22 Electric Fields

22.1 Field Patterns

Like charges repel, unlike charges attract.

Electrons are responsible for charging in most situations.

- An **uncharged atom** contains an equal number of protons and electrons.
- An **uncharged solid** contains equal number of electrons and protons.

Most plastic materials can be charged quite easily by **rubbing with a dry cloth**.

1. Electrons are **transferred from the cloth** to the rod when rubbed.
2. So the rod becomes positively charged, and the cloth becomes negatively charged.

Electrical conductors such as metals contains lots of **free electrons**, which move about inside the metal and are not attached to any one atom.

To charge a metal

1. It must be **isolated from the Earth**.

   Otherwise, any charge given to it is neutralised by electrons transferring between the conductor and the Earth.

2. Then the isolated conductor can be **charged by direct contact** with any charged object.

If a positively charged isolated conductor is earthed, electrons transfer from the Earth to the conductor to **discharge it**.

Electrically insulating materials do not contain free electrons - all electrons in an insulator are **attached to individual atoms**. Some insulators are easy to charge because their surface atom easily gain or lose electrons.

The Shuttling Ball Experiment

The shuttling ball experiment shows that an **electric current is a flow of charge**. A conducting ball is suspended by an insulating thread between two vertical plates.

When a high voltage is applied across the two plates, the ball bounces back and forth between the two plates.

1. Each time it **touches the negative plate**, the ball gains some electrons and becomes negatively charged.
2. It is then repelled by the negative plate and pull across to the positive plate.
3. When the contact is made, electrons on the ball **transfer to the positive plate**.
4. The ball is now positively charged and is repelled back to the negative plate to repeat the cycle.

The shuttling ball causes a current around the circuit, because the electrons are transferred from the negative plate to the positive plate by the shuttling ball.

For a ball shuttling back and forth at frequency f.

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

Gold Leaf Electroscope

The gold leaf electroscope is used to **detect charge**.

1. If a charge object is **in contact with the metal cap** of the electroscope, some of the charge on the object **transfers to the electroscope**.
2. As a result, the gold leaf and the metal stem which is attached to the cap **gain the same type of charge**.
3. The leaf rises because it is repelled by the stem.

If another object with the same type of charge is brought near the electroscope, the leaf **rises further** because the object forces some charge on the cap to transfer to the leaf and stem.

Field Lines and Patterns

Any two charged objects exert **equal and opposite forces** on each other without being directly in contact.

- An **electric field** is said to surround each charge.
- If a **small positive test charge** is placed near a body with a **much bigger charge**, the path a free positive test charge follow sis called a field line.

The direction of an electric field line is the direction a positive test charge would move along.

22.2 Electric Field Strength

Provided the object's size and charge are both sufficiently small, the object may be used as a **test charge** to measure the strength of the field at any position in the field.

The electrical field strength E at a point in the field is defined as the **force per unit charge** on a positive test charge placed on that point.

The unit of E is the **newton per coulomb** $\mathrm{N\,C^{-1}}$.

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

The Lighting Rod

Air is an insulator provided it is not subjected to an electric field that is too strong - such a field **ionises the air molecules** by pulling electrons out of the molecules.

In a lightening strike to the ground

1. A cloud becomes more and more charged.
2. The electric field in the air becomes stronger and stronger.
3. The **insulating property of air suddenly breaks down**.
4. A massive discharge of electric charge occurs between the cloud and the ground.

When there is a lightening rod connected to the ground.

1. When a charged cloud is overhead, it creates a **very strong electric field near the tip** of the rod.
2. The air molecules near the tip are ionised by this very strong field.
3. The **ions discharge the thundercloud** making a lightening strike less likely.

Electric Field Between Parallel Plates

Field lines between two oppositely charge parallel plates are

- Parallel to each other.
- At **right angles to the plates**.
- From the positive plate to the negative plate.

The field between the plates is **uniform**, because the electric field has the **same magnitude and direction** everywhere between the plates.

$$\text{Electric field strength } E = \frac{V}{d}$$

where V is the potential difference between the plates, and d their separation.

Proof

1. The force on a small charge in the field is given by $F = QE$.
2. If the charge is moved from the positive to the negative plate, the work done $W = Fd = QEd$.
3. The potential difference is the **work done per unit charge** when a small charge is moved through the field.

$$V = \frac{W}{Q}$$
$$V = Ed$$
$$E = \frac{V}{d}$$

Field Factors

- Around any charged body, the greater the charge on the body, the stronger the electric field is.

