Module 1

Key Concepts:

• The electric force
• The electric field
• Field lines
Reading quiz:
What do you know about atoms, elementary particles, and charges?
Select multiple correct answers!

A. Neutral objects become negatively charged by acquiring additional electrons from other objects.
B. Protons and electrons have charges $q_e$ and $-q_e$, respectively, where $q_e$ is the smallest quantum of charge.
C. Protons and neutrons and electrons are all charged particles making up atoms.
D. Electrically neutral materials contain the same number of protons and electrons.
E. Neutral objects become positively charged by acquiring additional protons from other objects.
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- B. Protons and electrons have charges \( q_e \) and \( -q_e \), respectively, where \( q_e \) is the smallest quantum of charge.
- D. Electrically neutral materials contain the same number of protons and electrons.
- E. Neutral objects become positively charged by acquiring additional protons from other objects.
Reading quiz:
What do you know about the electrostatic force that can exist between two interacting objects? Pick the correct statements from the choices below.

A. It requires physical contact between the interacting objects.
B. It depends on the net charge of each of the interacting objects.
C. It varies inversely as $1/r^2$, where $r$ is the distance between the interacting objects.
D. It can be attractive.
E. It can be repulsive.
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E. It can be repulsive.
Gravitation

The “elementary particle” constituents of ordinary matter are **protons, neutrons, and electrons**.

All these particles have a **fundamental property** called **mass**.

Massive particles interact via the **gravitational force**.

Massive particles attract each other.
The gravitational force

**Newton's law of gravitation** gives the force between two point masses, \( m_1 \) and \( m_2 \), separated by a distance \( r_{12} \). Let \( F_{12} \) be the force object 1 exerts on object 2.

\[
F_{12} = -G \frac{m_1 m_2}{r_{12}^2} \hat{r}_{12}
\]

\( G = 6.67 \times 10^{-11} \text{Nm}^2/\text{kg}^2 \) = gravitational constant

Forces are interactions. \( F_{12} = -F_{21} \) (Newton’s third law)

Consequences of interactions are described by **Newton's laws of motion**, which predict how matter behaves when acted on by forces.

Newton’s first law sets the stage by defining an inertial frame.

Newton's second and third laws are valid in all inertial reference frames.

**2nd law:** \( F_{\text{net}} = ma \)

**3rd law:** \( F_{12} = -F_{21} \)
Action at a distance

We introduce the concept of the gravitational field to explain action at a distance.

We say that massive particles produce gravitational fields and are acted on by gravitational fields.

The magnitude of the gravitational field produced by a massive object at a point P is the gravitational force per unit mass it exerts on another massive object located at that point. The direction of the gravitational field is the direction of that force.

Near the surface of Earth the gravitational field produced by Earth is nearly constant and has magnitude \( F/m = g = 9.8 \text{ m/s}^2 \). Its direction is downward.
Electromagnetic phenomena

Protons and electrons have another fundamental property called charge. Charged particles interact via the electromagnetic force. Initially we only consider charged particles at rest.

Then the electromagnetic force is the Coulomb force. Charged particles at rest attract or repel each other.
Electric charge

• Electric charge can be either positive or negative, but comes in individual units, or quanta, in multiples of the charge on the electron or proton, with magnitude $q_e = 1.6 \times 10^{-19}$ C.

• In an isolated system, the total electric charge is conserved and remains constant in time.

• The fundamental force law between two point electric charges, $q_1$ and $q_2$, separated by a distance $r$ is given by Coulomb’s law.

$$F_{12} = k_e \frac{q_1 q_2}{r_{12}^2} \hat{r}_{12}$$

$F_{12}$ is the force object 1 exerts on object 2.

Forces are interactions. $F_{12} = -F_{21}$ (Newton’s third law)

$1/(4\pi \varepsilon_0) = k_e = 9 \times 10^9$ Nm$^2$/C$^2$  \ (SI unit of charge: Coulomb (C))

• Principle of superposition: $F_1 = F_{21} + F_{31} + F_{41} + ...$
Newton's law of gravitation gives the force between two point masses, \( m_1 \) and \( m_2 \), separated by a distance \( r_{12} \). Let \( \mathbf{F}_{12} \) be the force object 1 exerts on object 2.

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Forces are interactions. \( \mathbf{F}_{12} = -\mathbf{F}_{21} \) (Newton’s third law)

Coulomb’s law gives the force between two point electric charges, \( q_1 \) and \( q_2 \), separated by a distance \( r \).

\[
\mathbf{F}_{12} = k_e \frac{q_1 q_2}{r_{12}^2} \hat{r}_{12}
\]

\( k_e = 9 \times 10^9 \text{ Nm}^2/\text{C}^2 = 9 \times 10^9 \text{ Nm}^2/\text{C}^2 \) = electrical constant

SI unit of charge: Coulomb (C)

Compare these force laws! Similarities? Differences?

Principle of superposition: \( \mathbf{F}_1 = \mathbf{F}_{21} + \mathbf{F}_{31} + \mathbf{F}_{41} + \ldots \)

Total force on object 1 = vector sum of all forces acting on object 1
How can we separate charges?

On a macroscopic scale charge can be separated by various means. **Examples:**

- **Contact electricity:** Electrons are more or less strongly bound in different materials and can be transferred from one material to the other through rubbing, etc.
- **Chemical separation:** In a battery a chemical reaction separates charges.
- **Diffusion:** The permeable wall of living cells let different ions pass through at different rates. This can result in net charges of opposite sign inside and outside the cell.
- **Convection:** Charge is separated by convection in thunderclouds.

Energy input is needed to separate charges. This energy is released again when the charges recombine, for example in a spark.
Polarization

When a charged object is brought near a neutral object it can polarize the neutral object. If electrons are repelled by the charged object, nuclei are attracted, or vice versa. In a conductor, some electrons are free to move. They move towards one side of the conductor, leaving excess positive charge on the other side.

Even in insulators the average position of the electrons can shift by a small amount with respect to the position of the nuclei, resulting in an effective surface charge density.
Electric Field

• The electric field $\mathbf{E}(\mathbf{r})$ at a position $\mathbf{r}$ is defined as the force $\mathbf{F}(\mathbf{r})$ on a positive test charge $q'$ at position $\mathbf{r}$ divided by $q'$.

$$\mathbf{E} = \frac{\mathbf{F}}{q'}$$

• A point charge $q$ at the origin produces an electric field at position $\mathbf{r}$ a distance $r$ from the origin given by

$$\vec{E} = \frac{q}{4\pi\varepsilon_0 r^2} \hat{r}.$$  

• Principle of superposition: $\mathbf{E} = \mathbf{E}_1 + \mathbf{E}_2 + \mathbf{E}_3 + \ldots$
Field lines

Rules for drawing field lines:

• Electric field lines begin on positive charges and end on negative charges, or at infinity.
• Lines are drawn symmetrically leaving or entering a charge.
• The number of lines entering or leaving a charge is proportional to the magnitude of the charge.
• The density of lines at any point (the number of lines per unit length perpendicular to the lines themselves) is proportional to the field magnitude at that point.
• At large distances from a system of charges, the field lines are equally spaced and radial as if they came from a single point charge equal in magnitude to the net charge on the system (presuming there is a net charge).
• No two field lines can cross since the field magnitude and direction must be unique.