Lecture 13

ELECTRICITY

Electric charge

Coulomb's law

Electric field and potential

Capacitance

Electric current

ELECTRICITY

Many important uses

Light
Heat
Rail travel
Computers
Central nervous system
Medical/dental

Historical

6^{th} century B.C., Greeks noticed sparks were produced when the fossilized tree resin called amber was rubbed with fur.

Greek word for **amber** is ***elektron*** from which the word electricity is derived.

End of the 19^{th} and early 20^{th} century:

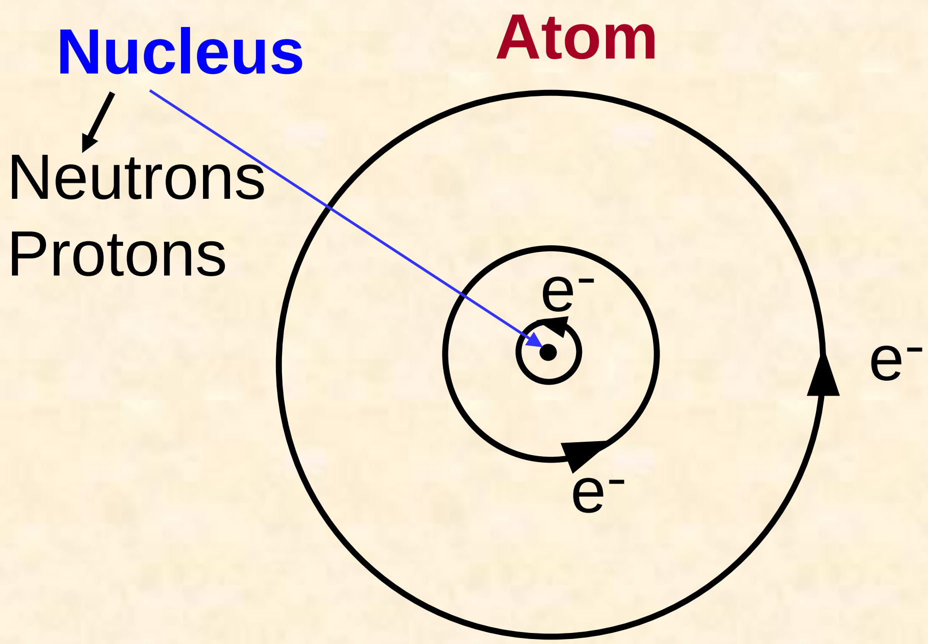
Fundamental discoveries concerning the electronic structure of the atom were made.

Electric charge and the atom

Electric charge is a characteristic of **sub-atomic particles.**

Simple View

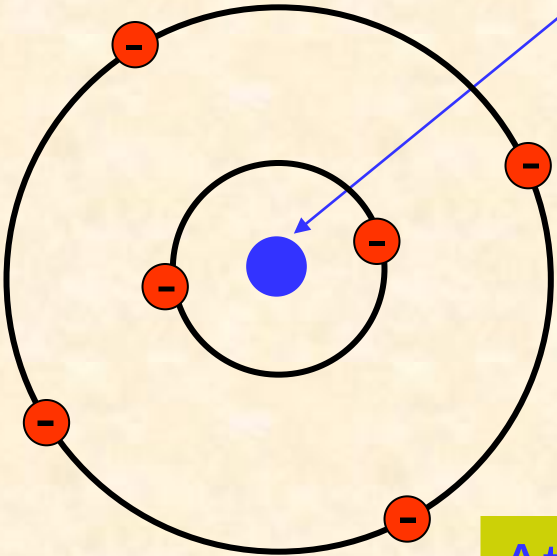
An atom is composed of 3 kinds of particles: **protons , electrons and neutrons.**



Particle	Charge	value
proton	**+e**	**1.6×10^{-19} Coulomb (C)**
electron	**-e**	**-1.6×10^{-19} Coulomb (C)**
neutron	**none**	**----------------**

Electric charge and the atom

Carbon Atom



Nucleus

6 protons: charge +6e
6 neutrons: (no charge)

6 electrons: charge -6e

Atoms are electrically neutral

Total **positive charge** of the **nucleus** = **total negative** charge of the **electrons** around the nucleus.

In General, these particles

- neither created nor destroyed,
- **electrons** can be displaced from one atom to an other.

