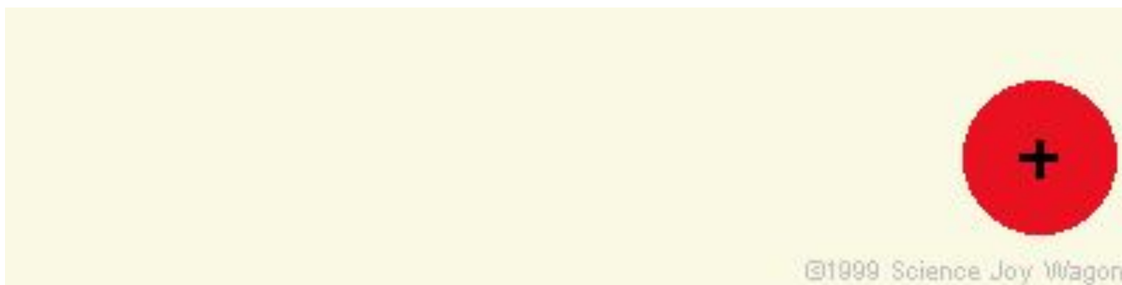
5.1 Electric fields
Day 3

Potential difference

Recall Work: $W = F\, d \cos(\theta)$

In order to bring two like charges together work must be done.
In order to separate two opposite charges, work must be done.

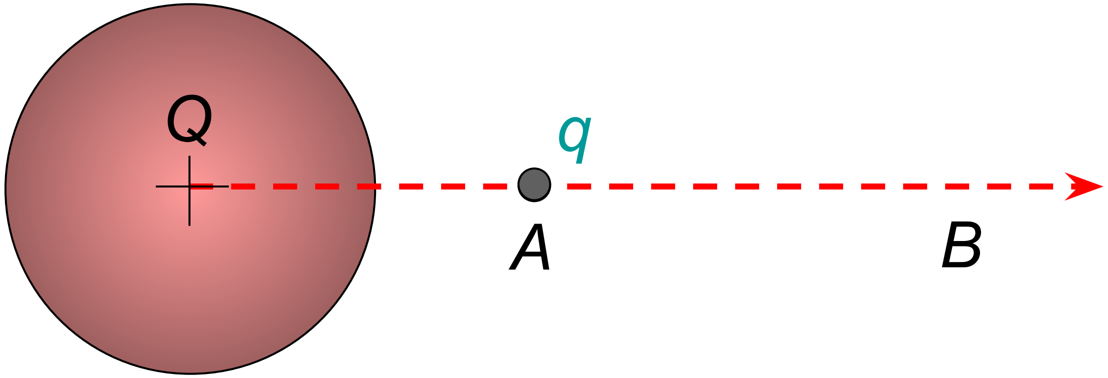


The greater charge monkey pushes, the greater work he has to do.
The closer he brings it, the harder for him it is.

Potential difference

- Because electric charges experience the electric force, when one charge is moved in the vicinity of another, work *W* is done.

- **Electric potential difference V (or $\Delta V = V_B - V_A$)** between two points A and B is amount of work done <u>per unit charge</u> in moving a positive test charge from point A to point B.



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

- units of *V* are JC^{-1} which are volts V.

