of the charges involved. French physicist Charles Coulomb (1736-1806) deduced dependence of this electric force on various physical quantities. The relationship is now commonly known as Coulomb's Law.
- As it was observed that electric forces experienced by charged particles act at a distance without coming into contact, Michael Faraday (1791 – 1867) uses the field concept to explain this phenomenon. An electric field is a region of space where an electric charge experiences a force (due to other charged bodies).





# Concept of an Electric Field

- Like the concept of a gravitational field existing in the region around a mass, in the region around an electric charge, there exists an **electric field**; an electric field extends outwards from every charge and permeates all of space. The electric field is a vector field; it consists of a distribution of vectors, one for each point in the region around a charged object. When another charged particle is placed within the region of the electric field, it interacts directly with field, experiencing a force.



# Coulomb's Law

- states that the force between two point charges is proportional to the product of the charges and inversely proportional to the square of the distance between them.

Mathematically, it is written as  $F \propto \frac{Qq}{r^2}$

$$F = \frac{1}{4\pi\epsilon_0} \frac{Qq}{r^2}$$

where  $Q, q$  = charges in coulombs [C]

$r$  = distance between the charges

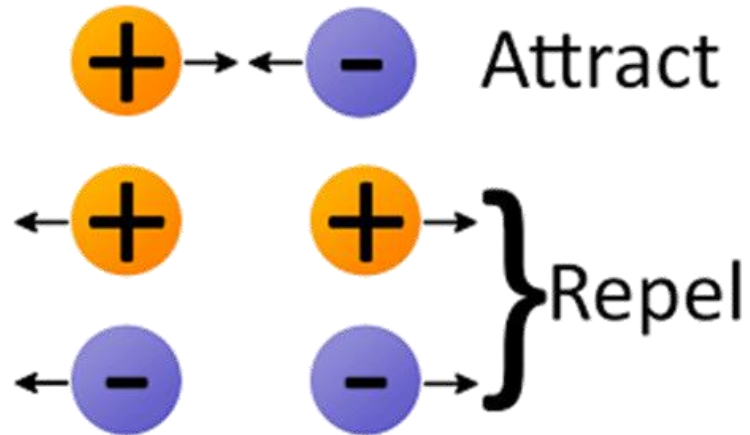
$\epsilon_0$  = permittivity of free space =  $8.85 \times 10^{-12} \text{ s}^4 \text{ A}^2 / \text{m}^3 \text{ kg}$



# Coulomb's Law



- like charges repel → sign of  $F$  is positive
- unlike charges attract → sign of  $F$  is negative

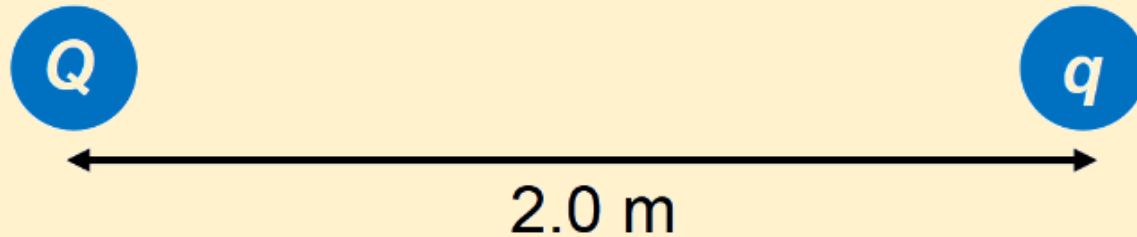


- both Coulomb's law and Newton's law of gravitation are sometimes referred to as *inverse-square law*.
- Electric force can be attractive or repulsive, but gravitational force is always attractive.



## Practice Example 1

Two charges  $Q$  ( $+3.0\mu\text{C}$ ) and  $q$  ( $-4.0\mu\text{C}$ ) are 2.0 m away from each other.



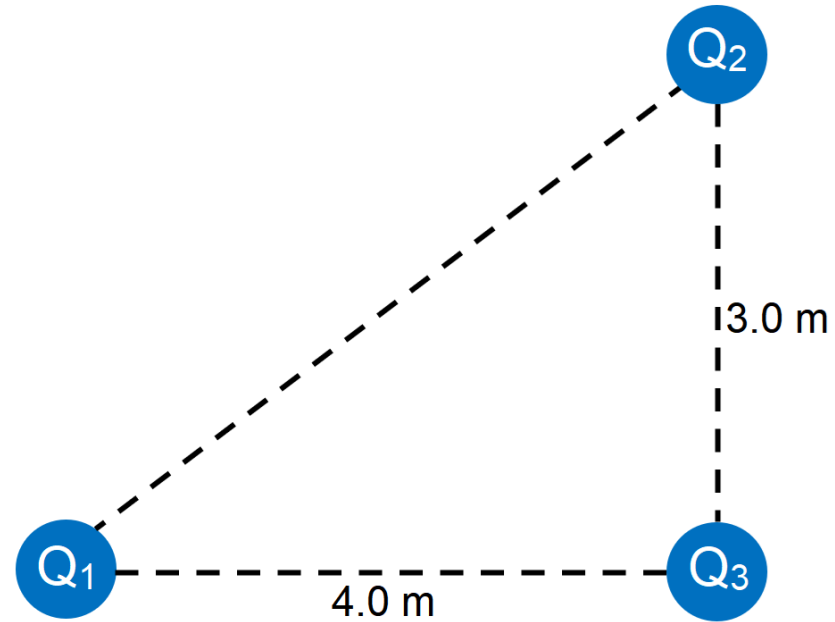
- (a) What is the magnitude and direction of the force acting on  $Q$  by  $q$ ?
- (b) If  $Q$  is replaced with a negative charge (same magnitude as  $Q$ ), what would be the magnitude and direction of the force on  $Q$  by  $q$ ?



## Practice Example 2

Three charges  $Q_1 = -1.0 \mu\text{C}$ ,  $Q_2 = -2.0 \mu\text{C}$ ,  $Q_3 = 3.0 \mu\text{C}$  are positioned at the corners of a right triangle as shown on the right.

Determine the magnitude and direction of the resultant force on charge  $Q_3$  by the other two charges  $Q_1$  and  $Q_2$ .





# Electric Field Strength

Symbol:  $E$

SI unit: Newton per Coulomb [N/C] or Volt per meter [V/m]

Vector quantity

- is a region of space in which a charge placed in that region experiences an electric force.
- $E$  at a point is defined as the electric force exerted per unit positive charge placed at that point

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

where  $F$  = is the electric force on the charge  $q$ .

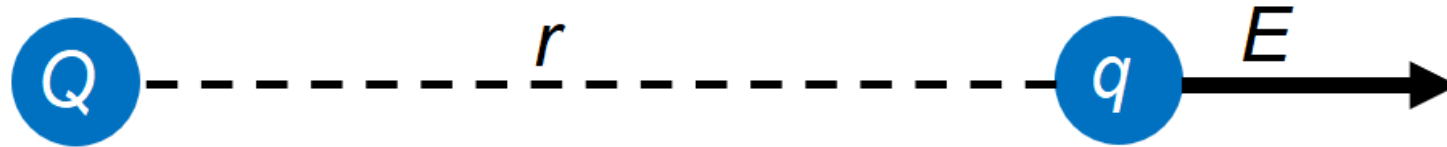


- *E-field* direction is that of the force acting on a positive charge.
- It points from a region of higher electric potential to a region of lower electric potential.
- Some references refer electric field strength as electric field.



# E-Field Strength due to a Point Charge

A positive point charge  $q$  is placed a distance  $r$  from another positive point charge  $Q$ .



The charge  $q$  will experience a force  $F$  given by Coulomb's law:  $F = \frac{1}{4\pi\epsilon_0} \frac{Qq}{r^2}$ .  
From the definition of electric field strength  $E = \frac{F}{q}$ , we can derive the formula for  $E$  due to charge  $Q$  at a distance  $r$

$$E = \frac{1}{4\pi\epsilon_0} \frac{Q}{r^2}$$



# E-Field Strength due to a Point Charge

$$E = \frac{1}{4\pi\epsilon_0} \frac{Q}{r^2}$$

where  $r$  = distance between the charge  $Q$  and the point where we are evaluating the E-field.



- *E-field* exists around any charged object and its field strength does not require the presence of another charge as  $q$ , which can be viewed as a **test charge**.
- **E-field due to multiple charges:**

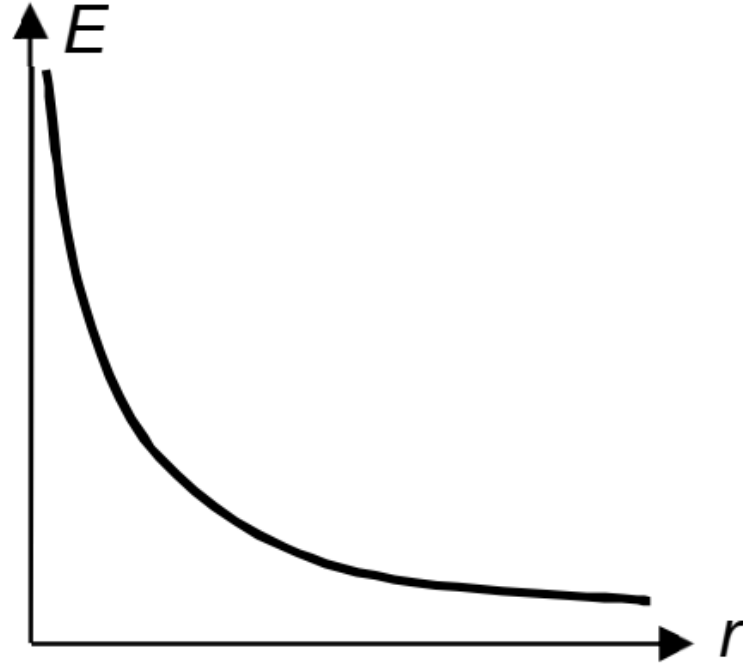
$$E = E_1 + E_2 + E_3 + \dots$$

\*Add them vectorially



# Variation of Electric Field Strength with Distance from Point Charges

$$E \propto \frac{1}{r^2}$$



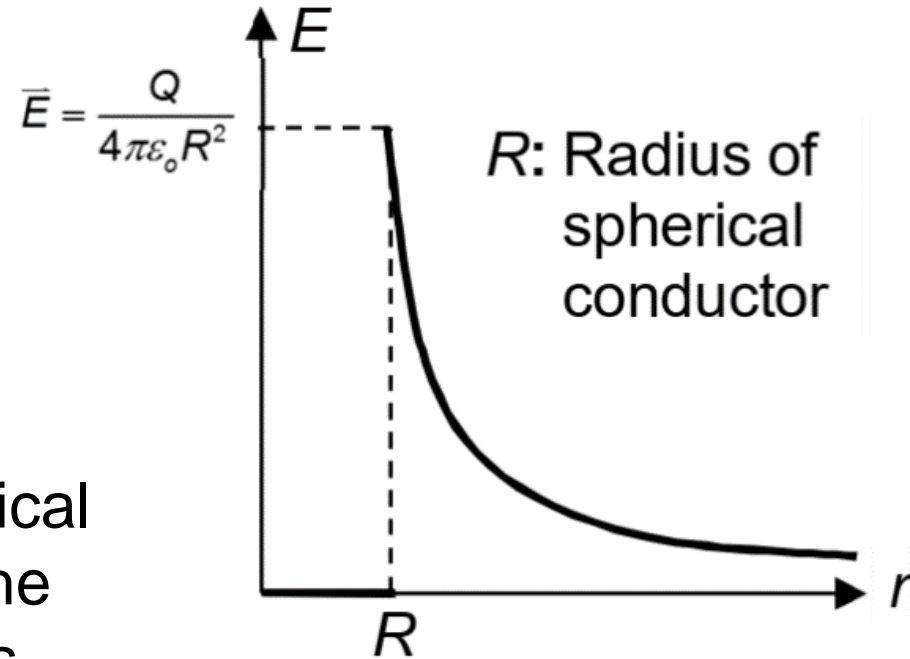


# Variation of Electric Field Strength with Distance from Spherical Conductor

For a total charge  $Q$ ,

- $E = 0$  for  $r < R$
- $E = \frac{Q}{4\pi\epsilon_0 r^2}$  for  $r \geq R$

For  $r \geq R$  (i.e. points outside the spherical conductor), the electric field setup by the spherical conductor is the same as if its entire charge were concentrated at the center of the sphere.