Electron removed – result → positive ion
Electron added – result → negative ion

Electric charge and the atom

Electric charge

• **basic physical property** of subatomic particles,

3 Characteristics of charge

1. Two types of charges, positive and negative

2. Charge **is conserved**
   Charges can be **separated** but **cannot be created or destroyed.**

3. **Like** charges **repel** and **unlike** changes **attract**

Electrostatic forces

result from the **separation** of positive and negative charges.

Electric charge

Basic unit of positive charge:

$+e = 1.6 \times 10^{-19}$ Coulomb

Basic unit of negative charge:

$-e = -1.6 \times 10^{-19}$ Coulomb (C)

Any charged object:

- Total charge is always a multiple of e
- Charge can only have values ±e, ±2e, ±3e ±..
- Charge is said to be **quantised**
- Never fractional charge ?

Electric charge

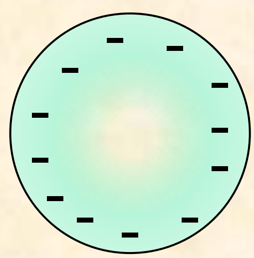
Electrically charged materials

Many examples

Almost any two non-conducting substances when rubbed together will become charged

Plastic comb run through your hair
comb will then attract bits of paper

Balloon and wool rubbed together:
balloon becomes negatively charged



Friction associated with rubbing does not create the charge

Charge transferred by movement of electrons

Charge is conserved
Neither created or destroyed

Total amount of charge in universe: constant

Electric charge

Types of Materials

Conductors:

- Example: metals, copper etc.
- charges are free to move.

Insulators:

- Example: Rubber, plastic etc
- charges are not free to move.

Semiconductors:

- Example: Silicon, Germanium
- movement of charges can be controlled by temperature or doping of the material.

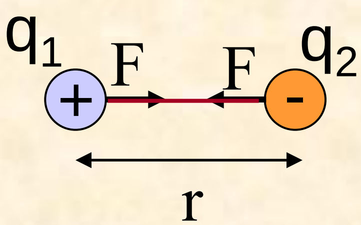
Application: electronic devices

Photoconductors:

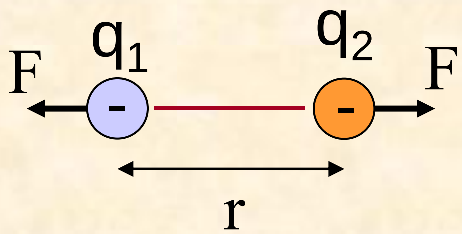
- **Example:** Selenium
- **In darkness:** Insulator (holds charge)
- **Exposed to light:** conductor (charge leaks away)
- Application: photocopier, laser printer

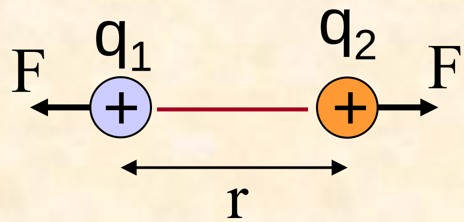
Electric charges and forces

Unlike charges



Like charges





$$F \propto \frac{q_1 q_2}{r^2}$$

Mathematical law that describes how **like charges repel and unlike charges attract** each other is called **Coulomb's law**.

Charles Coulomb (1736-1806) French physicist,

Coulomb's law: "the **force** between two point charges is **proportional** to the **product of their charge** and **inversely proportional** to the **square of their separation**"

Direction of the force: along line joining the point charges.

Coulomb's Law

$$F \propto \frac{q_1 q_2}{r^2} \qquad F = k\frac{q_1 q_2}{r^2}$$

SI unit of charge is called the Coulomb

Force F is known as the **Coulomb force** or **electrostatic force** and its units are Newtons

distance r is in metres

Hence units of k are Nm^2C^{-2}

The constant k is determined by experiment to be 9×10^9 Nm^2C^{-2} (in a vacuum)

k is sometimes written as $$k = \frac{1}{4\pi\varepsilon_0}$$

where ε_0 is called the permittivity of vacuum

$$\varepsilon_0 = 8.85 \text{x} 10^{-12}\ C^2N^{-1}m^{-2}$$

$$F = \left(\frac{1}{4\pi\varepsilon_0}\right)\frac{q_1 q_2}{r^2}$$

Coulomb is a very large quantity of charge

Coulomb's Law

Example: Two charges, each of one Coulomb, are a distance of 1 metre apart. What is the force between them?

$$F = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2} = \frac{1\text{C} * 1\text{C}}{4\pi\ 8.85\text{x}10^{-12}\text{C}^2\text{N}^{-1}\text{m}^{-2} * 1\text{m} * 1\text{m}}$$