$$1\,Volt = \frac{1\,Joule}{1\,Coulomb}$$

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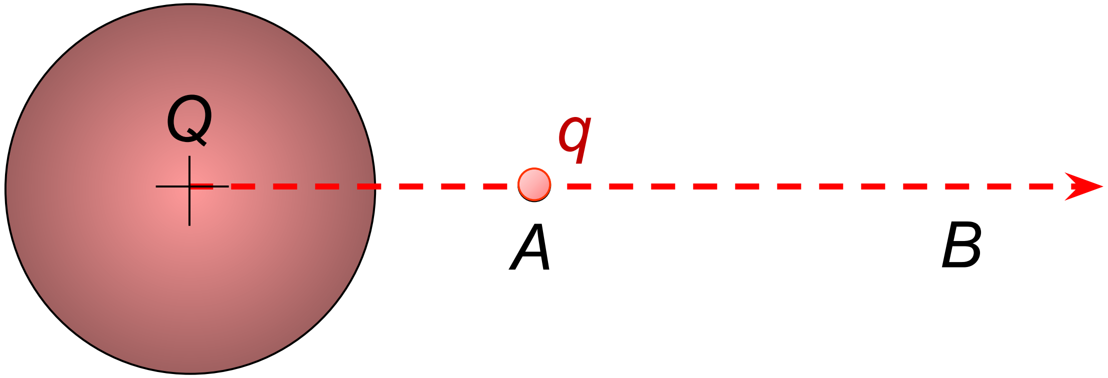

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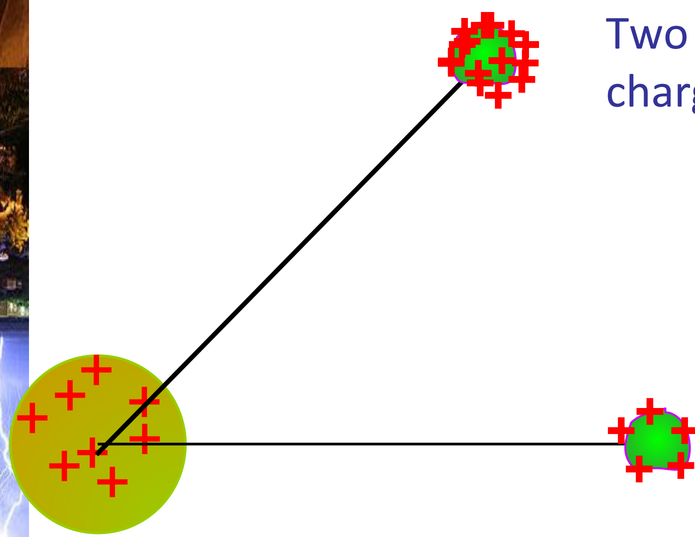
$$1\,Volt = \frac{1\,Joule}{1\,Coulomb}$$