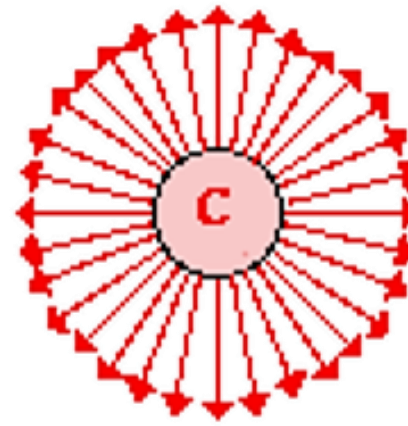
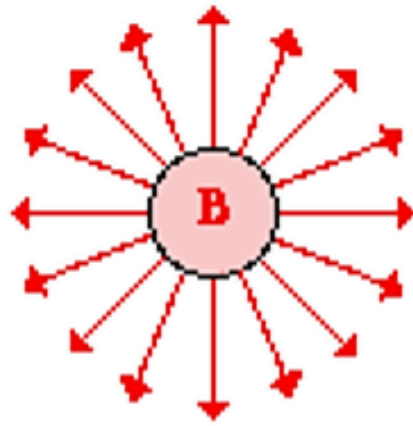
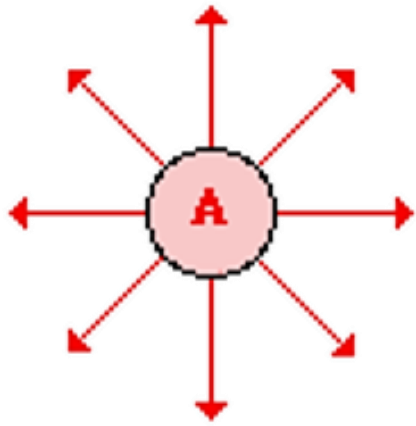


# Electric Field Lines

- are used to visualize electric fields.

## Properties of Electric Field Lines

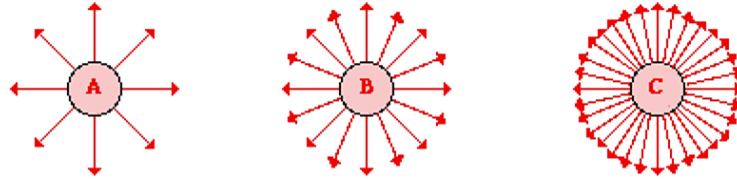
1. E-field lines originate from a positive charge and terminate in a negative charge.
2. Closer the lines, the stronger the electric field in that region.
3. No two field lines can cross.



The density of electric field lines around these three objects reveals that the quantity of charge on C is greater than that on B which is greater than that on A.



# Electric Field Strength between Parallel Charged Plates



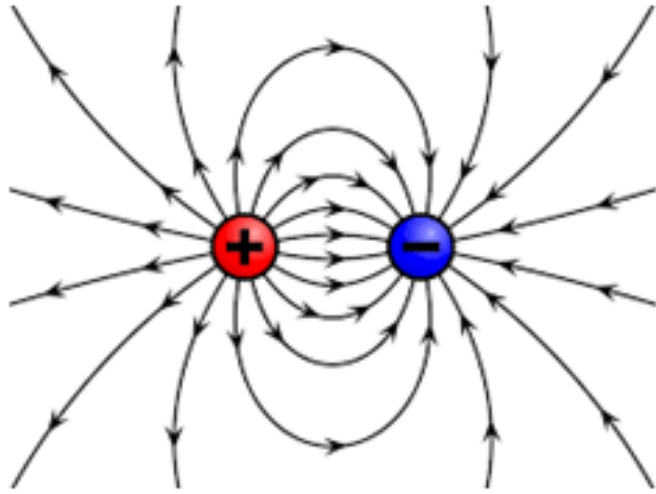
The direction of the field line **represents** how a positively charged particle will experience an electric force and move when placed in that point.

- As seen in the figure above, A has a weak field and will exert only a small force on charges in the field.
- B has a stronger field and will exert more force on the charges in the field.
- C has the strongest field, and will exert the most force on charges in its field

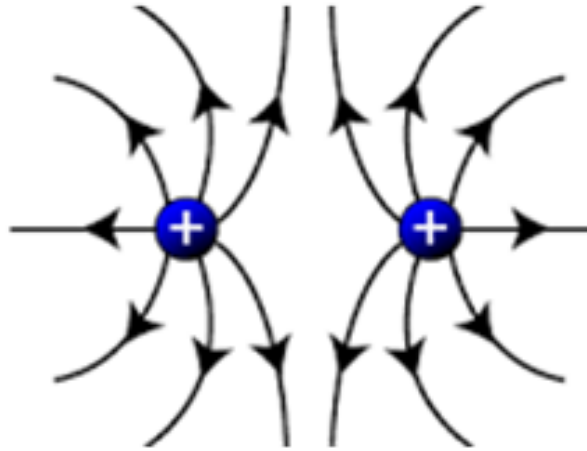


# Electric Field Lines

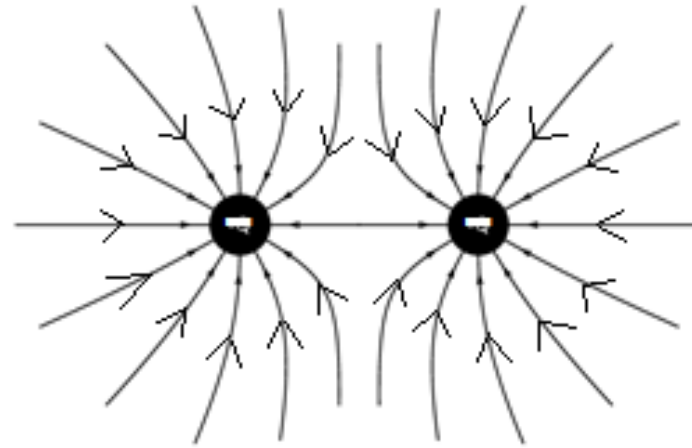
When placed side by side, the field lines will interact with one another to create new field patterns as follows:



Two oppositely charged particles



Two positive charges

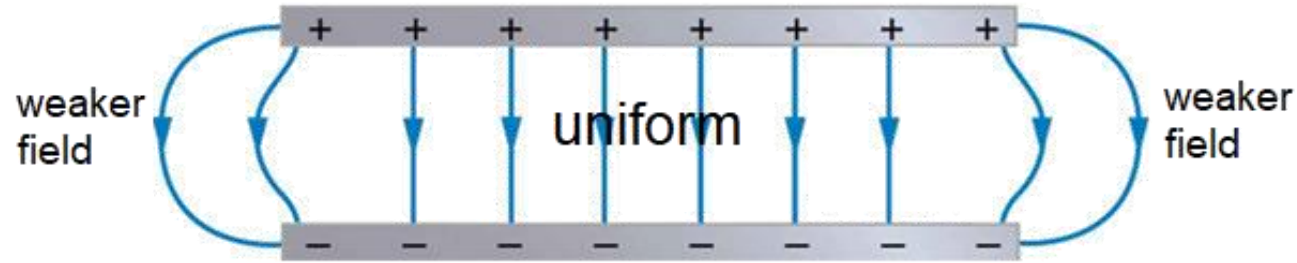
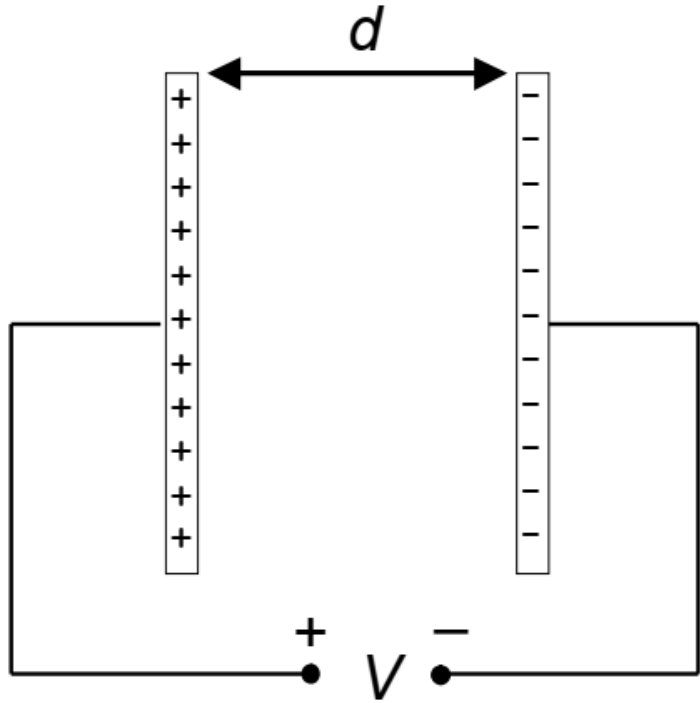


Two negative charges





# Electric Field Strength between Parallel Charged Plates



- Between two electrically charged plates, electric field strength is **uniform/constant**.
- This means that everywhere throughout the field, the force experienced by the charged particle remains the same.

$$E = \frac{\Delta V}{d}$$

where  $\Delta V$  = potential difference between the plates  
 $d$  = separation distance of the plates



# Electric Field Strength between Parallel Charged Plates

$$E = \frac{\Delta V}{d}$$

where  $\Delta V$  = potential difference between the plates  
 $d$  = separation distance of the plates




- towards the ends of the plates, the electric field gets **weaker** as field lines are **curved**. This is because the field gets further the center of the plate and field strength is no longer constant.