F = $9\text{x}10^9$ N = 9 billion Newtons

Coulomb force is very large compared with gravitational force

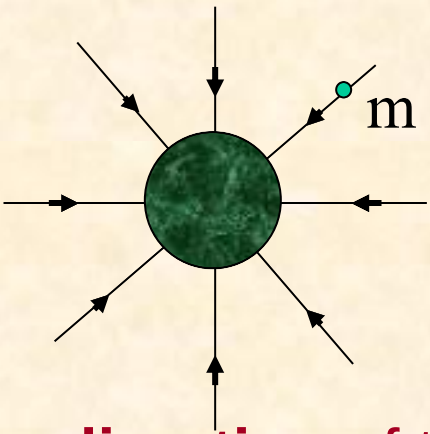
Electric field

Electric field describes the way in which the presence of one or more charges affect the surrounding space

Electric Field

Electrostatic force and gravitational force can both act through space even when there is no **physical contact between the objects** involved.

Gravitational field: g



mass m experiences a force: $F = mg$

$PE \approx mgh$

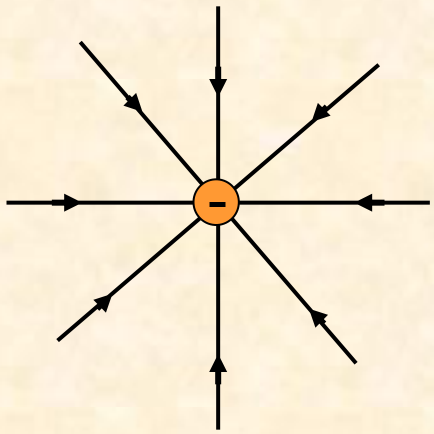
Field lines show the **direction** of the force and indicate its relative **magnitude**

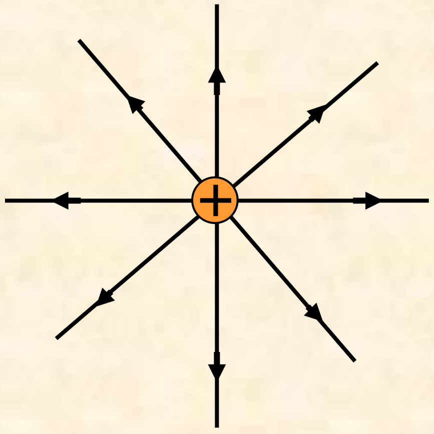
In the case of charged particles, what transmits the force between them?

An **electric field exists** in a region of space around a charged object.

Electric Field

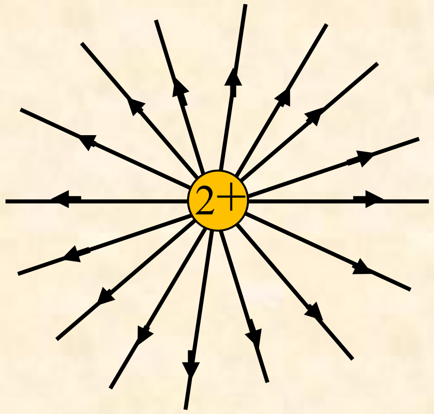
Electric field lines





Electric field near a **negative charge** is directed **radially into** the charge as shown

Electric field near a **positive charge** is directed **radially out** from the charge



Double the charge
Double the number
of field lines

Similar to gravitational field lines

Electric field lines show

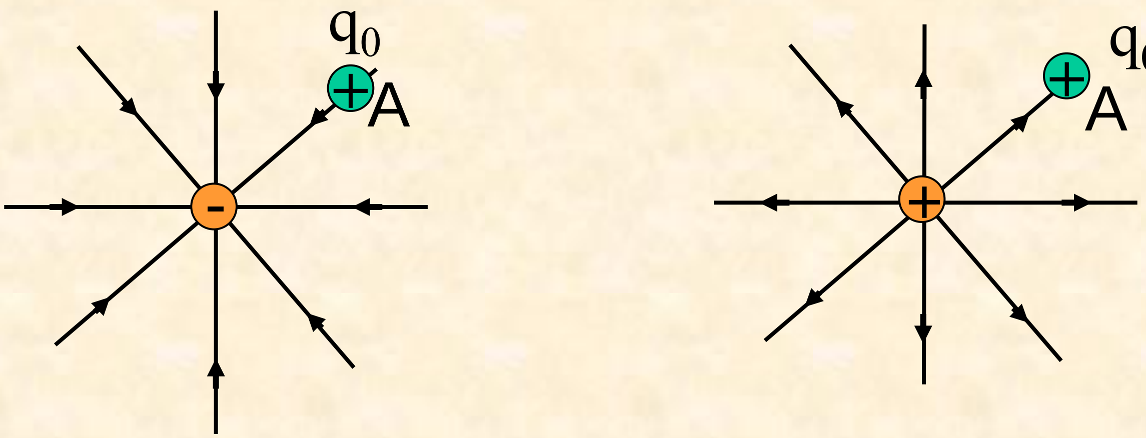
- direction of the force
- indicate its relative magnitude