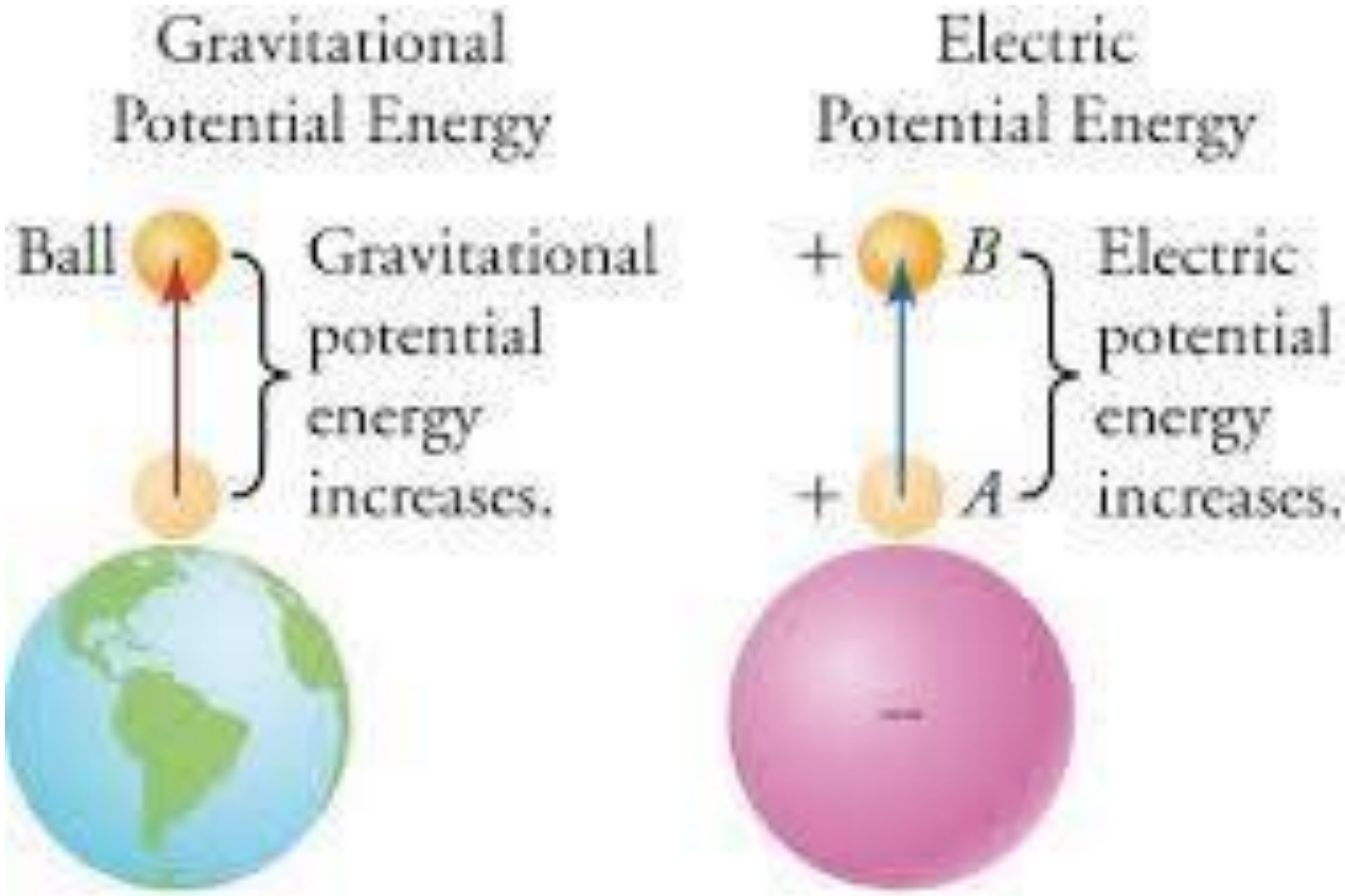
Now the same way as before with electric field, potential difference does not depend on the charge.

- Note important difference between energy and potential:
- A point has potential, charge placed there has electric potential energy



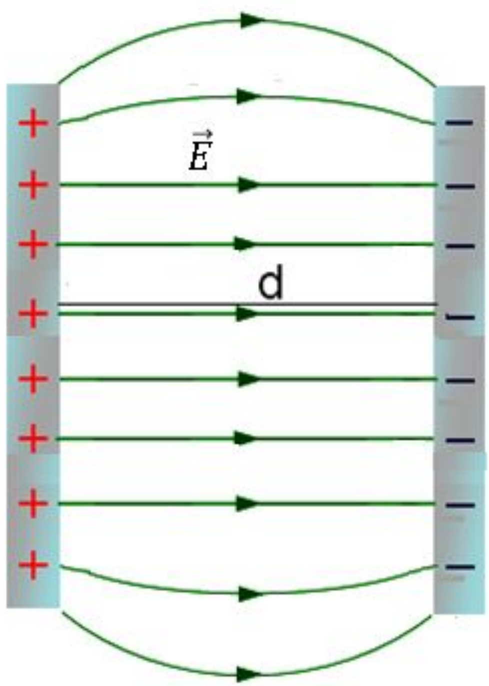
Two points that are at the same distance from the charged object have the same potential.

So, when two charged objects are placed there, they are at the *same potential*, but the one with more charge on it has higher electric potential energy. It is harder to push it there.



Gravitational Potential Energy
Ball
Gravitational potential energy increases.
Electric Potential Energy
+
B
+
A
Electric potential energy increases.
−

Capacitor: two parallel conducting plates charged uniformly with opposite charge



uniform electric field (the one that has **constant magnitude and direction**) is generated between two oppositely charged parallel plates. Edge effect is minimized when the length is long compared to their separation.

