

## 2.1. Electric charge & electric field



### **What comes to your mind when you hear electricity?**

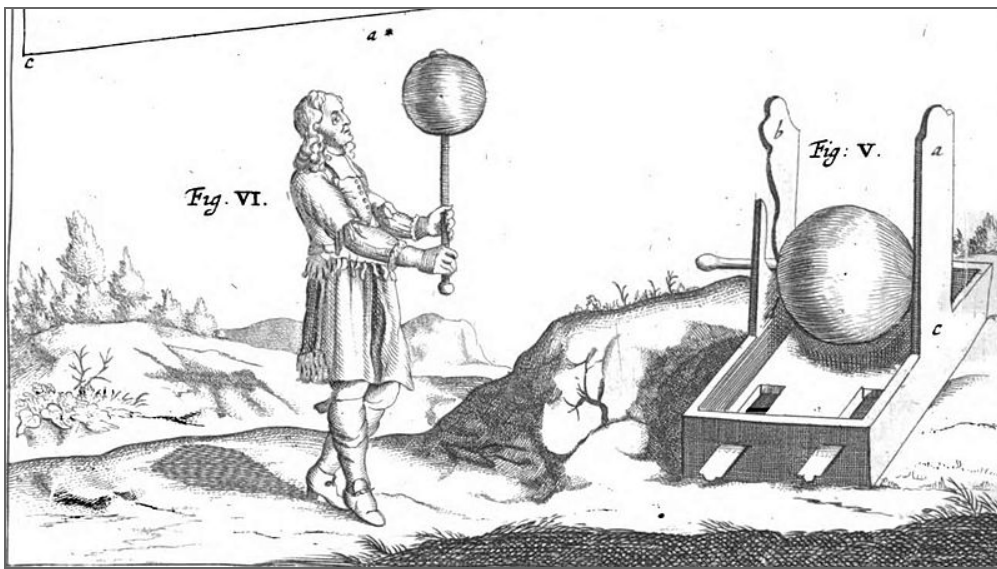
- modern technology, i.e. EVs, computers, smartphones, etc.
- human body relies on electrical signals i.e. heart & brain
- electric forces
  - involved in holding atoms & molecules together
  - are the origin of forces such as friction or normal force can at the atomic level
- gravitational forces remains 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 → 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 repelled/attracted light objects
- → there is **contactless** force beyond gravitation → es07



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## Static electricity

- are there different types of charge?
- when do they attract and when do they repel each other?
- → es13 + es04



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## 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**
  - $e = 1.602 \times 10^{-19} \text{C}$

## 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**
- → **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

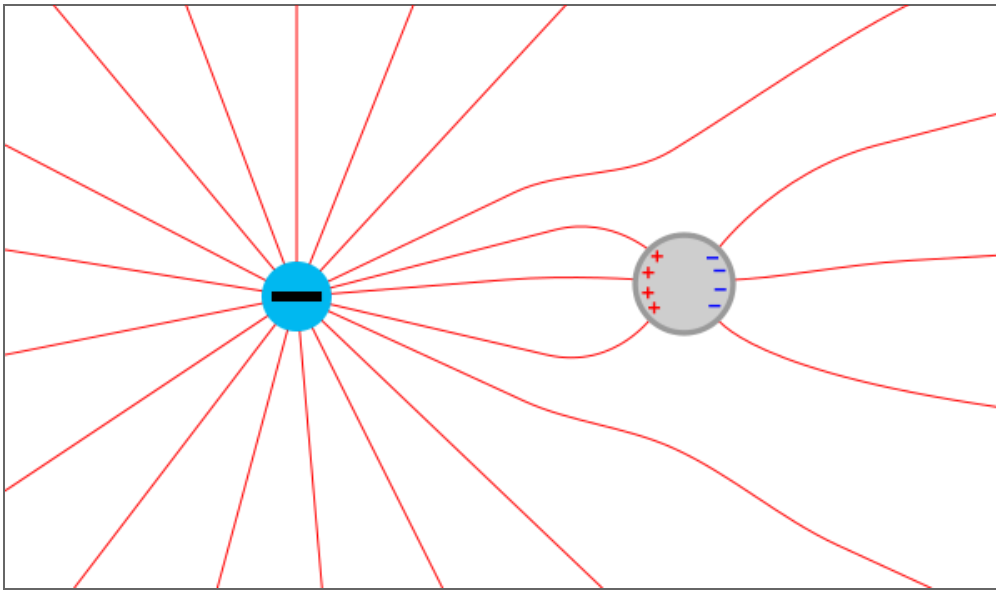
es09 + es10

- **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**



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## 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
- → 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:
  - $k \approx 9.0 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2$  (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