Electric Field

Consider positive **test** charge q_0 (fictitious) at A

Assume test charge is small and does not affect any other charges

Consider force on positive test charge

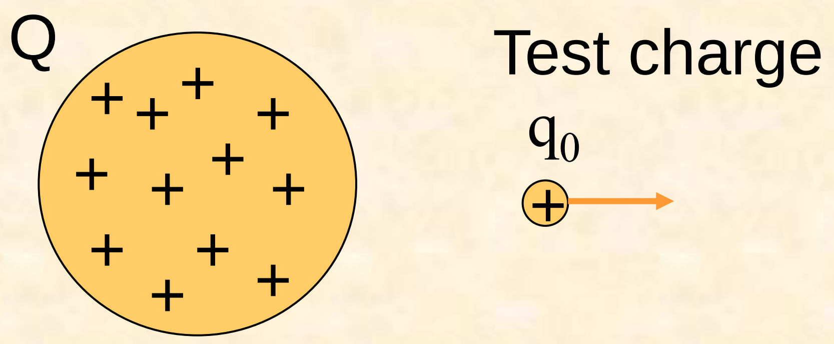


Electric field represents the electric force a stationary positive charge experiences.

Electric Field

The electric field E is said to exist in the region of space around a charged object.

Example:



Force F experienced by test charge q_0 at a given location

Electric field E due to charge Q at location of small **test charge q_0** is given by;

$$E = \frac{F}{q_0}$$

SI unit of electric field

Newtons per coulomb (NC^{-1})

Electric Field

$$E = \frac{F}{q_0} \qquad F = q_0 E$$

Analogous to
F= mg in gravitational field

$$F = k\frac{Qq_0}{r^2} = Eq_0$$

$$E = k\frac{Q}{r^2}$$

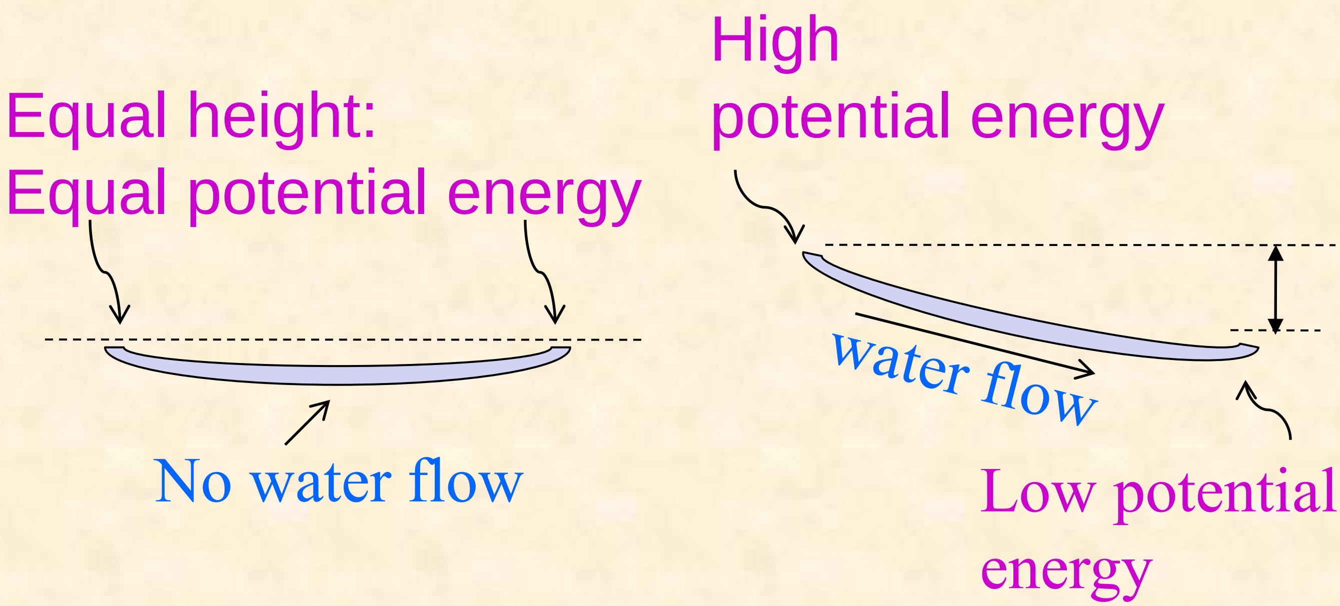
Electric field at a given point **depends only on the charge Q** on the object setting up the field and the distance r from the object to the specific point in space

