2.1. Electric charge & electric field

What comes to your mind when you hear electricity?

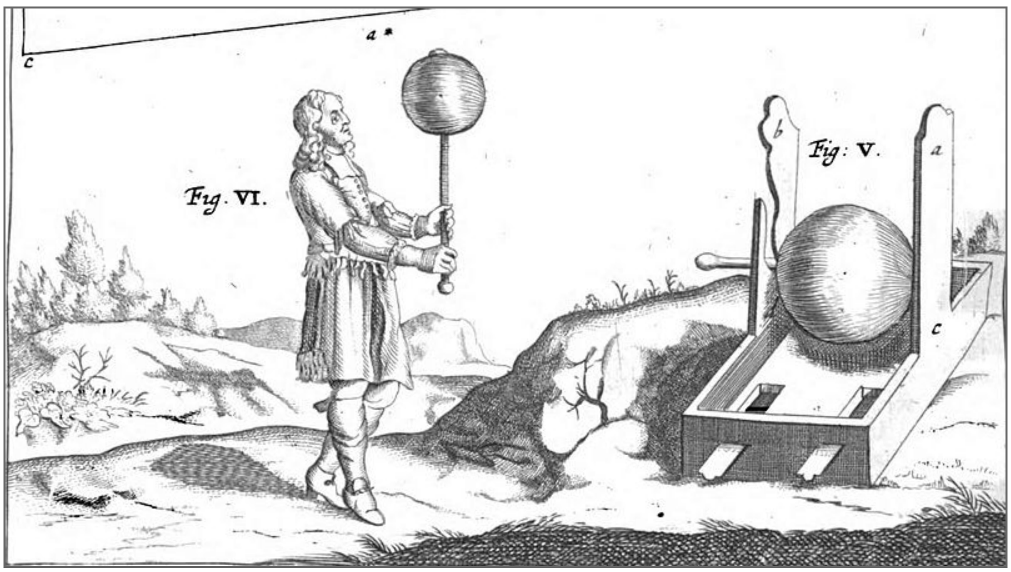
- modern technology, i.e. EVs, computers, smartphones, etc.
- human body relies on electrical signals i.e. heart & brain
- electric forces
    - involved in holding atoms & molecules together
    - are the origin of forces such as friction or normal force can at the atomic level
- gravitational forces remains a separate entity

Short history of studying electricity

- since ancient Greece, the effect of static electricity known
    - “elektron" is Greek for “amber”
    - rub amber with cloth $\rightarrow$ amber attracts small pieces
- scientific investigation of electricity around late 1700:
    - Charles Augustin de Coulomb (1736 - 1806)
    - Benjamin Franklin (1706–1790)
    - Michael Faraday (1791 - 1867)
    - Karl Friedrich Gauss (1777-1855)
    - Alessandro Volta's (1745-1827)
    - … and many more …

Otto von Guericke & his sulfur globe

- 1672: reported that after rubbing sulfur globe, globe repealed/attracted light objects
- $\rightarrow$ there is **contactless** force beyond gravitation $\rightarrow$ `es07`



*from **wikipedia**, public domain*

Static electricity

- are there different types of charge?
- when do they attract and when do they repel each other?
- $\rightarrow$ `es13 + es04`

*from **wikipedia** under **CC 2.0 Generic license**, unedited*

Static electricity

- two types of charge: **positive** and **negative**
- arbitrary convention by **Benjamin Franklin** (1706–1790):
    - rubbing amber/plastic → **negative charge**
    - rubbing glass rod → **positive charge**
- charges of **same type repel** each other
- charges of **opposite type attract** each other

Charge origin

- **simplified atomic model:**
    - tiny nucleus with **positively charged protons** and neutral neutrons
    - **negatively charged electrons** orbit nucleus
- **neutral atom:** equal number of protons & electrons
- **ion:** atom that gained or lost electrons
- **polar molecules**: charge **distribution is non-uniform**, e.g. water molecule with positive side (H) and negative side (O)
- **elementary charge**
    - smallest observed charge: **electron or proton**
    - $\mathrm{e} = 1.602 \times 10^{-19}\mathrm{C}$