### Practice Example 3

Draw the electric field lines of a negative point charge  $-Q$  and a positively charged plate shown on the left.

negative  
charge  $-Q$



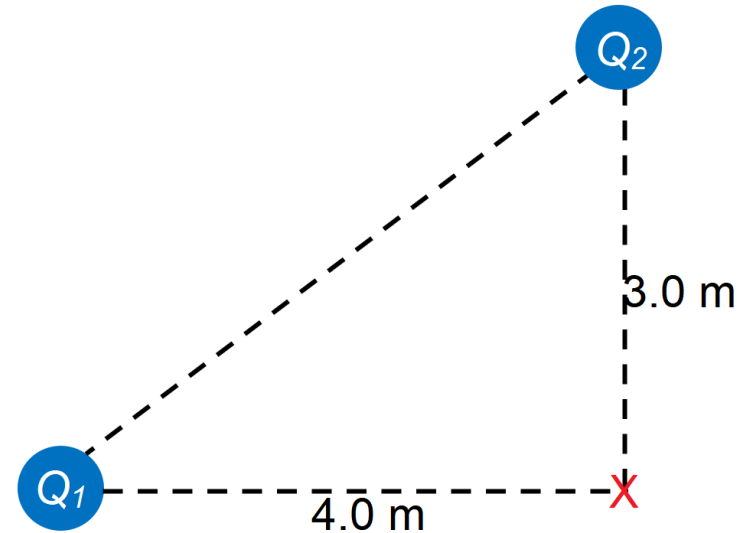
positive  
plate



## Practice Example 4

Two charges  $Q_1 = -1.0 \mu\text{C}$ ,  $Q_2 = -2.0 \mu\text{C}$  are positioned at the corners of a right triangle as shown below.

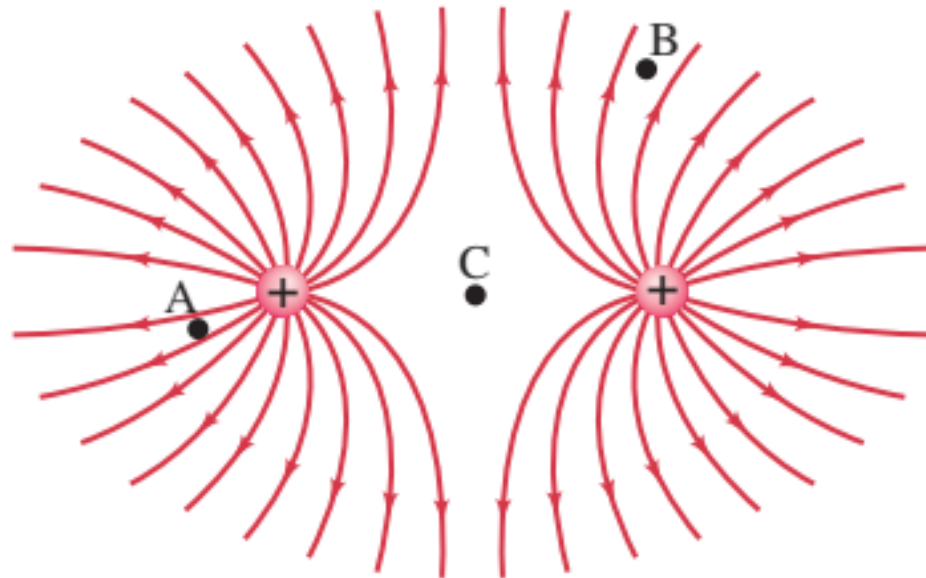
Determine the magnitude and direction of electric field strength at the corner X.





## Practice Example 5

Consider three points A, B, and C located near two positively-charged particles of the same charge. List down the positions in from the highest to lowest magnitude of electric field strength. Explain



### Practice Example 6

Two parallel plates are charged with a potential difference of 120 V. If the plates are 2.50 cm apart,

(a) what is the electric field between the plates?

(b) what is the electric force on a  $\text{Ca}^{2+}$  ion at a point between the plates?



# Electric Potential

Symbol:  $V$

SI unit: Volts [V] or Joules per Coulomb [J/C]

Scalar

- at a point in an electric field is defined as the work done per unit positive charge to bring a test charge from infinity to the point (without any change in kinetic energy).

$$V = \frac{U}{q}$$

where  $U$  = electric potential energy per unit positive charge at the point in the field



# Electric Potential Energy

Symbol:  $U$

SI unit: Joules [J]

Scalar

- of a charge in an electric field is defined as the work done to bring the charge from infinity to the point by an external agent.



- Electric potential  $V$  can be positive or negative depending on the polarity of charge  $q$ .
- In contrast, gravitational potential is always negative.
- Absolute values of  $V$  and  $U$  are meaningful only if we have defined a reference zero. Most of the time, when calculating values between 2 points, we are determining the change in potential  $\Delta V$  (instead of the absolute value of potential  $V$ ).



# Electron Volt (eV)

A more convenient unit for small energy.

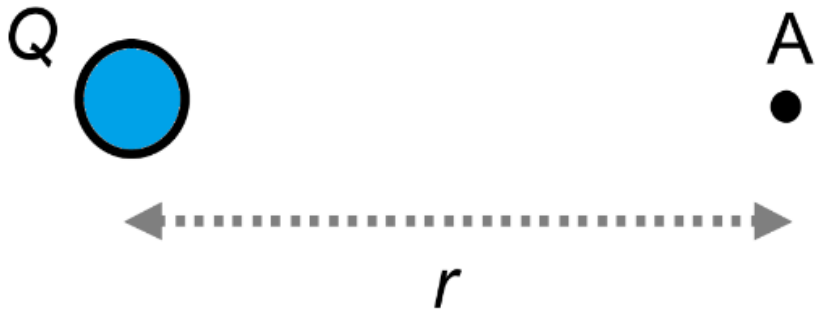
The electron-volt is the energy gained by an electron when it is accelerated through a p.d. of one volt

$$1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$$





# Potential due to a Point Charge



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

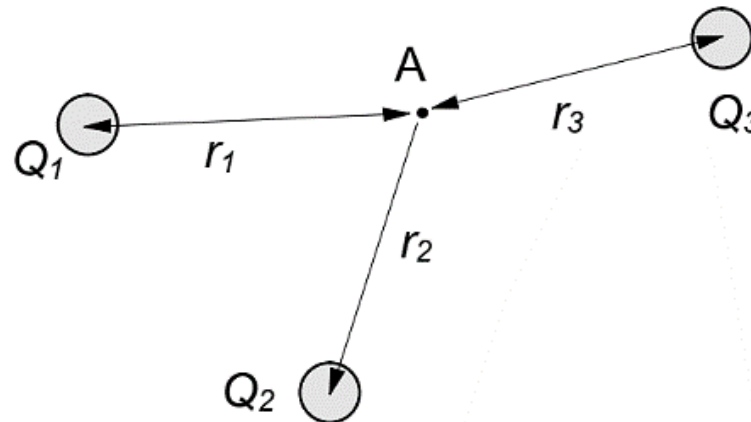
where  $Q$  = charge

$r$  = distance from the charge  $Q$

$\epsilon_0$  = permittivity of free space =  $8.85 \times 10^{-12} \text{ s}^4 \text{ A}^2 / \text{m}^3 \text{ kg}$

**For several point charges**

$$V_A = V_1 + V_2 + V_3 + \dots$$



# Potential due to a Point Charge

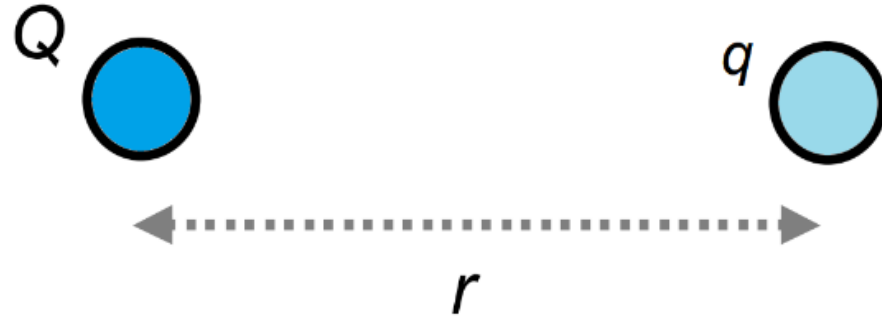


- If  $Q$  is positive, then the **electric potential** at point A is **positive**.
  - The direction of work done by the external agent is the same as that of displacement when bringing the test charge from infinity to the point in the electric field due to the **repulsive** field
- If  $Q$  is negative, then the **electric potential** at point A is **negative**.
  - The direction of work done by the external agent is opposite to that of displacement when bringing the test charge from infinity to the point in the electric field due to the **attractive** field



# Potential Energy of Point Charges

$$U = \frac{1}{4\pi\epsilon_0} \frac{qQ}{r}$$



where  $q, Q$  = charge

$r$  = distance from the charge  $Q$

$\epsilon_0$  = permittivity of free space =  $8.85 \times 10^{-12} \text{ s}^4 \text{ A}^2 / \text{m}^3 \text{ kg}$



# Potential Difference

$$\Delta V = V_{final} - V_{initial} = V_B - V_A$$

**Note:** The positive or negative sign of the potential must be substituted into  $V_{final}$  and  $V_{initial}$

# Work Done

Work done  $W$  by an external force (or the change in potential energy of the system) in moving the charge  $q$  is

$$W = q\Delta V$$

or

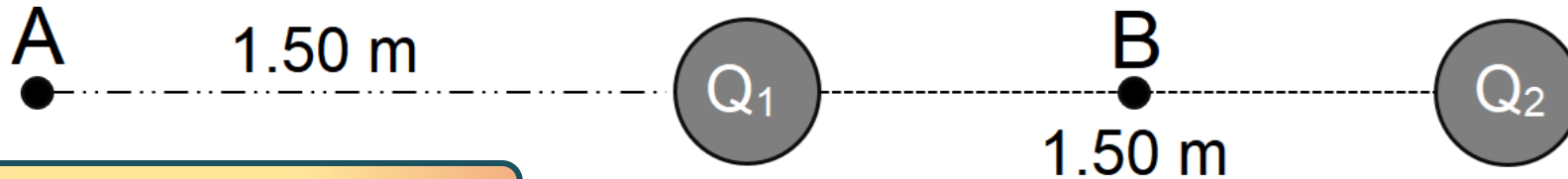
$$\Delta U = q\Delta V$$

**Note:** The positive or negative sign of the charge and p.d. must be substituted into  $q$  and  $\Delta V$ .



### Practice Example 7

Determine the potential at points **A** and **B**, due to small charges  $Q_1$  and  $Q_2$ . The charges carry  $Q_1 = +3.0 \text{ nC}$  and  $Q_2 = -3.0 \text{ nC}$  and are 1.50 m apart.



