جـــامـعـة بــاجــي مخـتـــار - عـنــابـة
BADJI MOKHTAR - ANNABA UNIVERSITY

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Chapter 2: Conductors

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In this chapter, we propose to study the properties of conductors in electrostatic equilibrium, at the macroscopic scale where the dimensions considered are very large compared to the interatomic distances.

This will be an opportunity to introduce the concepts of capacitor capacitance and ohmic conductor resistance, useful in electricity.

What is a Conductor

In electricity, a ***conductor*** is a material medium in which certain electric charges, called "free charges“, are capable of moving under the action of an electric field.

When such a material is placed in an electric field, the free electrons move in a direction opposite to the field.

Example: water, metals.....

Another class of materials is called ***isolator*** in which all the electrons are bound to their respective atoms or molecules. This means, there are no free electrons.

Example: wood, plastic.....

What is an Electrostatic Equilibrium ???

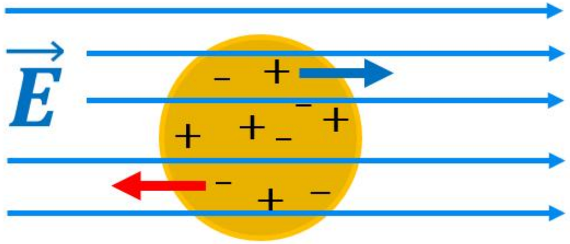
A conductor is said to be in electrostatic equilibrium if *all charges are immobile* (no charge displacement in this medium).

This means that there must be **no net electric force** on any mobile charge.

In brief,

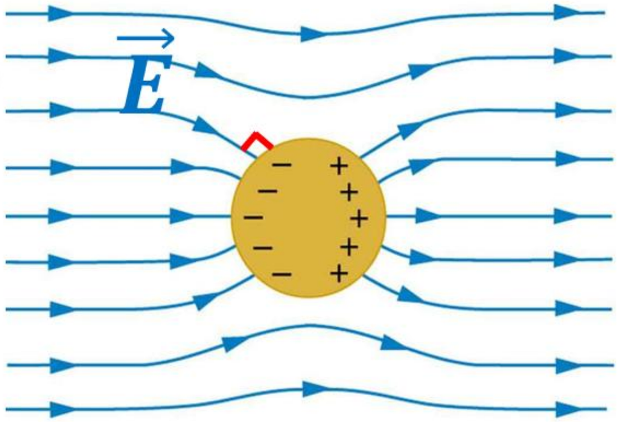
Conductors *contain* ***free charges*** *that move easily.*

When the conductor is put into a static electric field, charges in the conductor quickly respond to reach a steady state called ***electrostatic equilibrium****.*



Out of equilibrium

A spherical conductor in static equilibrium with an originally uniform electric field.



In equilibrium

Free charges move within the conductor, polarizing it, until the electric field lines are perpendicular to the surface.

The field lines end on excess negative charge on one section of the surface and begin again on excess positive charge on the opposite side.

No electric field exists inside the conductor, since free charges in the conductor would continue moving in response to any field until it was neutralized.

1- Properties of a conductor in isolated electrostatic equilibrium

➢ Electric field is zero inside a conductor in equilibrium

Since the charges inside the conductor in equilibrium are **at rest**, they are not subject to any force, this means that the electrostatic field in the conductor in equilibrium is zero:

$$\vec{F} = q\,\vec{E} = \vec{0} \quad \Rightarrow \quad \vec{E} = \vec{0}$$

- *At any point inside a conductor in equilibrium, the electric field* ***E is zero***.

➢ Potential inside the conductor is constant

The difference in potential dV between two infinitely close points M and M' inside the same conductor is then given by:

$$dV = -\vec{E}\,.\,\overrightarrow{dl} = 0\,; \qquad \overrightarrow{MM'} = \overrightarrow{dl} \quad \Rightarrow \quad V = Const$$

Since $E = 0$ inside the conductor, the potential is therefore uniform throughout the entire volume of the conductor.

- *A conductor in electrostatic equilibrium constitutes an* ***equipotential volume***.