Conductors vs. Insulators

- **free electrons**:
    - electrons that can "detach from their parent atoms" and move through the material/lattice
- **conductors** (e.g. metals): high abundance of free electrons
- **insulators** (e.g. wood): low abundance of free electrons
- **semiconductors** (e.g. silicon): intermediate abundance of free electrons

Conservation of charge

- net electric charge **cannot be created or destroyed**
- $\rightarrow$ **charges can only be separated** but their sum remains constant
- **example**: rubbing a glass rod with a cloth:
    - glass rod gains positive charge by emitting free electrons
    - cloth gains equal negative charge by receiving free electrons
    - **total charge remains zero**
- **grounding**:
    - connection to Earth
    - Earth acts as a **charge reservoir**

Inducing charge by conduction

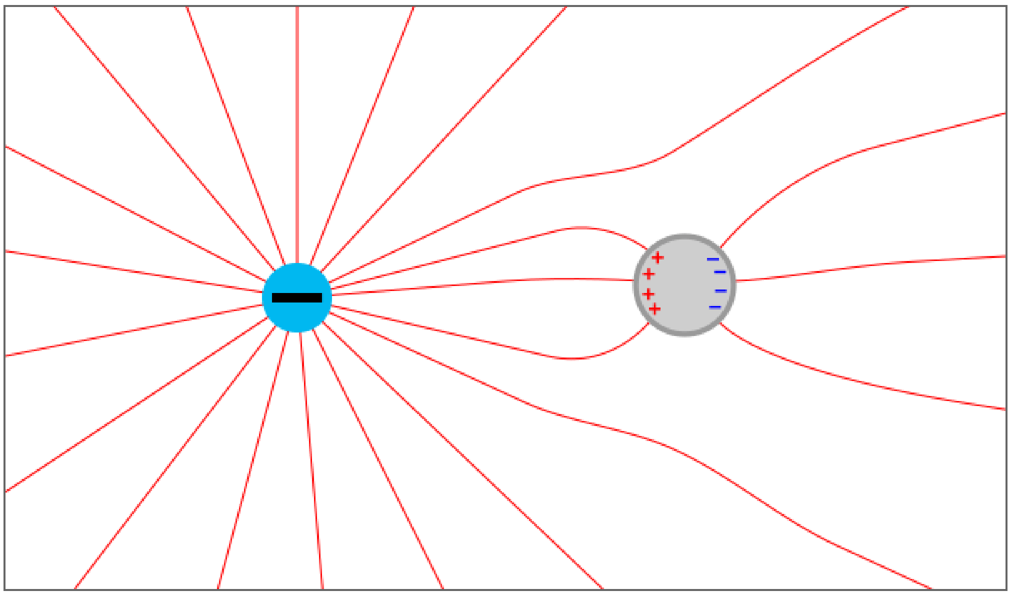
`es09 + es10`

- **contact required**
- free electrons move from one conductor to another
- after contact, both objects have the **same charge**

Inducing charge by (electrostatic) induction

`es09 + es10`

- **no contact required**



*from **wikipedia** under **CC 1.0 Universal license**, unedited*

Inducing charge by (electrostatic) induction

`es09 + es10`

- **no contact required**
- in conductor/influence:
    - **redistribution of free electrons** in nearby conductor which causes charge separation
- in insulators/polarization:
    - electrons cannot move freely
    - **molecules change their orientation** which causes charge separation
- $\rightarrow$ induced charge separation **does not change total charge**

Electrostatic force & Coulomb's law

`es08 + script simulation`

- how to quantify/compute electrostatic force?
- investigated by **Charles Augustin de Coulomb** (1736–1806)
- honoring his contribution, charge Q is measured in the SI unit **coulomb** [C]