### Practice Example 8

Calculate the potential energy of the point charges in *Practice Example 7*





# Equipotential Lines

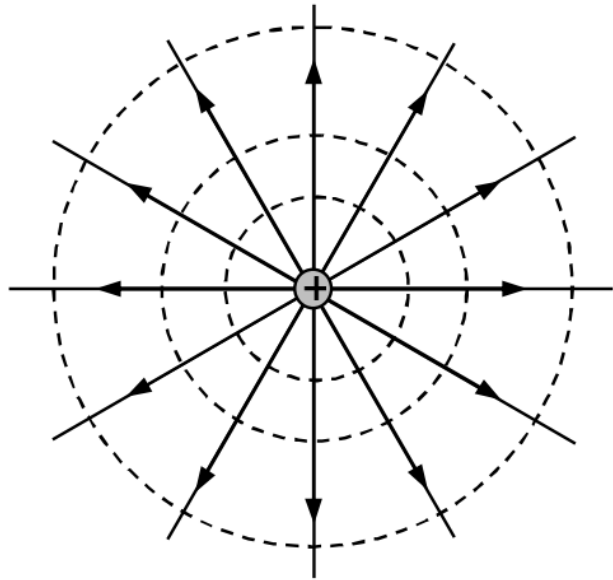
- Are like contour lines on a map which trace lines of equal electric potential.
- In 3D space, they are called **equipotential surfaces**



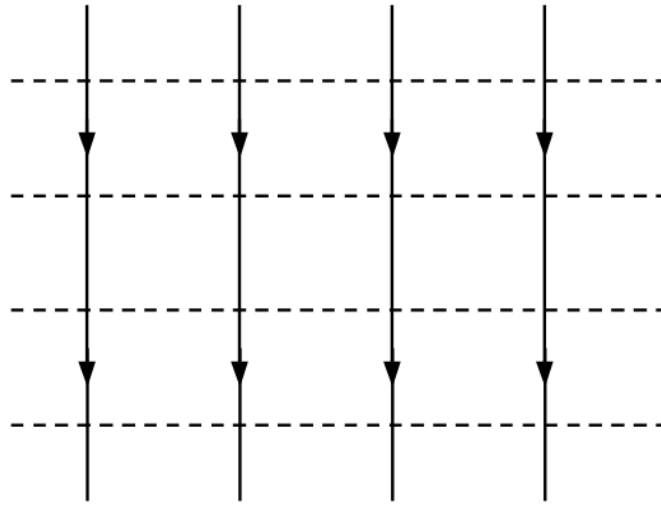
- They are perpendicular to electric field lines.
- Movement along an equipotential line or surface requires no work.
- This is because there is no component of electric force along such path (which is always perpendicular to the electric field lines).
- Usually, they are drawn using dashed lines (Solid lines for E-field).
- The surface of a charged conductor of any shape is an equipotential surface.
- The spacing between the equipotential surfaces will be closer where the field is stronger



# Equipotential Lines



E field due to  
point charge



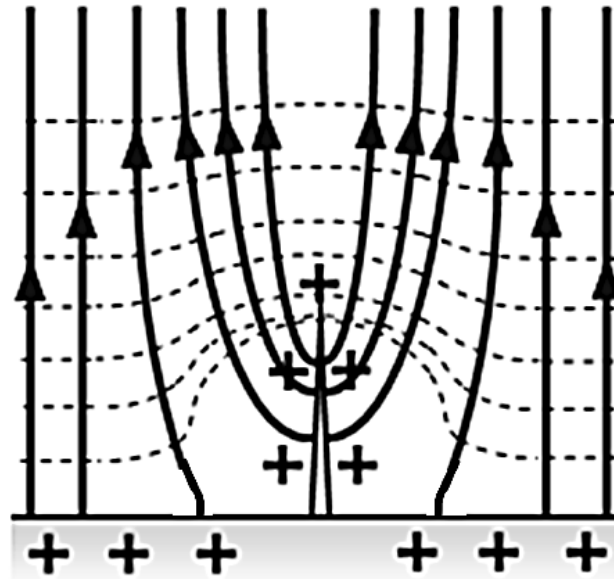
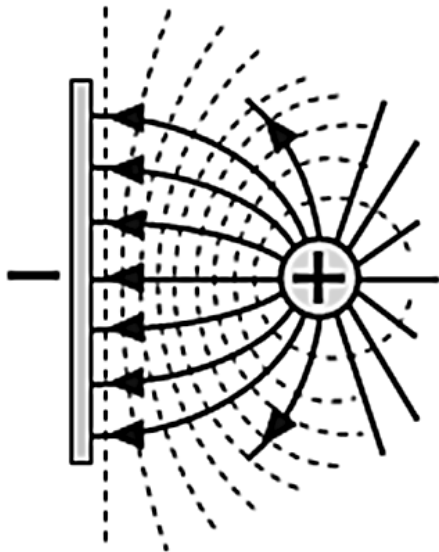
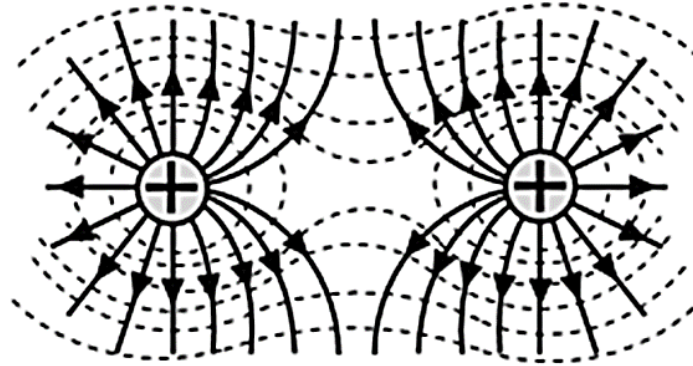
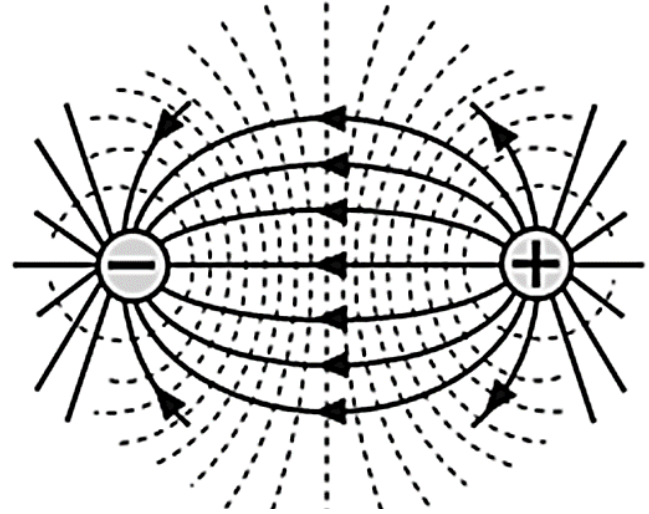
Uniform E field  
due parallel plates

**Dashed lines:** Equipotential lines



# Equipotential Lines

Dashed lines:  
Equipotential  
lines



# Electric Potential Gradient

The electric field strength at a point is numerically equal to the potential gradient at that point.

$$E = -\frac{dV}{dr}$$

- $\frac{dV}{dr}$  is a vector and has units  $V/m$  or  $N/C$ .
- The negative sign shows that the potential decreases along the direction of the *E-field*



# Electric Potential Gradient

## Derivation

From the definition of potential,

$$V = \frac{W}{q} = \frac{1}{q} \int_{\infty}^r F_{ext} dr = \frac{1}{q} \int_{\infty}^r (-F) dr$$

Since the electric field strength  $E = \frac{F}{q}$ , the expansion becomes

$$V = \int_{\infty}^r (-E) dr$$

This implies that electric field strength  $E$  can be obtained from the derivative of electric potential  $V$  with respect to  $r$ .