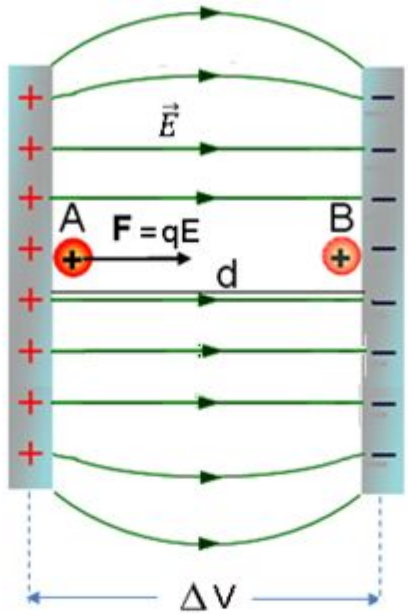
- Positive charge accelerates from higher to lower potential (from positive to negative).
- Negative charge accelerates from lower to higher potential. (from negative to positive)

In uniform electric field

- ① **Work done by electric field force F**

If a charge, q, is moved on its own from A to B, through a potential difference, ΔV, the work done on it by electric force is equal to the decrease in its electric potential energy which is converted into kinetic energy:

$$W = Fd = q\,Ed = q\,\Delta V = \tfrac{1}{2} mv^2$$

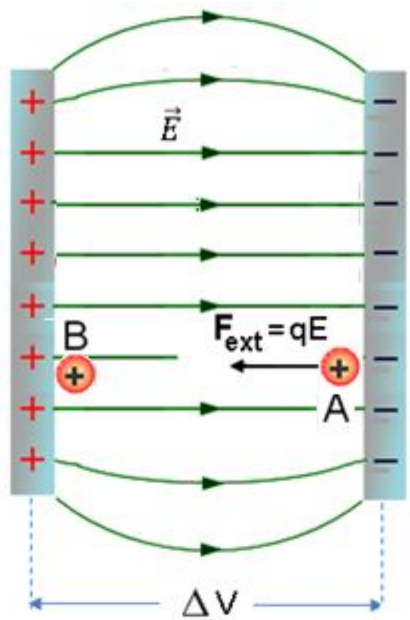


- ② **Work done by external force F_{ext}**

on charge against an electric field, from A to B is stored in the charge as the change in electrical potential energy, U.
(F_{ext} has to be equal to electric force in magnitude, opposite in direction)

$$W = F_{ext}\,d = qEd$$
$$W = q\,\Delta V$$

$$qEd = q\,\Delta V \Rightarrow E = \frac{\Delta V}{d} \Rightarrow (E) = NC^{-1} = Vm^{-1}$$



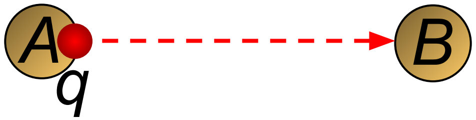
Potential difference

PRACTICE: A charge of $q = {}^{+}15.0\ \mu C$ is moved from point *A*, having a voltage (potential) of 25.0 V to point *B*, having a voltage (potential) of 18.0 V.

(a) What is the potential difference undergone by the charge?

(b) What is the work done in moving the charge from *A* to *B*?

SOLUTION:



(a) $V = V_B - V_A = 18.0 - 25.0 = -7.0$ V.

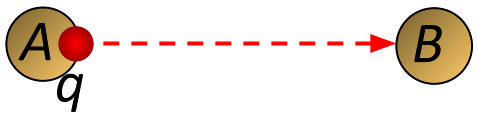
(b) $W = qV = 15.0\times10^{-6}\times(-7.0) = -1.1\times10^{-4}$ J.

- Many books use ΔV instead of V.

Potential difference

PRACTICE: An electron is moved from Point *A*, having a voltage (potential) of 25.0 V, to Point *B*, having a voltage (potential) of 18.0 V.