Electrical Potential Difference

Electrical Potential Difference

more commonly known as voltage (V)

e.g. 1.5 V battery



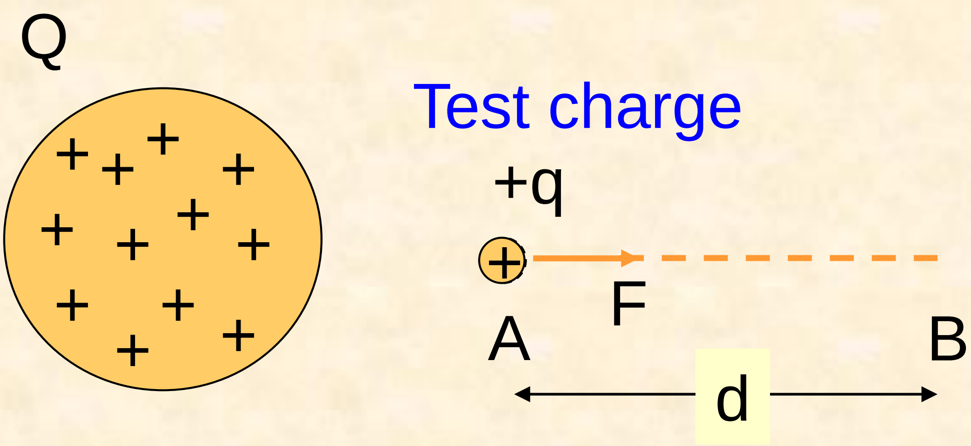
In a battery, chemical reactions produce electrical potential difference between terminals.

Causes electrons to flow in external circuit

Charged objects often possess **electrical potential** that can be transformed into **kinetic energy**

Electrical Potential Difference

Definition of voltage



Test charge experiences a repulsive Coulomb force, therefore **it has electrical potential energy due to its position**

Test charge free to move from A to B,
- Coulomb force does work
- potential energy decreases

$$W_{AB} = Fd$$

Electrical Potential Difference

Voltage between A and B is defined as the **change in electric potential energy** as charge q moves from A to B

$$V_{AB} = \frac{\Delta PE}{q}$$

$$V_A = \frac{PE_A}{q}$$

V_a is the potential energy per unit charge at A

Note: Electric Potential (due to Q) exists at point A even if there is no test charge q there.

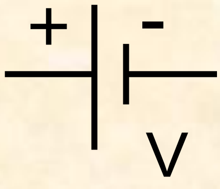
Voltage is defined as:

- **potential energy per unit charge**
- **or potential difference**

SI unit for voltage is the volt (V)   1V = 1J/C

Volt; named after Alessandro Volta (1745-1827), Italian scientist who invented the battery.

Voltage of a battery is the potential difference between its two terminals



Electrical Potential Difference (*V*)

The energy given to a charge by a voltage is:

$$\Delta PE = qV$$

$W_{AB} = \Delta PE$

F=qE (E is the electric field)

Since $W_{AB} = Fd$, $W_{AB} = (qE)d = \Delta PE = q\,V$

V = Ed (if the field E is constant)

Units: V (volts) E (NC^{-1}) d (metres)

Voltage of a battery is the potential difference between its two terminals

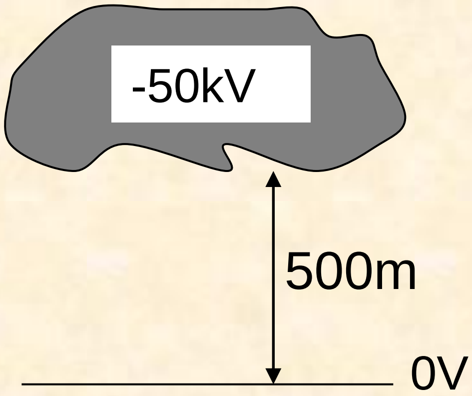
Electrical Potential Difference (*V*)

$V = Ed$ (if the field E is constant)

Units: V (volts) E (NC^{-1}) d (metres)

Example :
The potential at the ground is zero. A storm cloud has a potential of -50kV at an altitude of 500m.
What is the associated electric field ?