$$\Rightarrow E = -\frac{dV}{dr}$$





# Force and Electric Potential Energy

Similarly,

$$F = -\frac{dU}{dr}$$

## Derivation

From the definition of potential,

$$U = \int_{\infty}^r F_{ext} dr = \frac{1}{q} \int_{\infty}^r (-F) dr$$

or

$$qE = -q \frac{dV}{dr}$$

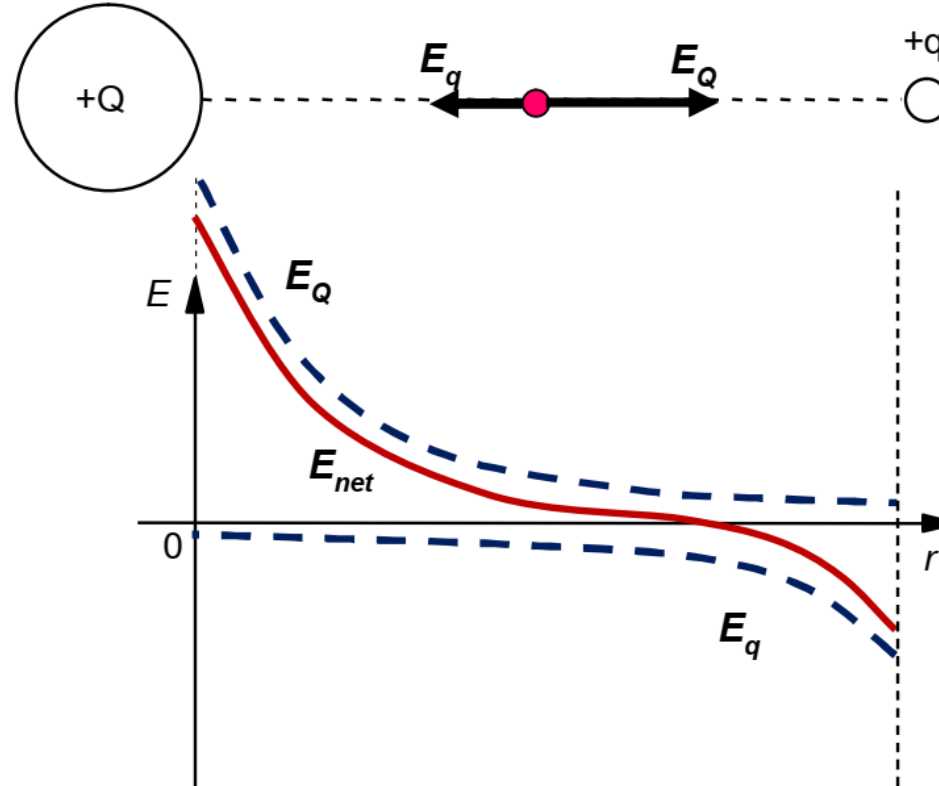
We have  $F = -\frac{dU}{dr}$



# Graphs of $E$ due to Two Charges

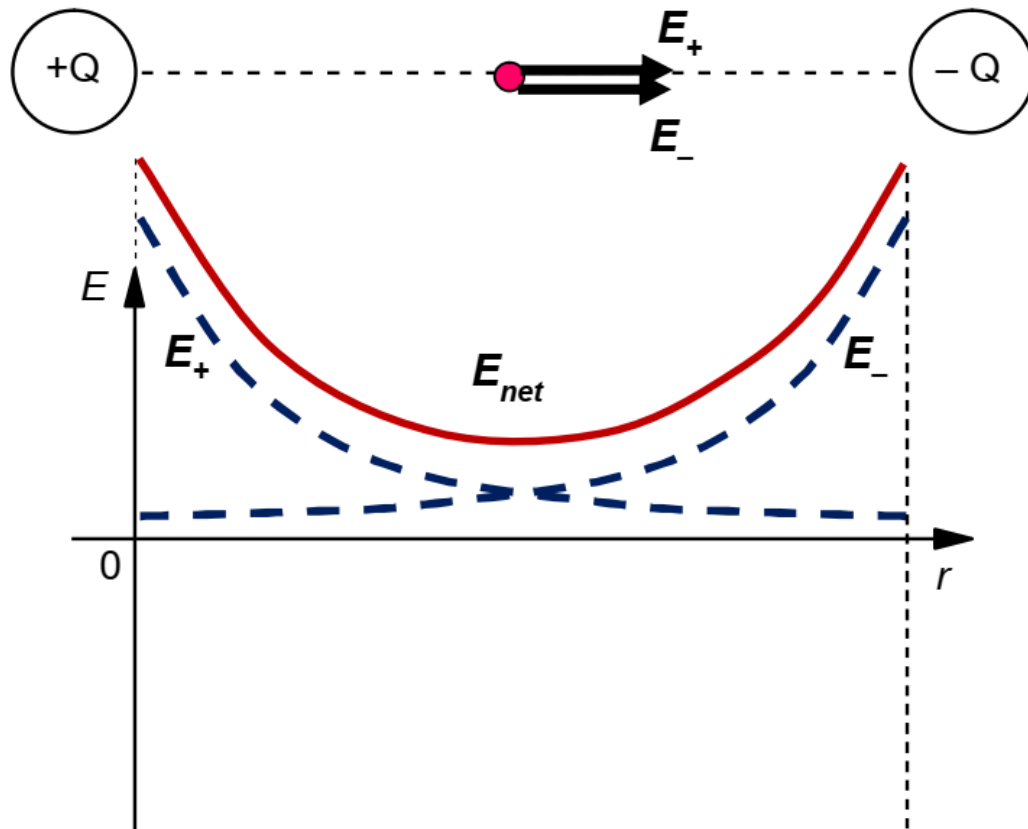
When plotting the graph of electric field strength,  $E$  against distance between the two charges,  $r$ , we can first sketch the  $E$  graphs due to the two charges independently. The resultant  $E$  graph is the vector sum of the two graphs.

Two unequal positive charges



# Graphs of $E$ due to Two Charges

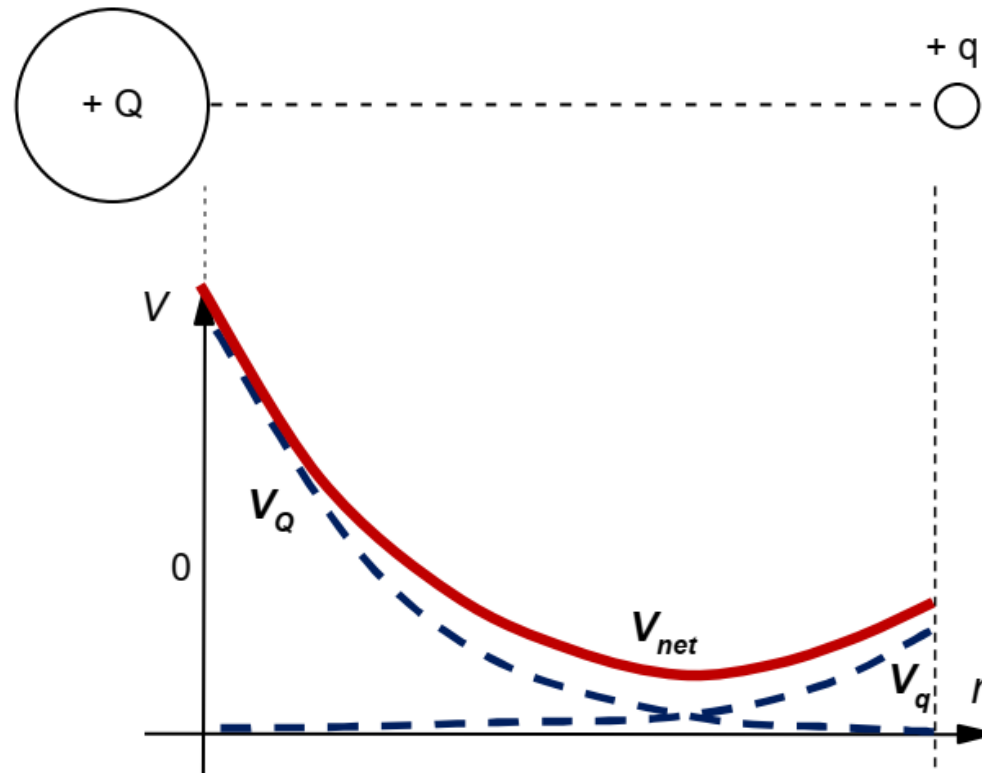
Two equal charges with different polarity



# Graphs of $V$ due to Two Charges

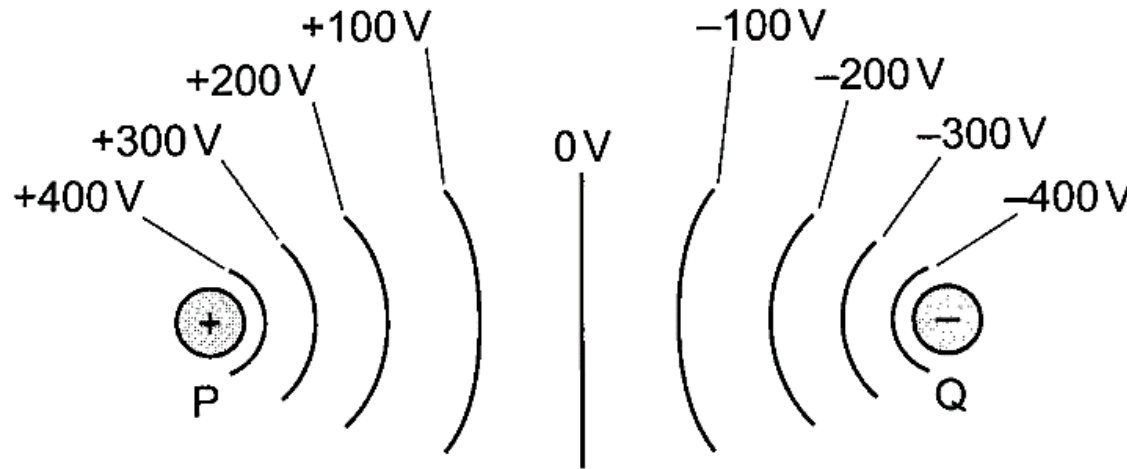
When plotting the graph of electric potential at a point,  $V$  against distance between the two charges,  $r$ , we can first sketch the  $V$  graphs due to the two charges independently. The resultant  $V$  graph is the scalar sum of the two graphs.

Two unequal positive charges



## Practice Example 9

An object with a positive charge is placed at P and a similar object with a negative charge is placed at Q. The diagram shows a number of lines along which the potential has a constant value



Draw a rough estimation of the variation of electric field strength  $E$  with distance  $x$  along the line PQ. Explain your answer.

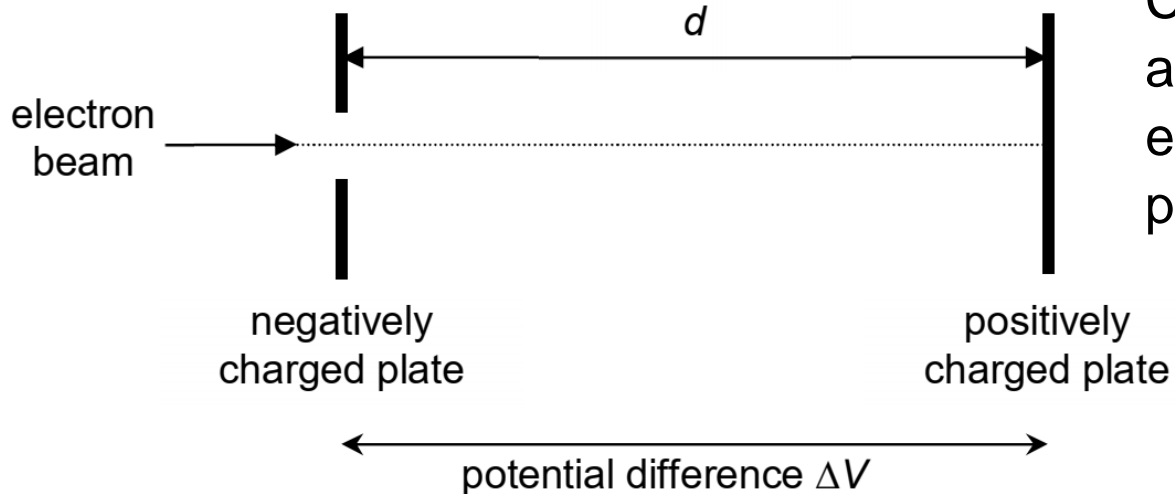




# Motion of Charged Particles in a Uniform Electric Field

In following sections, the motion of electrons in a uniform electric field would be analysed in terms of its kinematic quantities. In order to simplify the analysis, the weight of the electron, which is negligible compared to the electric force, may be ignored.

## Electric Field Parallel to Motion



Consider a beam of electrons accelerated from rest through an electric field in the region between two parallel charged plates.