(a) What is the work done (in eV and in J) on the electron by the external force during the displacement?



SOLUTION:

· $W = q(V_B - V_A)$. $W = -e(18.0\text{ V} - 25.0\text{ V}) = 7.0\text{ eV}$.

$7.0\text{ eV }(1.60\times10^{-19}\text{ J / eV}) = 1.12\times10^{-18}\text{ J}$.

(b) If the electron is released from Point B, what is its speed when it reaches Point A?

SOLUTION: $q\Delta V = \Delta E_K$

$(1/2)mv^2 - (1/2)mu^2 = 1.12\times10^{-18}$

$(1/2)(9.11\times10^{-31})v^2 = 1.12\times10^{-18}$

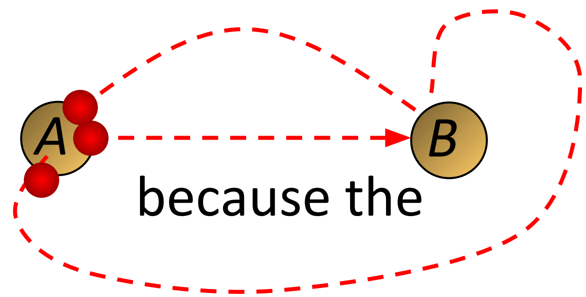
$v = 1.57\times10^6\text{ ms}^{-1}$.

•Since the electron is more attracted to A than B, we have stored this energy as potential energy.

Potential difference – path independence

EXAMPLE: A charge of $q = {}^{+}15.0\ \mu C$ is moved from point *A*, having a voltage (potential) of 25.0 V to point *B*, having a voltage (potential) of 18.0 V, in three different ways. What is the work done in each case?

SOLUTION:



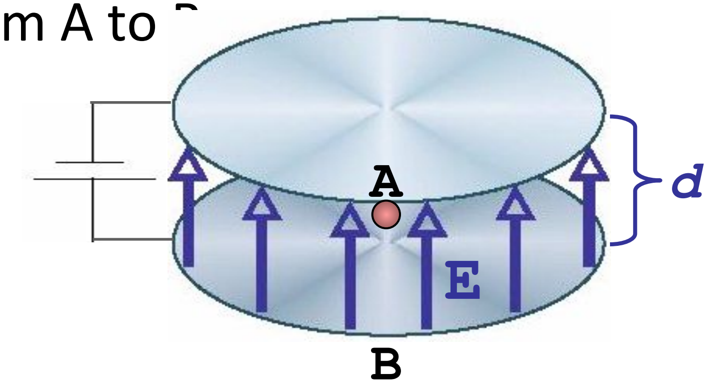
•The work is independent of the path because the electric force is a **conservative force**.

•$W = qV = 15.0\times10^{-6}\times {}^{-}7.0 = {}^{-}1.1 \times10^{-4}$ J. Same for all.

• **G**ravitational force is also a conservative force. You remember that work done by gravitational force will be the same (converted into KE) if we throw a stone from certain height with the same speed in any direction.

Potential difference – between parallel plates

PRACTICE: Two parallel plates with plate separation d are charged up to a potential difference of V simply by connecting a battery (shown) to them. The electric field between the plates is E. A positive charge q is moved from A to



(a) How much work is done in moving q through the distance d?

(b) Find the potential difference V across the plates.

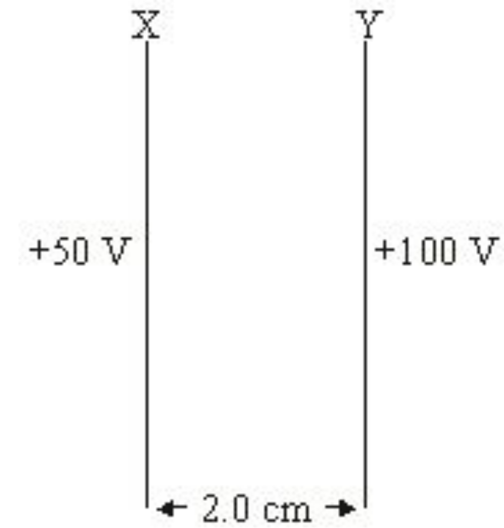
SOLUTION: $W = Fd \cos \theta$, $F = Eq$, and $W = qV$.