Distribution of charges

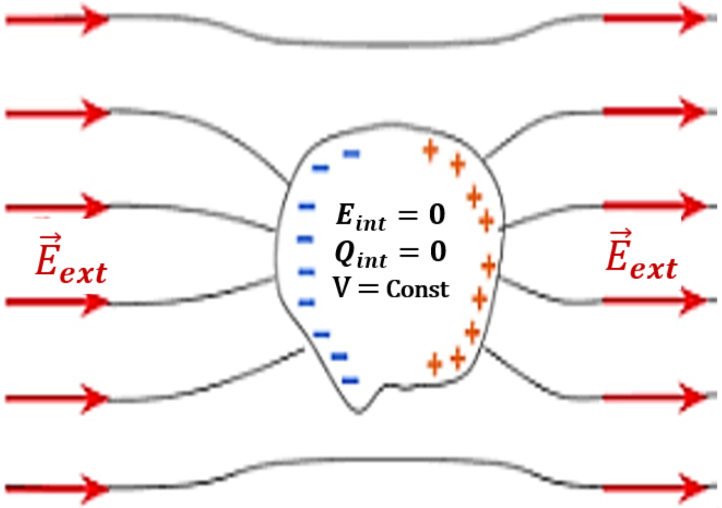
Consider a conductor with a net charge Q and choose any closed surface such that it lies under the surface of the conductor.

By Gauss's theorem, we have: $$\phi = \oiint \vec{E}_{int} \cdot \overrightarrow{dS} = \frac{Q_{int}}{\varepsilon_0}$$

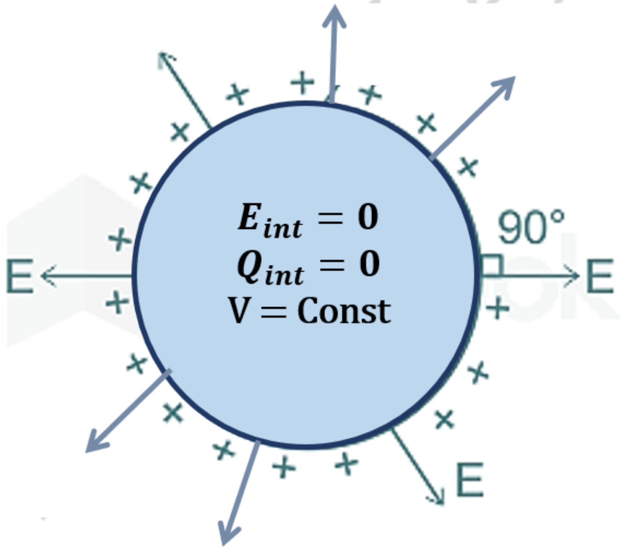
Since $E_{int} = 0$, we deduce that: $Q_{int} = 0 \Rightarrow \rho = 0$

- ***Inside*** *a charged conductor in equilibrium, the electric charge is* ***zero****.*
- *All uncompensated charges are therefore necessarily* ***located on the surface*** *of the conductor.*

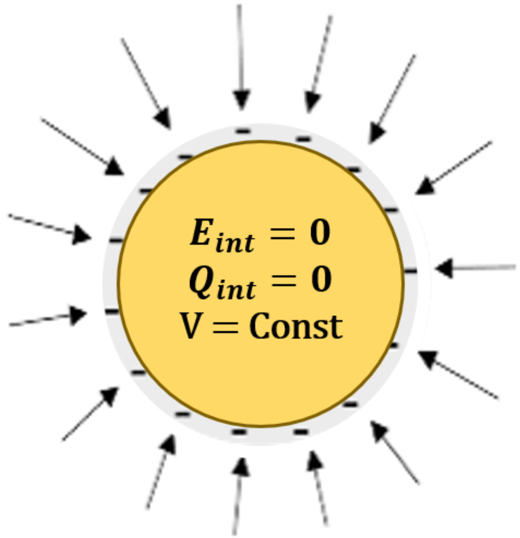
Some cherged conductors



Neutral conductor



Charged positively

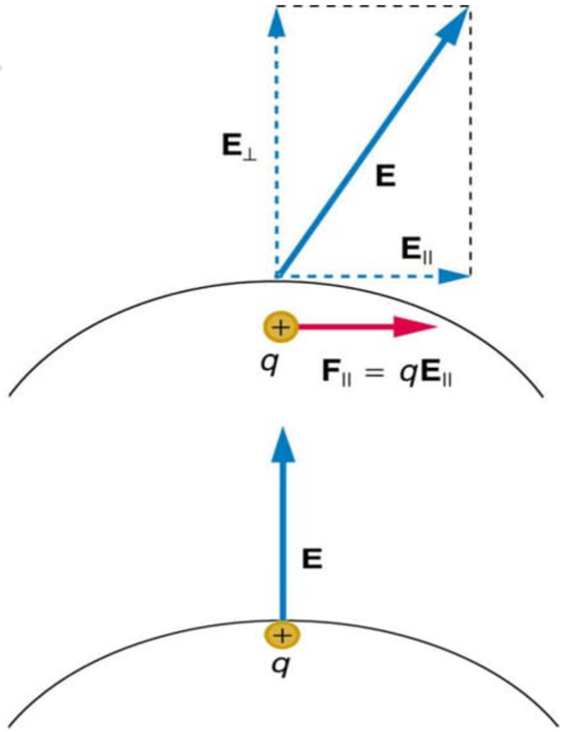


Charged negatively

➢ The electric field at the surface of a conductor

If the electric field had a component parallel to the surface of a conductor, free charges on the surface would move, a situation contrary to the assumption of electrostatic equilibrium.