# Electric Field Parallel to Motion

- To determine the acceleration  $a$  of the electron,

$$F_e = F_{net}$$

$$qE = m_e a$$

$$a = \frac{qE}{m_e}$$

(in the direction of the positive charge plate)

- To determine the time  $t$  for the electrons to hit the far plate,

$$s_x = u_x t + \frac{1}{2} a_x t^2$$

$$d = 0 + \frac{1}{2} \left( \frac{qE}{m_e} \right) t^2$$

$$t = \sqrt{\frac{2m_e d}{qE}}$$



# Electric Field Parallel to Motion

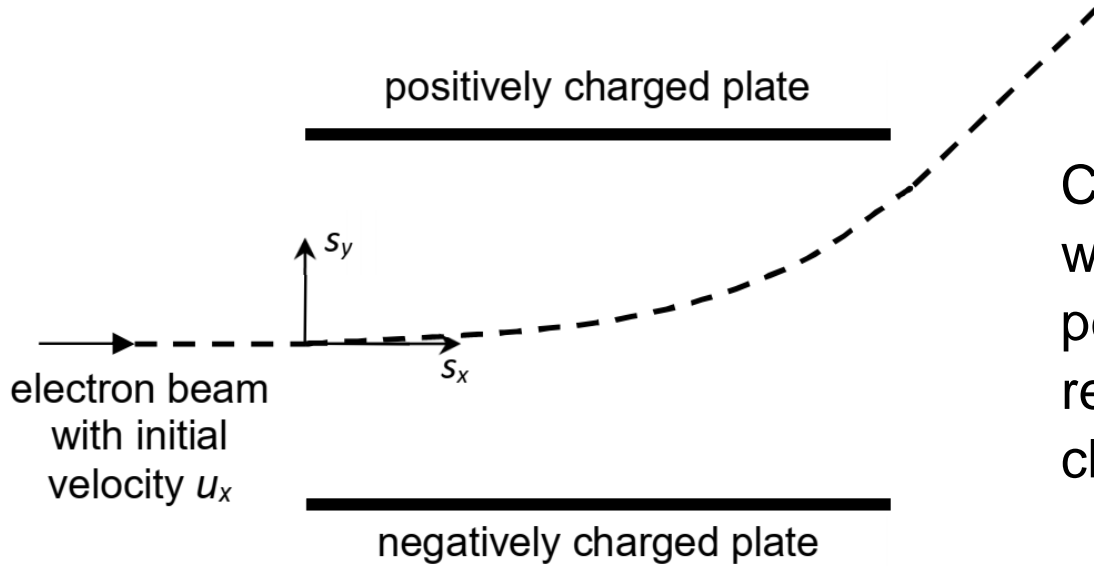
- To determine the velocity  $v$  of the electrons just before they hit the far plate:
  - via Conservation of Energy:

$$E_{P(\text{lost by electrons})} = E_{K(\text{gained by electron})} \Rightarrow q\Delta V = \frac{1}{2}m_e v^2 - 0$$

$$v = \sqrt{\frac{2q\Delta V}{m_e}}$$



# Electric Field Perpendicular to Initial Motion



Consider a horizontal beam of electrons, with an initial velocity  $u_x$ , entering perpendicularly into an electric field region between two horizontal parallel charged plates.

- To determine the acceleration  $a$  of the electron

$$F_e = F_{net}$$
$$qE = m_e a$$

$$a = \frac{qE}{m_e}$$

(in the direction of the positive charge plate)



# Electric Field Perpendicular to Initial Motion

Considering horizontal motion,

$$s_x = u_x t + \frac{1}{2} a_x t^2$$

Since there is no acceleration in the horizontal direction,  $a_x=0$ ,

$$s_x = u_x t + 0$$

$$\rightarrow t = \frac{s_x}{u_x}$$

Considering vertical motion,

$$s_y = u_y t + \frac{1}{2} a_y t^2$$

$$s_y = 0 + \frac{1}{2} \left( \frac{qE}{m_e} \right) t^2$$

Eliminating  $t$  from the equations above (equations for  $t$  and  $s_y$ ),

$$s_y = \frac{1}{2} \left( \frac{qE}{m_e} \right) \left( \frac{s_x}{u_x} \right)^2$$



# Electric Field Perpendicular to Initial Motion

- For the case when the electron has a sufficiently high initial velocity relative to the uniform electric field strength, the electron beam would be able to leave the region between the plates without hitting any of the plates. The electron's path upon leaving the plates would be a straight line since there will be no resultant force acting on it.
- However, if the electron's initial velocity is insufficiently fast relative to the electric field strength, the electron beam would hit one of the plates and not be able to leave the region between the plates





# Comparison Between Gravitational and Electric Fields

	Gravitational Field	Electric Field
<b>Origin of Forces</b>	Due to mass interaction	Due to charge interaction
<b>Nature of forces</b>	Conservative and attractive	Conservative and can be attractive or repulsive
<b>Quantitative Law</b>	Newton's Law of Universal Gravitation: $F_G = G \frac{m_1 m_2}{r^2}$	Coulomb's Law: $F_E = \frac{1}{4\pi\epsilon_0} \frac{Qq}{r^2}$
<b>Field Strength</b>	Force per unit mass: $g = \frac{F_g}{m} \quad (\text{in N/kg})$	Force per unit positive charge: $E = \frac{F_e}{q} \quad (\text{in N/C})$
<b>Field set up by isolated mass/charge</b>	$g = \frac{GM}{r^2}$	$E = \frac{Q}{4\pi\epsilon_0 r^2}$



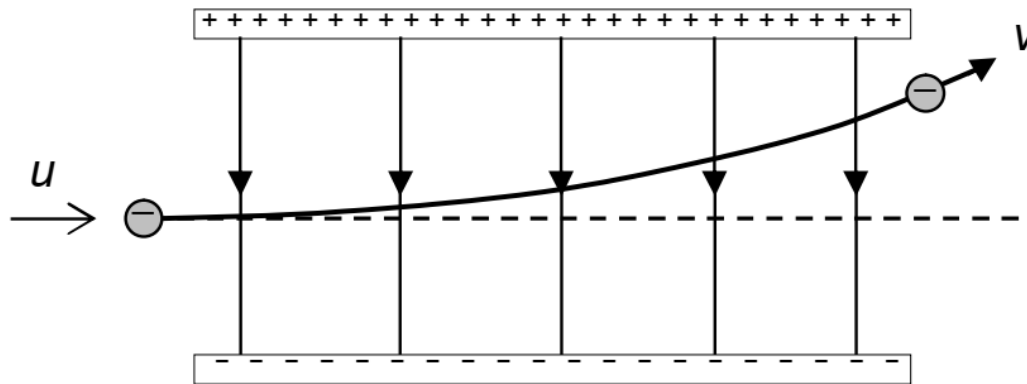
# Comparison Between Gravitational and Electric Fields

	Gravitational Field	Electric Field
<b>Potential</b>	Work done per unit mass in bringing test mass from infinity to the particular point in a gravitational field.	Work done per unit positive charge in bringing test charge from infinity to the particular point in an electric field
<b>Potential due to isolated mass/charge</b>	$\phi = -\frac{GM}{r}$	$V = \frac{1}{4\pi\epsilon_0} \frac{Q}{r}$
<b>Potential due to multiple mass/charge</b>	$\phi_{net} = -G \left[ \frac{M_1}{r_1} + \frac{M_2}{r_2} + \dots \right]$	$V_{net} = \frac{1}{4\pi\epsilon_0} \left[ \frac{Q_1}{r_1} + \frac{Q_2}{r_2} + \dots \right]$
<b>Potential energy of a 2-mass/ 2-charge system</b>	$U_G = -\frac{GMm}{r}$	$U_E = \frac{1}{4\pi\epsilon_0} \frac{Qq}{r}$
<b>Relation between field and potential</b>	$g = -\frac{d\phi}{dr}$	$E = -\frac{dV}{dr}$



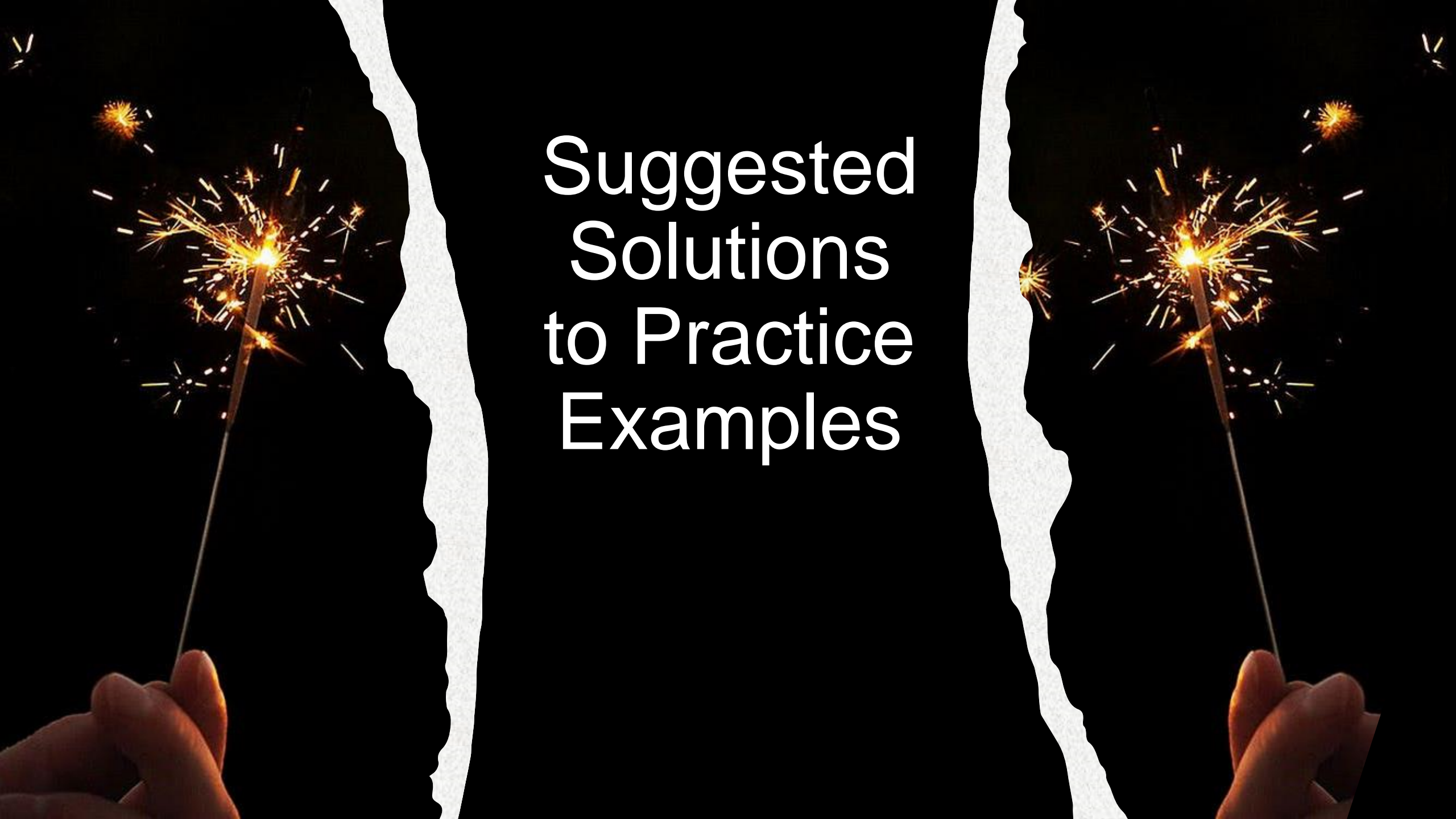
## Practice Example 10

An electron is projected horizontally with a speed of  $2.0 \times 10^7 \text{ m/s}$  into the uniform electric field set up between the two parallel charged plates spaced 35 cm apart as shown. It is deflected through a vertical distance of 10 cm in  $1.0 \times 10^{-7} \text{ s}$  before emerging from the electric field.