- For a metal conductor, the more concentrated the charge is on the surface, the greater the strength of the electric field is above the surface.

For a charge on a plate of surface area A, the electric field strength between the plates $E \propto \frac{Q}{A}$.

Introducing a constant of proportionality ε_0 satisfying

$$\frac{Q}{A} = \varepsilon_0 E$$

where $\varepsilon_0 = 8.85 \times 10^{-12} \mathrm{F\,m^{-1}}$.

22.3 Electric Potential

The Van de Graff Generator

Charge created when the rubber belt **rubs against a pad** is carried by the belt up to the metal dome of the generator. As charge gathers on the dome, the **potential difference** between the dome and Earth increases until **sparking** occurs.

1. **Work is done** to charge the dome because a force is needed to move the charge on the belt up the dome.
2. **Electrical energy** of the dome increases as it charges up.
3. Some of this energy is **transferred from the dome** when a spark is created.

The **electric potential** at a certain position in any electric field is defined as the **work done per unit positive charge** on a positive test charge when it is moved from infinity to that position.

- The position of zero potential is infinity.
- The unit of electric potential is the **volt** equal to $1 \mathrm{J\,C^{-1}}$.

For a positive test charge

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

Potential Gradients

Equipotentials are surfaces of constant potential.

- A test charge moving a long an equipotential has **constant potential energy**.
- **No work is done** by the electric field on the test charge because the force due to the field is at right angles to the equipotential.

Both equipotentials for an electric and gravitational field are **surfaces of constant potential energy** for an appropriate test object - in one case a test charge, the other a test mass.

The **potential gradient** at any position in an electric field is the **change in potential per unit change of distance** in a given direction.

- If the field is **non-uniform**, the potential gradient varies according to position.

  The closer the equipotentials are, the greater the potential gradient is at right angles to the equipotentials.

- If the field is **uniform**, the equipotentials between the plates are **equally spaced lines** parallel to the plates.

  The potential gradient between two parallel plates is

  - Constant.
  - Such that the potential increases in the opposite direction to the electric field.
  - Equal to $E = \dfrac{V}{d}$

The electric field strength is equal to the negative of the potential gradient.

$$E = -\frac{dV}{dx}$$

22.4 Coulomb's Law

The forces between two charged objects depends on how close they are to each other.

Coulomb's law states the force between two **point charges** distance r apart

$$F = \frac{kQ_1Q_2}{r^2}$$

The constant of proportionality $k = \dfrac{1}{4\pi\varepsilon_0} = 9.0 \times 10^9 \mathrm{mF}^{-1}$.

Coulomb's law is therefore written as

$$F = \frac{1}{4\pi\varepsilon_0}\frac{Q_1Q_2}{r^2}$$

Proof

ε_0 is defined as the constant of proportionality such that, $\frac{Q}{A} = \varepsilon_0 E$ where charge Q is evenly distributed over a surface area A.

$$\begin{aligned} \varepsilon_0 E &= \frac{Q}{A} \\ E &= \frac{Q}{\varepsilon_0 A} \\ &= \frac{1}{4\pi\varepsilon_0}\frac{Q}{r^2} \end{aligned}$$

So the force experienced by a charge q placed near Q is

$$F = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{r^2}$$

22.5 Point Charges

- A **point charge** is a convenient expression for a charged object in a situation where distances under consideration are much **greater than the size of the object**.
- A **test charge** in an electric field is a point charge that **does not alter the electric field** in which it is placed.

Consider the electric field due to a point charge $+Q$

$$F = \frac{1}{4\pi\varepsilon_0}\frac{Qq}{r^2}$$
$$E = \frac{F}{q} = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r^2}$$

Radial Fields

The electric field lines of force surrounding a point charge are **radial** - the **equipotentials** are concentric circles centred on Q.

At distance r from Q, the electric field strength $E = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r^2}$.

The curve is an **inverse-square law** curve because E is proportional to $\frac{1}{r^2}$.

- The field strength equations for both gravitational and electric field are inverse-square relationships.
- Because both the force between two point charges and the force between two point masses vary with distance according to the inverse-square law.

$$V = \frac{1}{4\pi\epsilon_0}\frac{Q}{r^2}$$

- Gravitational potential in a gravitational field is **always negative**, because the force is always attractive.
- Electric potential in the electric field near a point charge Q can be positive or negative according to whether Q is a positive or negative charge.

The area under a section of the graph of **electric field strength against distance** gives the work done per unit charge when a positive test charge is moved through the distance represented by that section.