(a) $W = Fd \cos 0° = (Eq)d$.

(b) $qV = Eqd \rightarrow V = Ed$.

Potential difference – between parallel plates

PRACTICE: Two parallel plates with plate separation 2.0 cm are charged up to the potential difference shown. Which one of the following shows the correct direction and strength of the resulting electric field?



SOLUTION:

·Since the greater positive is plate Y, the electric field lines point from Y ⟶ X.

·From $V = Ed$ we see that

$E = V / d$

$= (100 - 50) / 2$

$= 25\ \text{V cm}^{-1}$.

	Direction	Strength / V cm^{-1}
A.	~~X → Y~~	25
B.	~~X → Y~~	100
C.	Y → X	25
D.	Y → X	100

Potential difference – the electronvolt (1eV)

·When speaking of energies of individual charges (like electrons in atoms), rather than large groups of charges (like currents through wire), Joules are too large and awkward.

·We define the **electronvolt** eV as the work done when an elementary charge *e* is moved through a potential difference *V*.

·From $W = qV$ we see that

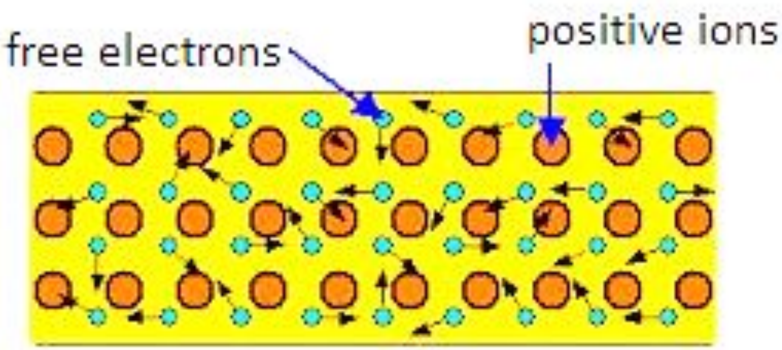
$$1\ \text{eV} = eV = (1.60\times10^{-19}\ \text{C})(1\ \text{V}) = 1.60\times10^{-19}\ \text{J}.$$

$1\ \text{eV} = 1.60\times10^{-19}\ \text{J}$	electronvolt conversion

electronvolts are almost exclusively used in atomic and nuclear physics.

Identifying sign and nature of charge carriers in a metal

·In 1916 conclusive proof that the charge carriers in a metal are electrons (-) was obtained by Tolman and Stewart.

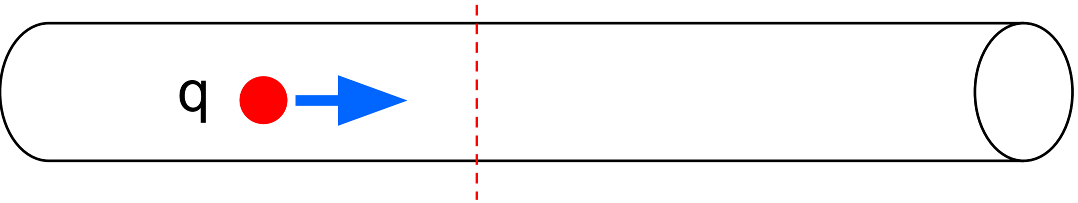


The metal atoms in a solid are bound together by the **metallic bond**.