Calculate the vertical component of the velocity  $v$  and the angle of the electron from the horizontal direction just before it emerges from the field.



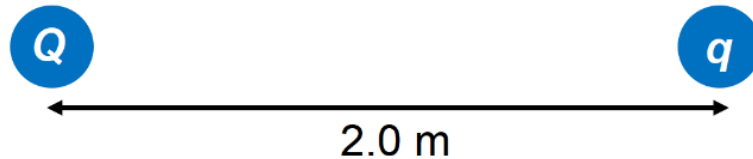
The background of the slide is black with a white, torn paper effect running vertically down the center. On either side of this tear, there are images of hands holding lit sparklers. The sparklers are bright yellow and orange, with many sparks flying out. The hands are visible at the bottom of the frame, holding the sticks of the sparklers.

# Suggested Solutions to Practice Examples

## Practice Example 1

Two charges  $Q$  ( $+3.0\mu\text{C}$ ) and  $q$  ( $-4.0\mu\text{C}$ ) are 2.0 m away from each other.

- (a) What is the magnitude and direction of the force acting on  $Q$  by  $q$ ?
- (b) If  $Q$  is replaced with a negative charge (same magnitude as  $Q$ ), what would be the magnitude and direction of the force on  $Q$  by  $q$ ?



### Solution:

(a) Magnitude of the force,

$$F = \frac{1}{4\pi\epsilon_0} \frac{Qq}{r^2} = \frac{1}{4\pi(8.85 \times 10^{-12})} \frac{(3 \times 10^{-6})(4 \times 10^{-6})}{2^2}$$
$$F = 27 \times 10^{-3} \text{ N}$$

Direction: to the right since the force is attractive.

(b) The magnitude would be the same,

$$F = 27 \times 10^{-3}.$$

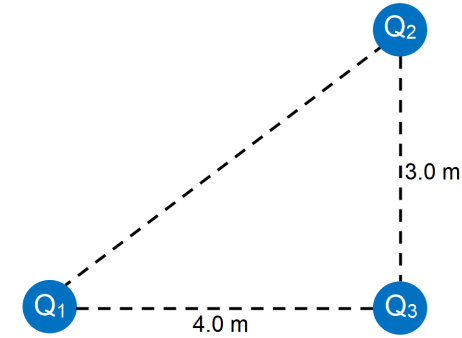
However, the direction would be to the left because the force between two negative charges is repulsive.





## Practice Example 2

Three charges  $Q_1 = -1.0 \mu\text{C}$ ,  $Q_2 = -2.0 \mu\text{C}$ ,  $Q_3 = 3.0 \mu\text{C}$  are positioned at the corners of a right triangle as shown on the right. Determine the magnitude and direction of the resultant force on charge  $Q_3$  by the other two charges  $Q_1$  and  $Q_2$ .



### Solution:

Magnitude

$$F_1 = \frac{1}{4\pi\epsilon_0} \frac{Q_1 Q_3}{r_{13}^2} = \frac{1}{4\pi(8.85 \times 10^{-12})} \frac{(1 \times 10^{-6})(3 \times 10^{-12})}{4^2} = 1.69 \times 10^{-3} \text{ N}$$

$$F_2 = \frac{1}{4\pi\epsilon_0} \frac{Q_2 Q_3}{r_{23}^2} = \frac{1}{4\pi(8.85 \times 10^{-12})} \frac{(2 \times 10^{-6})(3 \times 10^{-12})}{3^2} = 6.0 \times 10^{-3} \text{ N}$$

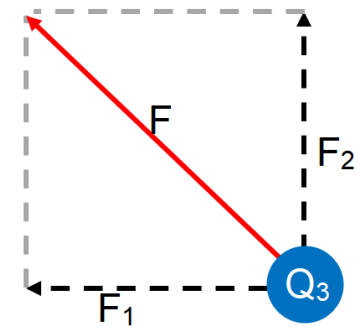
Magnitude of force on  $Q_3$ :

$$F = \sqrt{F_1^2 + F_2^2} = \sqrt{(1.69 \times 10^{-3})^2 + (6.0 \times 10^{-3})^2} = 6.23 \times 10^{-3} \text{ N}$$

Direction:

$$\theta = \tan^{-1} \frac{F_2}{F_1} = \tan^{-1} \frac{6}{1.69} = 74.26^\circ$$

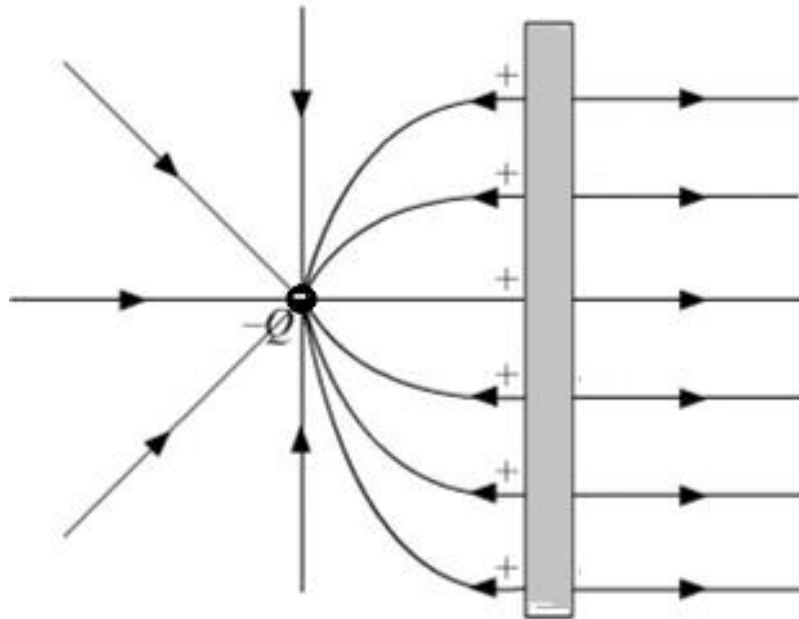
Force diagram on  $Q_3$ :





### Practice Example 3

Draw the electric field lines of a negative point charge  $-Q$  and a positively charged plate shown on the left.



negative  
charge  $-Q$



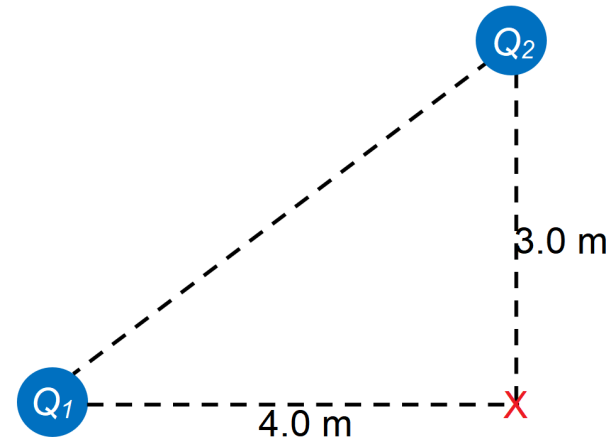
positive  
plate



### Practice Example 4

Two charges  $Q_1 = -1.0 \mu\text{C}$ ,  $Q_2 = -2.0 \mu\text{C}$  are positioned at the corners of a right triangle as shown below.

Determine the magnitude and direction of electric field strength at the corner X.



#### Solution:

Magnitude

$$E_1 = \frac{1}{4\pi\epsilon_0} \frac{Q_1}{r_{1X}^2} = \frac{1}{4\pi(8.85 \times 10^{-12})} \frac{1 \times 10^{-6}}{4^2} = 562 \text{ N/C}$$

$$E_2 = \frac{1}{4\pi\epsilon_0} \frac{Q_2}{r_{2X}^2} = \frac{1}{4\pi(8.85 \times 10^{-12})} \frac{2 \times 10^{-6}}{3^2} = 1998 \text{ N/C}$$

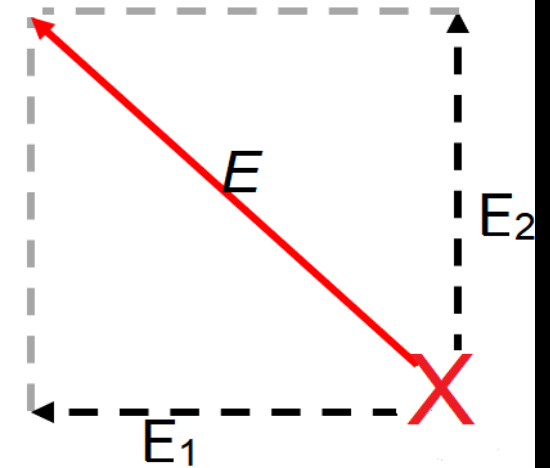
Magnitude of force on  $Q_3$ :

$$F = \sqrt{E_1^2 + E_2^2} = \sqrt{(562)^2 + (1998)^2} = 2045 \text{ N/C}$$

Direction:

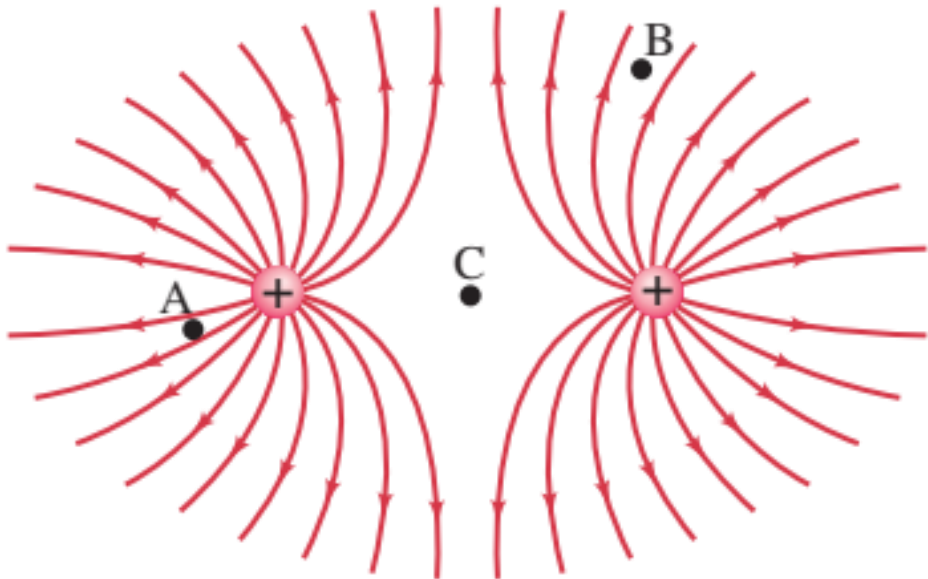
$$\theta = \tan^{-1} \frac{E_2}{E_1} = \tan^{-1} \frac{1998}{562} = 74.3^\circ$$