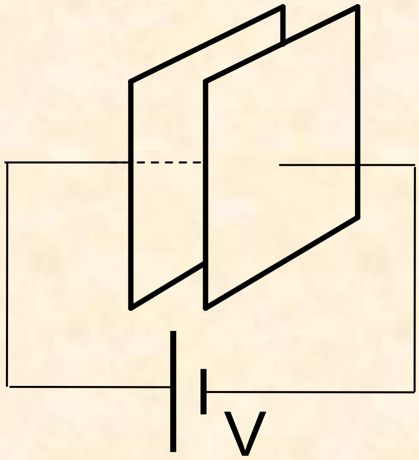
$V = Ed$

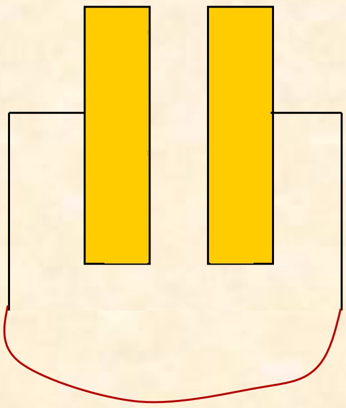


$E = V/d = (-50\times10^{3})/500$ V/m

$E = -100$ V/m

Electrical Capacitance





A pair of metal plates separated by an insulator. When subjected to a potential V, charges ±Q will accumulate on the two plates.

Electrical **capacitance** (denoted C) is the **ability to store charge**, expressed as **ratio of charge to potential difference**:

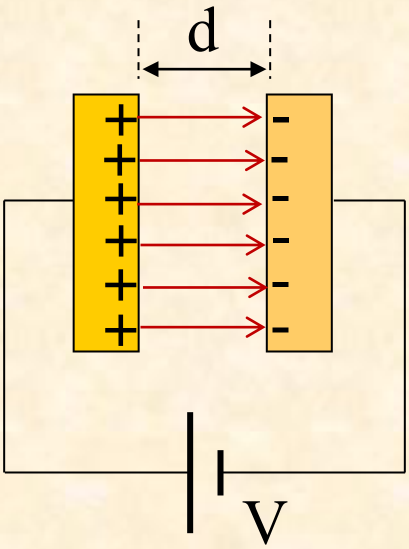
where Q is the charge on either plate $C = \frac{Q}{V}$

SI unit of capacitance is coulomb per volt: given the name **farad (F)** (**Michael Faraday** 1791-1867.- English physicist & chemist)

Voltage removed: charge remains on the plates

Electrical Capacitance

Parallel Plate capacitor



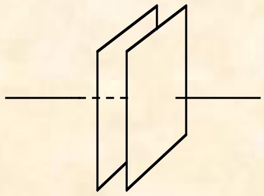
A uniform electric field is created between the plates: E=V/d

$$C = \frac{Q}{V}$$

Parallel plates separated by free space (≈ air)

capacitance is given by

$$C = \frac{A\varepsilon_0}{d}$$



- A is the common surface area of the plates
- d is their separation
- ε_o= 8.85 x 10^{-12} $C^2N^{-1}m^{-2}$
is the "permittivity of free space"

Electrical Capacitance

Application

Electric energy stored in a capacitor

Ventricular fibrillation

Fast uncoordinated twitching of the heart muscles

Remedy

•Strong jolt of electrical energy

•Restores regular beating of the heart

Defibrillator

•Electrical energy stored in a capacitor

•Energy released in ≈ few milliseconds

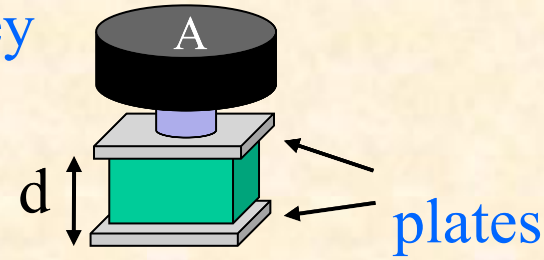
Electrical Capacitance

Application

Computer keyboard

$$C = \frac{A\varepsilon_0}{d}$$

Key



Push key

- moves plates closer together
- changes capacitance
- detected by computer electronics

Capacitors
used in random access memory (RAM) chips

Electric Current

The electric current (denoted I) is the charge flowing per second:

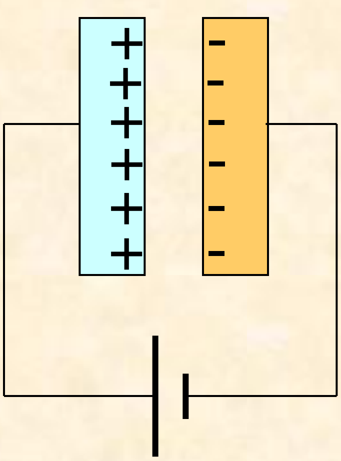
$$I = \frac{Q}{t}$$

It is a measure of the flow rate of charges (analogous to the flow of liquid).