When a metal solidifies from a liquid, its atoms form a regular lattice arrangement. The shape of the lattice varies from metal to metal but the common feature of metals is that as the bonding happens, electrons are donated from the outer shells of the atoms to a common sea of electrons that occupies the entire volume of the metal.
The positive ions sit in fixed positions on the lattice. There are ions at each lattice site because each atom has now lost an electron. Of course, at all temperatures above absolute zero they vibrate in these positions.

Electric current (symbol I)

◊ the flow of electric charge q that can occur in solids, liquids and gases.



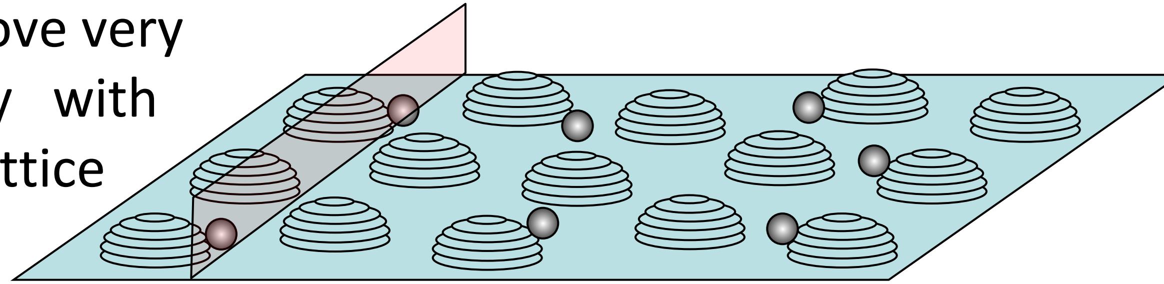
- DEF: the rate at which charge flows past a given cross-section.
- measured in amperes (A)

$$I = \frac{q}{t} \qquad 1A = \frac{1C}{1s}$$

Solids – electrons in metals and graphite, and holes in semiconductors
Liquids – positive and negative ions in molten and aqueous electrolytes
Gases – electrons and positive ions stripped from gaseous molecules by large potential differences.

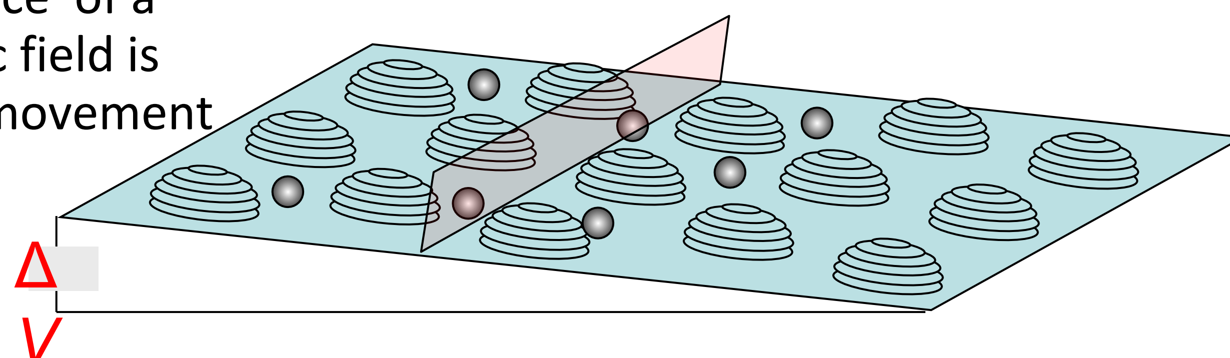
Drift velocity

· In a metal, free electrons move very rapidly, but collide constantly with the atoms in the crystalline lattice structure of the metal.



· Note that through any cross-section of the conductor, the net current is zero. At macroscopic level current is zero.

· If we place that same portion of conductor under the influence of a potential difference (electric field is established), there is a NET movement toward the lower potential:



· net current is NOT zero in this case.

·The electrons still have a high velocity, but this time the net migration is in the direction of the lower potential.

·The speed of this net migration is called the **drift velocity**.