E-field diagram on X: (E-field points towards negative charges)



## Practice Example 5

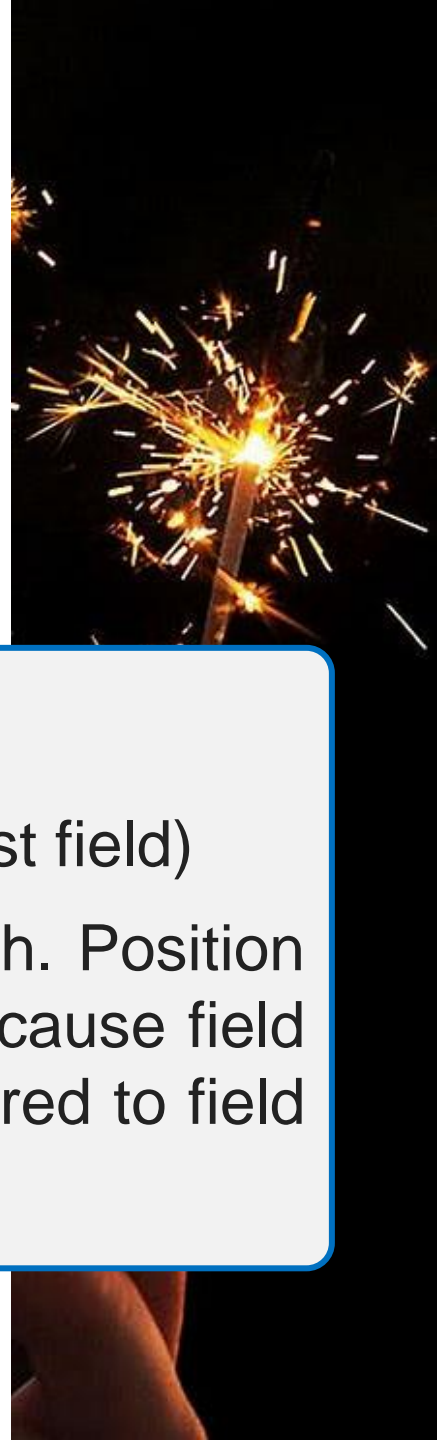
Consider three points A, B, and C located near two positively-charged particles of the same charge. List down the positions in from the highest to lowest magnitude of electric field strength. Explain



**Answer:**

(strongest field) **A**→**B**→**C** (weakest field)

At point **C**, there is zero field strength. Position **A** has the strongest field strength because field lines are closer to each other compared to field lines around position **B**.



## Practice Example 6

Two parallel plates are charged with a potential difference of 120 V. If the plates are 2.50 cm apart,

- (a) what is the electric field between the plates?
- (b) what is the electric force on a  $\text{Ca}^{2+}$  ion at a point between the plates?

### Solutions:

(a) E-field

$$E = \frac{\Delta V}{d} = \frac{120 \text{ V}}{2.5 \times 10^{-2}}$$

$$E = 4.8 \times 10^3 \text{ V/m}$$

(b)  $\text{Ca}^{2+}$  ion has  $2e$  charge where  $e = 1.602 \times 10^{-19} \text{ C}$

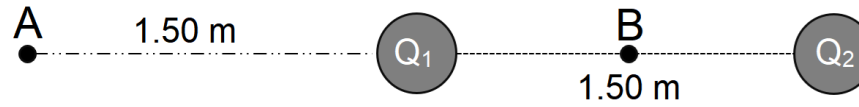
$$F = EQ_{\text{Ca}}$$

$$F = (4.8 \times 10^3) 2(1.602 \times 10^{-19})$$

$$F = 1.54 \times 10^{-15} \text{ N}$$



## Practice Example 7



Determine the potential at points **A** and **B**, due to small charges  $Q_1$  and  $Q_2$ . The charges carry  $Q_1 = +3.0 \text{ nC}$  and  $Q_2 = -3.0 \text{ nC}$  and are 1.50 m apart.

### Solutions:

Point **A**:

$$V_A = \frac{1}{4\pi\epsilon_0} \frac{Q_1}{r_1} + \frac{1}{4\pi\epsilon_0} \frac{Q_2}{r_2} = \frac{1}{4\pi\epsilon_0} \left[ \frac{Q_1}{r_1} + \frac{Q_2}{r_2} \right]$$
$$V_A = \frac{1}{4\pi(8.85 \times 10^{-12})} \left[ \frac{3 \times 10^{-9}}{1.50} + \frac{-3 \times 10^{-9}}{3} \right] = 9.0 \text{ V}$$

Point **B**:

$$V_B = \frac{1}{4\pi\epsilon_0} \frac{Q_1}{r_1} + \frac{1}{4\pi\epsilon_0} \frac{Q_2}{r_2} = \frac{1}{4\pi\epsilon_0} \left[ \frac{Q_1}{r_1} + \frac{Q_2}{r_2} \right]$$
$$V_B = \frac{1}{4\pi(8.85 \times 10^{-12})} \left[ \frac{3 \times 10^{-9}}{0.75} + \frac{-3 \times 10^{-9}}{0.75} \right] = 0 \text{ V}$$



### Practice Example 8

Calculate the potential energy of the point charges in *Practice Example 7*

**Solution:**

$$U = \frac{1}{4\pi\epsilon_0} \frac{Q_1 Q_2}{r}$$

$$V_A = \frac{1}{4\pi(8.85 \times 10^{-12})} \left[ \frac{(3 \times 10^{-9})(-3 \times 10^{-9})}{1.50} \right]$$

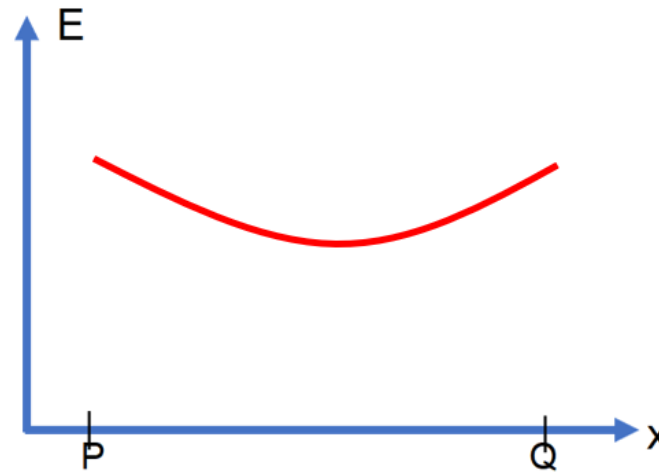
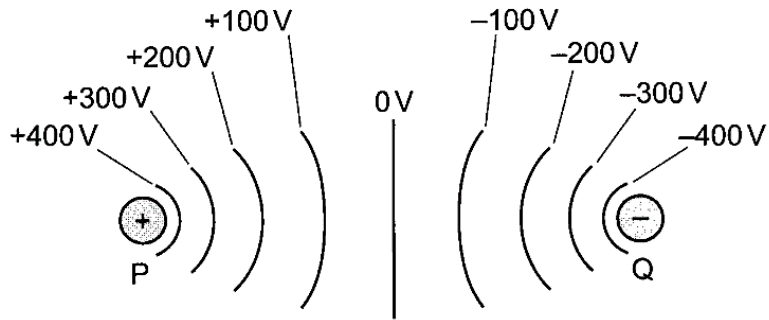
$$V_A = 5.4 \times 10^{-8} \text{ J}$$





## Practice Example 9

An object with a positive charge is placed at P and a similar object with a negative charge is placed at Q. The diagram shows a number of lines along which the potential has a constant value. Draw a rough estimation of the variation of electric field strength  $E$  with distance  $x$  along the line PQ. Explain your answer.

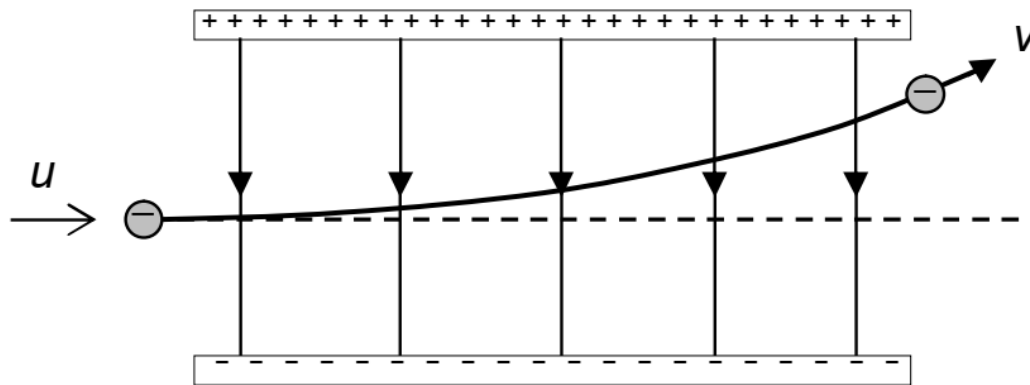


The potential difference across equipotential lines is constant at -100 V from P to Q but the distance between successive equipotential lines increases from 400 V to 0 V and decreases from 0 V to -400 V. As  $E = -\frac{dV}{dr}$ , electric field strength first decreases then increases.



## Practice Example 10

An electron is projected horizontally with a speed of  $2.0 \times 10^7 \text{ m/s}$  into the uniform electric field set up between the two parallel charged plates spaced 35 cm apart as shown. It is deflected through a vertical distance of 10 cm in  $1.0 \times 10^{-7} \text{ s}$  before emerging from the electric field.



Calculate the vertical component of the velocity  $v$  and the angle of the electron from the horizontal direction just before it emerges from the field.



## Practice Example 10

### Solution:

Given:  $u_x = 2 \times 10^{-7} \text{ m/s}$ ,  $s_y = 0.10 \text{ m}$ ,  $t = 1.0 \times 10^{-7} \text{ s}$

Vertical component of  $v$ :  $s_y = u_y t + \frac{1}{2} a_y t^2$

$$u_y = 0. \quad s_y = \frac{1}{2} a_y t^2$$

$$a_y = \frac{2s_y}{t^2} = \frac{2(0.1)}{1 \times 10^{-7}} = 2.0 \times 10^{13} \text{ m/s}^2$$

Meanwhile

$$v_y = u_y + a_y t$$

$$v_y = a_y t = (2.0 \times 10^{13})(2.0 \times 10^{-7})$$

$$v_y = 2.0 \times 10^6 \text{ m/s}$$

Angle:

$$v_x = u_x = 2.0 \times 10^7 \text{ m/s}$$

$$\tan \theta = \frac{v_y}{v_x} = \frac{2.0 \times 10^6}{2.0 \times 10^7}$$

$$\theta = 5.7^\circ$$



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