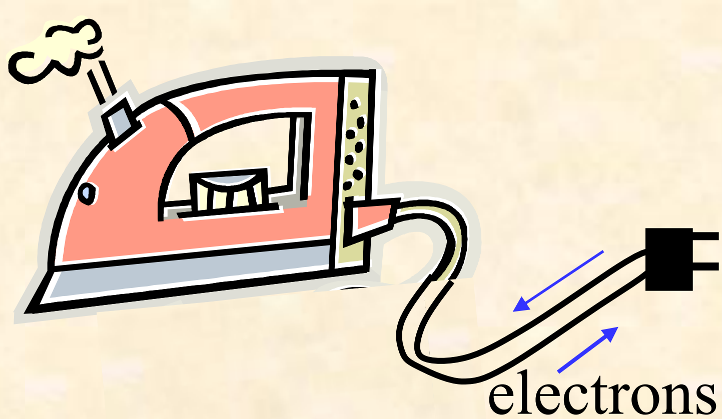
SI unit of current is ampere (I) coulomb/second
Named after French physicist André Ampere.

Note:

In a capacitor, the charges don't move, thus I = 0 amps



In electrical cables, charges flow to an appliance when switched on: current I ≠ 0



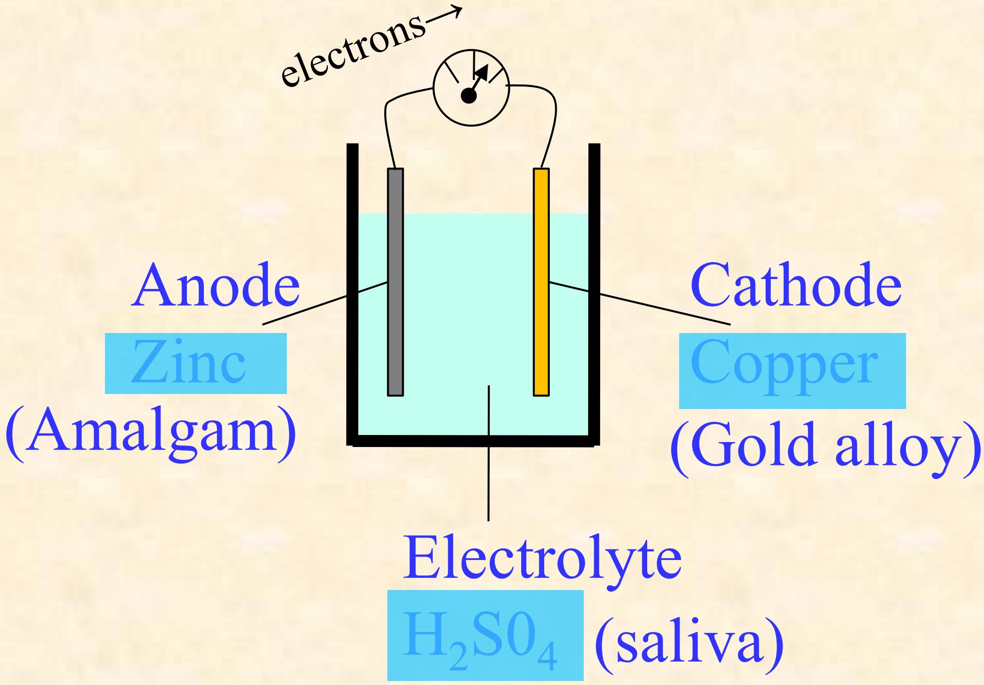
Electric Current

Electrochemical cell (battery)