Drift speed

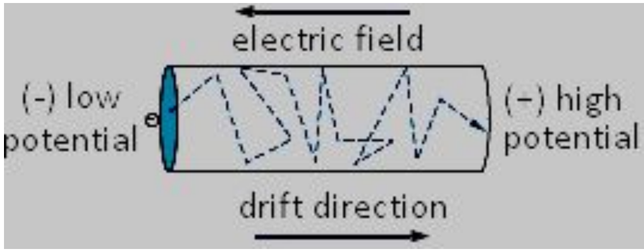
- When a battery is connected across the ends of a metal wire, an electric field is produced in the wire.
- All free electrons in the circuit start moving at the same time.
- Free electrons are accelerated reaching enormous speeds of about 10^6 ms^{-1}. They collide with positive ions of crystal lattice generating heat that causes the temperature of the metal to increase.
- After that, they are again accelerated because of the electric field,

  until the next collision occurs.

- Due to the collisions with positive ions of crystal lattice, hence changing direction, it is estimated that the drift velocity is only a small fraction of a metre each second (about 0.1mm/s).

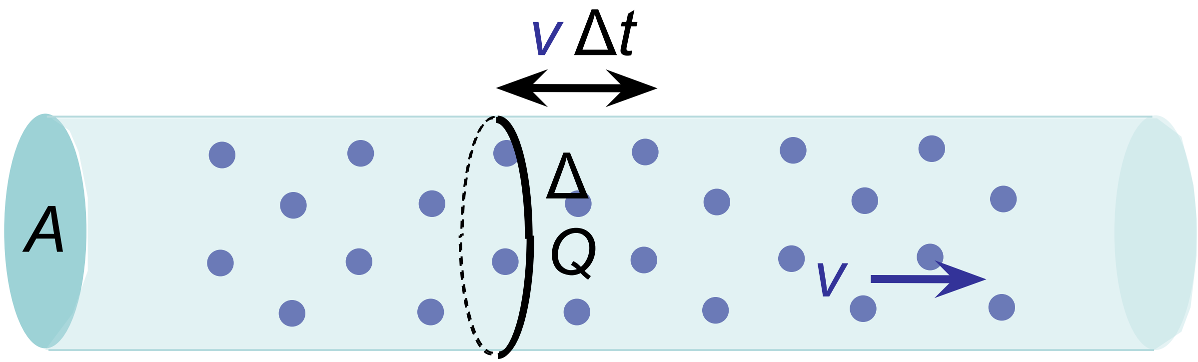
example: it takes ~ 3 hour for an electron to travel through 1m in an electric circuit of a car.

it's not even a snail's pace!!!!!



Drift speed

- Imagine a cylindrical conductor that is carrying an electric current I.
- The cross-sectional area of the conductor is A
- It contains charge carriers each with charge q.
- n is charge carriers density (# charges/unit volume)
- We assume that each carrier has a speed v



·Through any time interval Δt, only the charges ΔQ between the two black cross-sections will provide the current I.

·The volume containing the charge ΔQ is $V = Av\Delta t$.

·Thus $\Delta Q = nVq = nAv\Delta tq$.

·Finally, $I = \Delta Q / \Delta t = nAvq$.

$I = nAvq$	current vs. drift velocity

Drift speed

$I = nAvq$	current vs. drift velocity

PRACTICE: Suppose the current in a 2.5 mm diameter copper wire is 1.5 A and the number density of the free electrons is $5.0\times10^{26}\ m^{-3}$. Find the drift velocity.

SOLUTION: Use $I = nAvq$, where $A = \pi d^2/4$.

$$A = \pi d^2/4 = \pi(2.5\times10^{-3})^2/4 = 4.91\times10^{-6}\ m^2.$$

$v = I / [nAq]$

$= 1.5 / [5.0\times10^{26}\times4.91\times10^{-6}\times1.6\times10^{-19}] = 0.0038$ ms^{-1}.