Electrostatic force & Coulomb's law

$$F = k\frac{Q_1 Q_2}{r^2}$$

- with:
  - $k \approx 9.0 \times 10^9\ N \cdot m^2/C^2$ (Coulomb's proportionality constant)
  - r is the distance between charges
  - Q_1 and Q_2 are the charges
- **force direction**
  - force acts **along the line connecting both charges**
  - **like charges repel**, **opposite charges attract**

Vector Form of Coulomb's Law

$$\vec{F}_{12} = \frac{1}{4\pi\varepsilon_0}\frac{Q_1 Q_2}{r^2}\hat{r}_{21}$$

- with:
  - $\vec{F}_{12}$: force Q_2 exerts on Q_1
  - fundamental constant **permittivity of free space** ε_0
  - $k = \frac{1}{4\pi\varepsilon_0}$
  - $\hat{r}_{21}$ is **unit vector** pointing from Q_2 to Q_1.
- **superposition principle**: for multiple charges, net force is the vector sum of all forces

Concept of the Electric Field

- observations so far:
  - charges q exert electrostatic force $\vec{F}$
  - electrostatic forces act at a distance & contactless
- **electric field** $\vec{E}$ connects q and $\vec{F}$:
  - $\vec{E}$ is a **vector field**
  - concept by Michael Faraday (1791–1867)
  - analogy with gravitational field: $\vec{F} = q\vec{E} \leftrightarrow \vec{F} = m\vec{g}$

Electric field form of Coulomb's law

- **idea**: measure field created by charge Q by placing a small *test charge* q (q has negatable effect of Q)
- using Coulomb's law, $\vec{E}$ is then:

$$\vec{E} = \frac{\vec{F}}{q} = \frac{1}{4\pi\epsilon_0}\frac{Qq}{r^2}\hat{r}_{21}\frac{1}{q} = \frac{1}{4\pi\epsilon_0}\frac{Q}{r^2}\hat{r}_{21}$$

- **superposition principle**: net field is the sum of individual fields:

$$\vec{E}_{net} = \vec{E}_A + \vec{E}_B + \vec{E}_C + \ldots$$

- **integral form**: integrate over distribution of **infinitesimal small charges** dQ

$$\mathrm{d}\vec{\mathrm{E}} = \frac{1}{4\pi\epsilon_0}\frac{\mathrm{dQ}}{\mathrm{r}^2}\hat{\mathrm{r}}$$

$$\vec{\mathrm{E}} = \int \mathrm{d}\vec{\mathrm{E}}$$

Field lines of electric field

`script simulation`

- motivation:
    - $\vec{E}$ is a vector field, i.e. each point in space is represented by a vector
    - vector length $==$ magnitude of field
    - vector orientation $==$ direction of field
    - as plot, **often perceived as cluttered**
- **concept of field lines**:
    - arrows indicate **direction & magnitude** of $\vec{E}$
    - **density of lines** represents field's magnitude
    - direction of $\vec{E}$ **tangent** to field lines
    - field lines **start on positive, end on negative** charges
    - **field lines do not cross**

Motion of charged particles inside electric field

- a charge q in an **electric field** $\vec{E}$ experiences force:

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

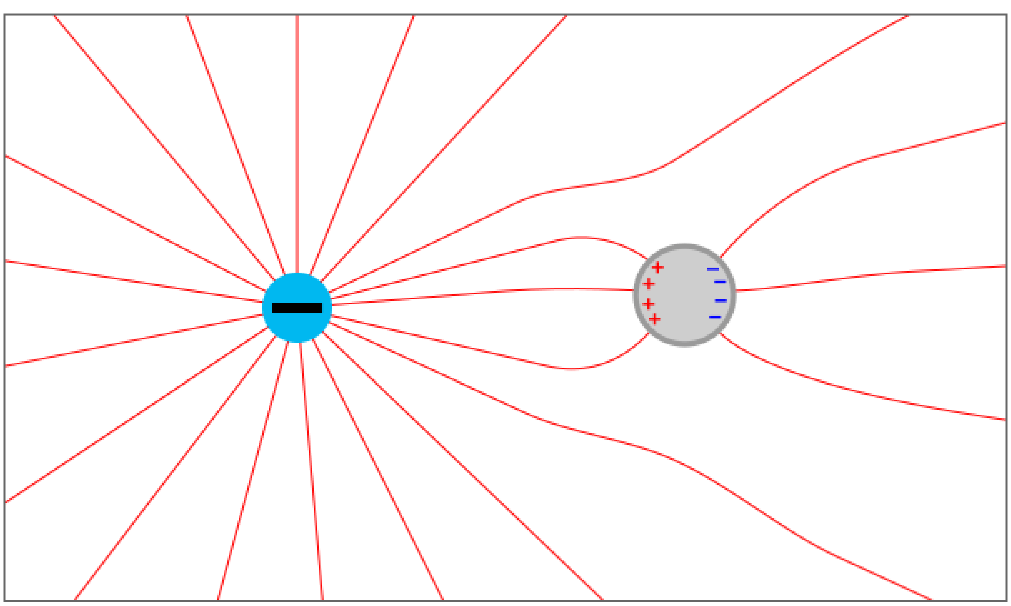
- for an **electron in uniform** E, acceleration is:

$$a = \frac{-eE}{m_e}$$

`see lecture tutorial`

Conductors in an electric field

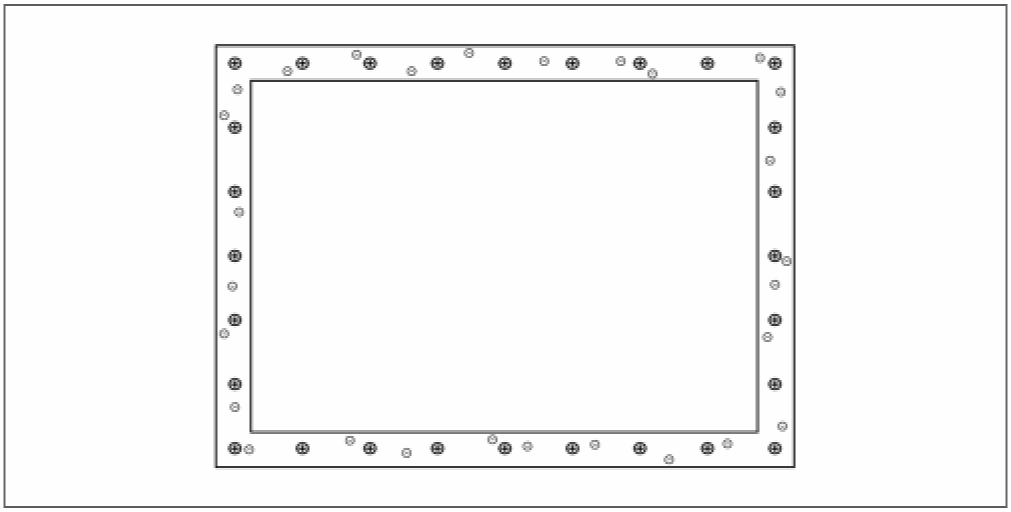
- reminder: **electrostatics, i.e. charges at rest**
- for conductors in static condition:
    - **electric field inside conductor is zero**: $\vec{E} = 0$
    - *if this would not be the case, there would be a force acting on free electrons causing them to move until they a reach position in which the net force is zero, i.e. the field is zero and they are at rest* ($\vec{F} = q\vec{E}$)
    - **net charge distributes on surface**
    - electric field **perpendicular** to surface



Faraday cage

`es16`

- conducting, closed surface with $\vec{E} = 0$ inside



*from **wikipedia**, public domain*