Dissimilar metals

Potential difference between anode and cathode

- charges flows (current)



at anode $$Zn \rightarrow Zn^{2+} + 2electrons$$

at cathode $$2H^{+} + 2electrons \rightarrow H_2$$

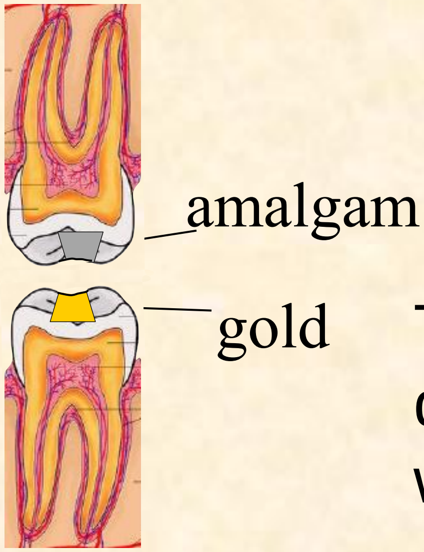
$2H^+$ from H_2SO_4

Zn atoms converted to ions that pass into solution
Zn electrode corrodes

Electric Current

Electrochemical cell in the oral cavity

Analogy



Electrical potential exists between dissimilar metals (different electrical potential)

Two different metals or different areas of composition within the one restoration

On contact electrical discharge occurs:
Small electrical shock>>>pain

Corrosion of restorative material

No contact,
small current may still flow—saliva (electrolyte)
0.5-1 μA, potential difference ≈ 500mV

Electrical currents in brain ≈ 0.01 μA

Electric Current

Dental effects

Voltage production in oral cavity

e.g. touching a metal fork to amalgam

Saliva facilitates the flow of electrons(current) from one metal to another.

Problem: if there is little dentine between restorative material and the pulp

Current can flow through the tooth and cause pain by stimulating the nerve cells in the pulp

Prevention.

Insulate metallic restorations from pulp.

Normally remaining dentine (insulator) is sufficient

Electric Current

Dental Applications

Electric pulp tester

Instrument which uses various values of electric current to excite a response from the nervous tissue within the pulp of suspect tooth.

Patient holds metal handle of pulp tester.

Results from Electric pulp test

No response
•indicates tooth has died
>>root canal therapy or removal advised

Fast response (compared to the adjacent teeth)
•indicates tooth is inflamed and pulp probably dying

Response (same as the other teeth)
• considered to be healthy

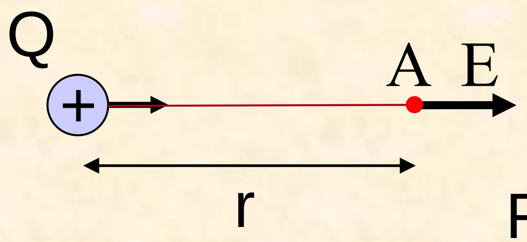
Pulp testers should not be used on patients with pacemakers because of the possibility of electrical interference

Electric Field

Example

Determine the electric field at A, a distance of 40cm from a positive charge Q of $2x10^{-3}$ Coulombs.

$k = 9x10^{9}\ Nm^{2}C^{-2}$



Find field E at point A 40 cm from Q.

$$E = k\frac{Q}{r^2}$$

$$E = 9 \times 10^{9}\ N.m^{2}C^{-2} \frac{(2 \times 10^{-3})\ C}{(0.4m)^{2}}$$

$$E = 112.5 \times 10^{6}\ NC^{-1}$$

Example:

The potential at the ground is zero. A storm cloud has a potential of -50kV. Calculate the speed of an electron reaching the ground. Electron mass: 9.11×10^{-31}kg.

The potential energy: qV

is transformed into kinetic energy: $1/2mv^2$

$1/2mv^2 = qV$

$$v = \sqrt{\frac{2qV}{m}}$$

$$v = \sqrt{\frac{2(-1.6\times10^{-19})(-50\times10^{3})}{9.11\times10^{-31}}}ms^{-1}$$

$$v = 1.3\times10^{8}\,ms^{-1}$$

Example

Calculate the capacitance of a parallel plate capacitor of area A =5 cm^2 and plate separation d= 0.1 cm? If the capacitor is connected to a 9 volt battery, what is the resulting charge on the positive plate? $\varepsilon_0 = 8.85 \times 10^{-12} C^2 N^{-1} m^{-2}$

$$C = \frac{A\varepsilon_0}{d}$$

$$C = \frac{5 \times 10^{-4} m^2 * 8.85 \times 10^{-12} C^2 N^{-1} m^{-2}}{0.1 \times 10^{-2} m}$$

$C = 4.4 \times 10^{-12} F = 4.4 pF$

$C = Q/V$ $\quad\quad$ $Q = CV$

$Q = 4.4 \times 10^{-12} F * 9V = 39.6$ coulombs