Therefore, the electric field is always **perpendicular** to the surface of a conductor.



- *The field is **normal** to the surface of a conductor in equilibrium.*

$$\phi = \oiint \vec{E} \cdot \overrightarrow{dS} = \frac{\sum Q_{int}}{\varepsilon_0}$$

Since the charge distribution is located on the surface, so: $\sum Q_{int} = \sigma S$

At any point just above the surface of a conductor (*in the immediate vicinity of a charged conductive surface*), the surface charge density σ and the magnitude of the electric field E are related by:

$$E\,S = \frac{\sigma\,S}{\varepsilon_0} \quad \Rightarrow \quad \boxed{E = \frac{\sigma}{\varepsilon_0}}$$

This relationship expresses ***Coulomb's theorem***

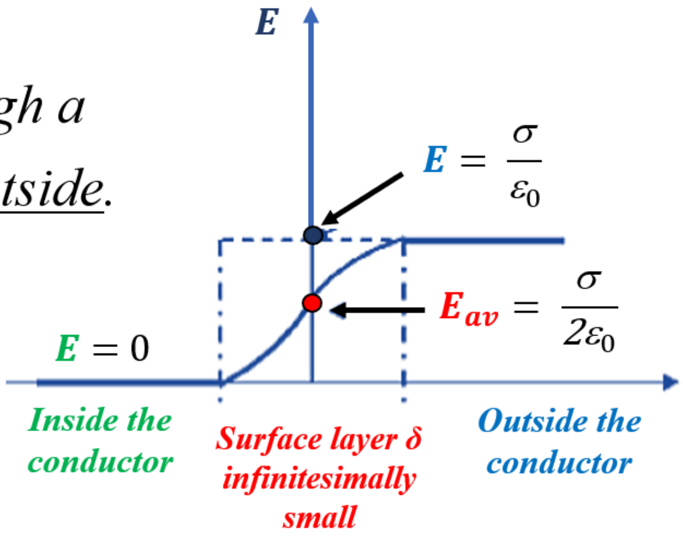
Remarks

- ✓ The electric field in the **immediate vicinity** of a conductor depends only on the charge distribution density.
- ✓ The electric field is discontinuous when passing through a conductor, since it is **zero** inside and equal to $\frac{\sigma}{\varepsilon_0}$ just outside.

This expression gives the value of the electric field at a point **close** to the surface and **outside** the conductor, while the field inside is zero.

- ✓ **On the surface** the field takes an average value

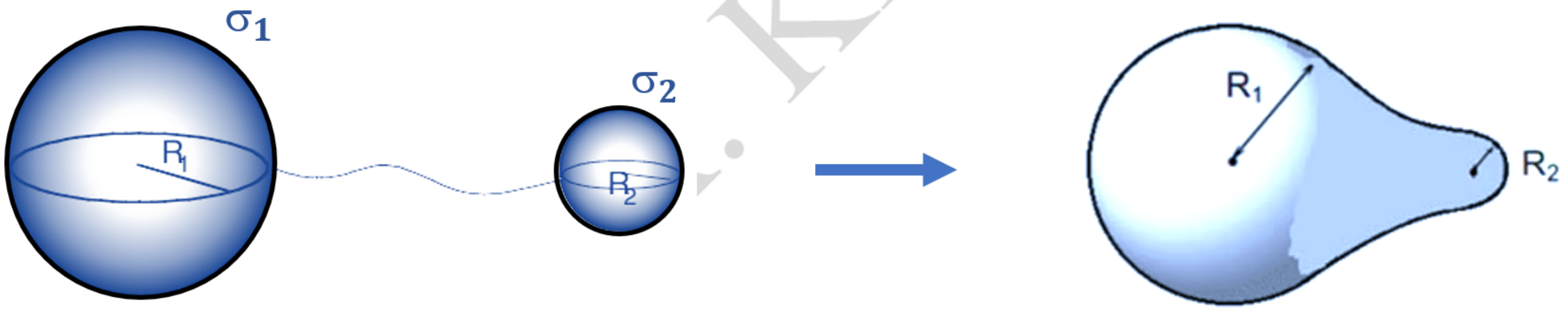
$$E_{av} = \frac{\sigma}{2\varepsilon_0}$$