$$\vec{F}_{12} = \frac{1}{4\pi\epsilon_0} \frac{Q_1 Q_2}{r^2} \hat{r}_{21}$$

- with:
  - $\vec{F}_{12}$ : force  $Q_2$  exerts on  $Q_1$
  - fundamental constant **permittivity of free space**  $\epsilon_0$
  - $k = \frac{1}{4\pi\epsilon_0}$
  - $\hat{r}_{21}$  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 negligible 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:

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



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

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

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

# 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:

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

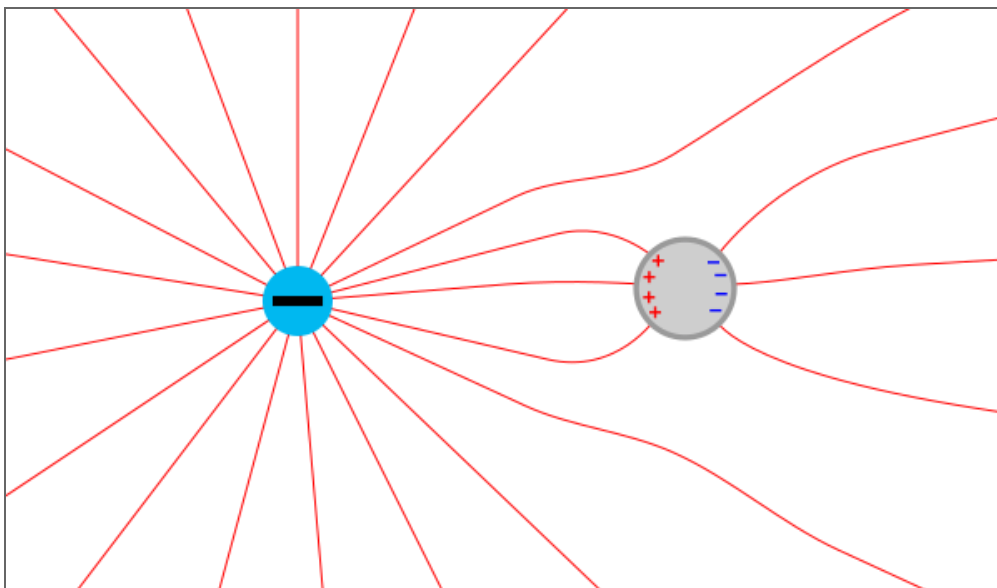
- for an **electron in uniform**  $E$ , acceleration is:

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

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 reach a 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

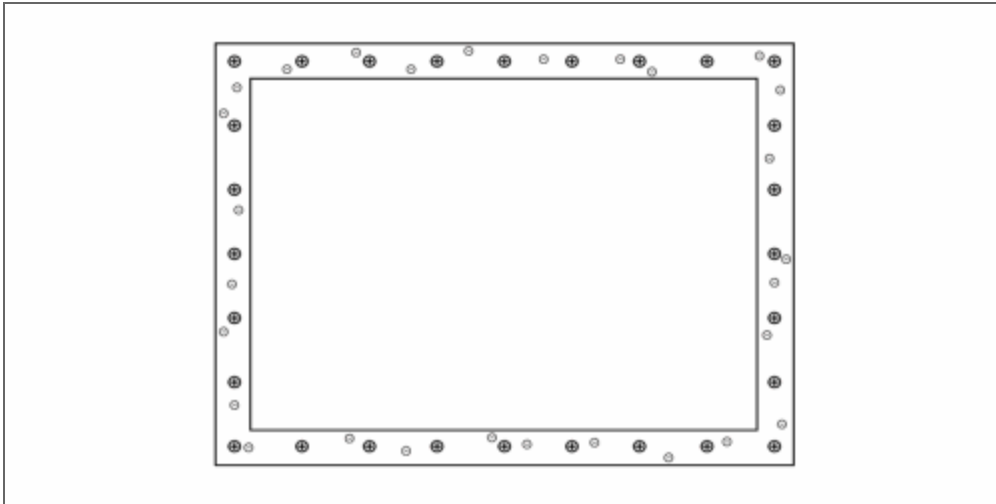


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# Faraday cage

es16

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



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