Variation of the electric field when crossing the surface of the conductor

- **Electric fields on irregular surfaces: Peak effect**

Consider two conducting spheres with respective radii R_1 and R_2 $(R_1 > R_2)$ brought to the same potential (connected by a conducting wire). Both spheres have a uniform charge density σ_1 and σ_2 .



$$dq_1 = \sigma_1\, dS \quad ; \quad dq_2 = \sigma_2\, dS \quad ; \quad dV = \frac{1}{4\pi\varepsilon_0}\frac{dq}{R}$$

$$V_1 = \frac{1}{4\pi\varepsilon_0}\oiint \frac{\sigma_1\, dS}{R_1} = \frac{1}{4\pi\varepsilon_0}\frac{\sigma_1\, 4\pi\, R_1^2}{R_1} \quad \Rightarrow \quad V_1 = \frac{\sigma_1\, R_1}{\varepsilon_0}$$

$$V_2 = \frac{1}{4\pi\varepsilon_0}\oiint \frac{\sigma_2\, dS}{R_2} = \frac{1}{4\pi\varepsilon_0}\frac{\sigma_2\, 4\pi\, R_2^2}{R_2} \quad \Rightarrow \quad V_2 = \frac{\sigma_2\, R_2}{\varepsilon_0}$$

Since the potentials are equal: $V_1 = V_2$ $\Rightarrow$ $\boxed{\frac{\sigma_2}{\sigma_1} = \frac{R_1}{R_2}}$
(*the spheres are connected by a conductive wire*)

If $R_1 >> R_2$, then $\sigma_2 >> \sigma_1$

Therefore, the sphere with the ***smallest radius*** carries the ***greatest charge density***. This result can be generalized to a conductor of any shape and explains the ionizing power of a point (**Peak effect**).

$$V = E\,R \quad \Rightarrow \quad \boxed{\frac{E_2}{E_1} = \frac{R_1}{R_2} \gg 1}$$

- *The **smaller the radius** of curvature of a conductor, the **stronger the electrostatic field**.*

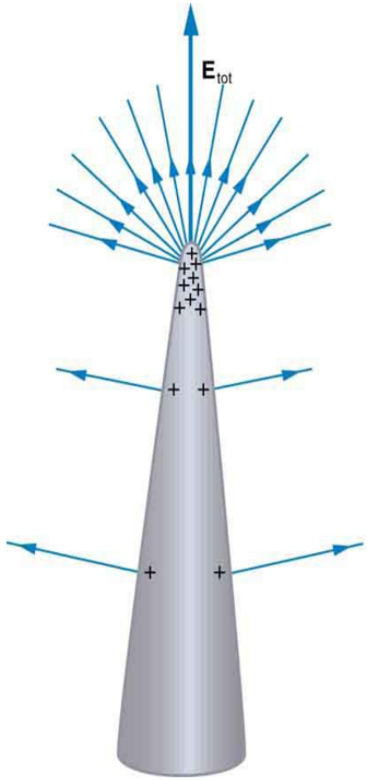
Consequence:

An accumulation of charges is observed at the end of the point.

Application:

Peak power is useful to facilitate the discharge of electricity; this is the role of lightning rods (*paratonnerres*) that are placed on buildings to protect them against lightning. **Lightning rods work best when they are most pointed**.

The lightning will pass preferentially through the tip (*pointe*) of the lightning rod and the high intensity electricity will flow to the ground, thus protecting the building.



2- Self-capacitance of an insulated conductor

Consider a conductor in electrostatic equilibrium isolated placed at a point O in space, charged with a surface distribution σ such as: $Q = \oiint \sigma \, dS$

This results, at any point in space, in a charge: $Q' = \alpha Q$

We will have at every point in space, a field: $\overrightarrow{E'} = \alpha \vec{E}$

Since E and Q vary always in proportion, which is also true for the conductor whose potential is V, we can therefore define a quantity C, called the ***self-capacitance*** of the isolated conductor, equal to their ratio.

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

Depends only on the geometry of the conductor.

The unit of a conductor's self capacitance is the Farad (*in homage to Faraday*).

It's a very large unit, we use sub multiples:

Microfarad (μF) = 10^{-6} F. Nanofarad (nF) = 10^{-9} F. Picofarad (pF) = 10^{-12} F.

Example: Capacity of a charged sphere of radius R.

Solution:

We know that: $V = \frac{1}{4\pi\varepsilon_0} \oiint \frac{\sigma \, dS}{R}$ and $Q = \oiint \sigma \, dS$ $\Rightarrow$ $V = \frac{Q}{4\pi\varepsilon_0 R}$

The capacitance of a spherical conductor is therefore written: $C = \frac{Q}{V} = 4\pi\varepsilon_0 \ R$

The **capacity** of a conducting sphere is proportional to its **radius**.

3- Electrostatic influence phenomena

In the case of an **isolated conductor**, whether ***neutral*** or ***charged***, the **total charge is conserved**.

Under the influence of an external electric field, the **total charge** can be redistributed, but remains unchanged.

Two types of influence are observed:

partial influence and **total influence**.

Partial electrostatic influence

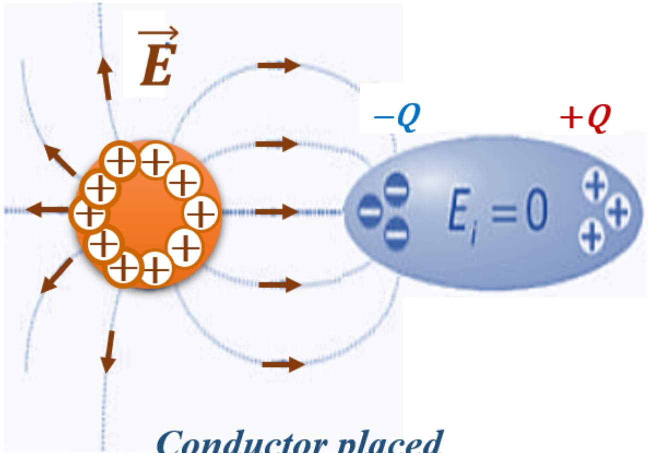
When we place an electric charge near a conductor, the electric field produced by such a charge causes, inside the conductor, movement of charges (by effect of Coulomb's forces) producing a redistribution of charges.

The positive charges go in the same direction as the field and the negative charges go in the opposite direction, creating two poles, one positive and one negative. Such movement of charges finishes when new equilibrium conditions are reached.

*In the insulated conductor, the charge has changed its distribution, but the total charge Q_T remains **zero**:*

$$Q_T = (+Q) + (-Q) = 0$$

Isolated conductor



Conductor placed in electric field

The phenomenon disappears when external charge is removed.

Total electrostatic influence

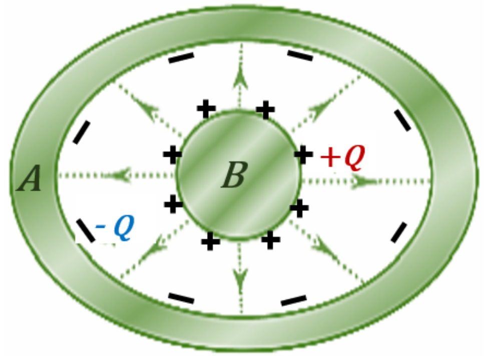
The total electrostatic influence between two conductors occurs when all field lines originate in the first conductor and terminate in the other.

The charge appearing on the **inner surface** of (**A**) is **equal** and **opposite** to the charge on conductor (**B**).

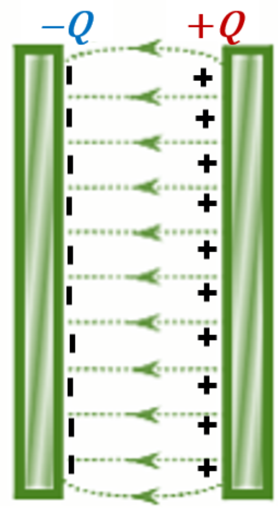
During an electrification by influence, there is no creation, but simply a displacement of charges.

Two conductors subjected to ***total electrostatic influence*** *have the* ***same charge*** *but* ***different sign****.*

This result applies directly to capacitors.



Conductor entirely surrounded to another



Two parallel plates conductors face to face

Ground connection

The Earth is generally considered as origin of potentials (zero electric potential). Furthermore, since the Earth's radius is very large compared to that of any other conductor we can manipulate, even if it absorbs or transmits an electrical charge, its potential remains almost constant.

We can compare this situation to sea level: even if a glass of water is poured into the sea, its level rise is imperceptible; Similarly, if a charge is added to or removed from the Earth, its potential does not change.

Therefore, a **grounded conductor** has two important properties:

- ✓ ***Its electrical potential is always zero.***
- ✓ ***Charge can move to and from the ground via the ground connection, satisfying the conductor's properties in electrostatic equilibrium.***

Grounding electrical installations is a safety measure to prevent electric shock (electrical discharges), as the potential of all grounded devices is zero.

Thank you for your attention