Electrostatics

Unit 2

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2.2 Electric forces and fields (page 60)	• Define an electric field. • Represent diagrammatically the electric field lines around and between two points. • Distinguish between the electric field inside, outside and between surfaces of a spherical metallic conductor. • State Coulomb's law. • Compare Coulomb's law and Newton's law of universal gravitation. • Calculate the force acting on a charge due to two other charges placed on the same plane (line of action). • Calculate the force between three charges placed in a line. • Calculate the electric field strength at a point due to charges placed in a line and at right angles.
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Section	Learning competencies
	• Derive an expression for the effective capacitance of capacitors connected in series and parallel. • Draw an electric circuit diagram for a simple capacitor, series and parallel connections of two or more capacitors using symbols. • Solve problems on combination of capacitors. • Define parallel plate capacitor. • Describe the factors that affect the capacitance of a parallel plate capacitor. • Calculate the capacitance of a parallel plate capacitor. • Find an expression for the electric potential energy stored in a capacitor. • Calculate the energy stored in a capacitor using one of three possible formulae. • State some uses of capacitors in everyday life.

2.1 Electric charge

By the end of this section you should be able to:

- State the law of conservation of charge.
- Describe and explain the charging processes: charging by rubbing, conduction and induction.
- Perform an experiment to charge an electroscope by conduction and by induction.
- Describe the distribution of charge on a conductor of variable shape.
- Explain how lightning is formed.
- Describe the use of a lightning rod.
- Describe how equipment works using electrostatics principles.
- Describe hazards and uses of electrostatics.

KEY WORDS

electrostatics *the build up of electric charge on the surface of objects*

charge *an electric charge, positive, negative, or zero, found on the elementary particles of matter*

atoms *the smallest components of an element having the chemical properties of that element*

positive charge *having a deficiency of electrons*

negative charge *having a surplus of electrons*

Electrostatics in everyday life

Have you ever felt a small electric shock when you have touched a metal door handle, or heard a crackling sound as you pull a woollen article of clothing over your head? Both these arise because of **electrostatics** – electric **charge** is transferred from one material to another. In this section you will learn more about this, its applications and its hazards.

Activity 2.1: Recalling other physical quantities that are conserved

In a small group, spend one minute writing a list of physical quantities that you have met that follow a conservation law. Hint: think back to Unit 1.

What is electric charge?

All objects are made up from tiny building blocks called atoms. Individual atoms are made up of particles that possess both mass and electric charge. A material such as Perspex is made up from a huge number of atoms, but although we are well aware of its mass, it does not seem to possess any charge at all. Why is this?

Every bit of mass in every atom adds up so that we feel its mass. In every single atom, however, the two sorts of electric charge cancel one another out: there is the same number of positive charges as negative ones, so we do not notice any overall charge. An 'uncharged' piece of Perspex contains a vast number of charges, but the numbers of the two kinds are equal. Charging it up involves upsetting the balance between positive and negative charges. Adding or removing a few more electrons would do this.

The elementary charge, $e = -1.6 \times 10^{-19}$ C, is the amount of charge on an electron (negative charge) or on a proton (positive charge). To find the total charge Q, you use $Q = N \times e$, where N is the number of electrons.

Conservation of charge

Electric charge cannot be created or destroyed, only transferred. The number of **positive** charges on an atom of a substance is the same as the number of **negative** charges on the atom. The atom is neutral. The charges from some atoms can be removed from the atom and transferred to another material in the process known as charging but the overall number of positive and negative charges does not change. This is the **law of conservation of charge**.

Like charges will repel each other (for example, two positive charges will repel each other, two negative charges will repel each other). Unlike charges will attract each other (so a positive charge will attract a negative charge and a negative charge will attract a positive charge).

Charging materials by rubbing

It is possible to charge some materials by rubbing them. When you rub a piece of Perspex, for example, some of the charge is transferred from the surface of the Perspex to the material you are using to rub it, and so the overall charge on the Perspex becomes unbalanced.

KEY WORDS

law of conservation of charge *the total electric charge of a system remains constant despite changes inside the system*

DID YOU KNOW?

The fact that some materials (such as amber) become charged after they are rubbed has been known for thousands of years. The Greek word for amber, *ἤλεκτρον* (electron), is the source of the word 'electricity'.

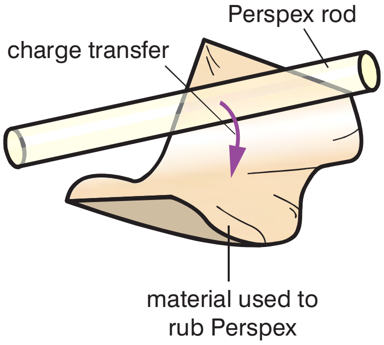

Figure 2.1 *Rubbing Perspex transfers charge from the surface of the Perspex to the material you are rubbing it with.*

Activity 2.2: Testing how charged bodies attract or repel one another

Take a bar of Perspex and pivot it. One way is to suspend it by a nylon thread (cotton, if the slightest bit damp, may allow the charges to leak off too readily). Charge the suspended rod by rubbing it. Bring a second charged Perspex rod up to the first one, and you will see the first one swing away.

Now charge the bar of Perspex again. Bring a charged rod of Polythene up to the suspended rod, and you will see the suspended rod moving towards it. What does this tell you about the charges on the Perspex and the Polythene?

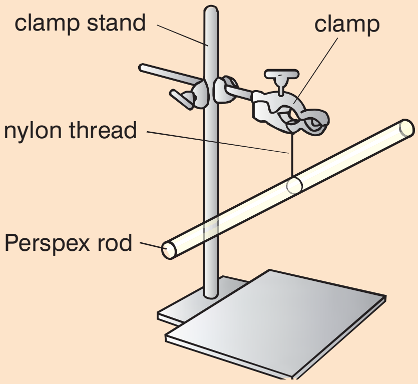

Figure 2.2 *Apparatus to test attraction or repulsion between charged bodies.*

Activity 2.3: The electrostatic attraction of water

Adjust a tap so a continuous but gentle stream of water is falling from it. Rub a plastic comb on your sleeve, and bring it up to the side of the water column. Describe and try to explain what happens.

Figure 2.3 *The electrostatic attraction of water.*

Activity 2.4: Hanging balloons using electrostatic attraction

Inflate a balloon and then briskly rub one side of it on your hair. Place the surface that you have rubbed towards a wall or door and release it when it appears to be sticking. What can you say about the nature of the surfaces to which the balloon sticks?

Figure 2.4 *Rubbing a balloon on hair.*

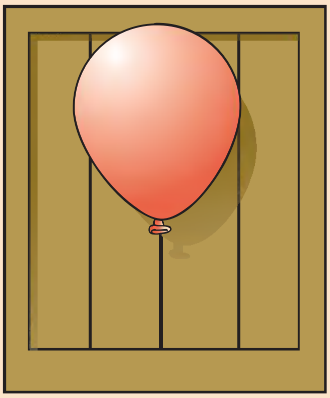

Figure 2.5 *A balloon sticking to a surface.*

Charging materials by conduction

If a charged object is brought into contact with an uncharged (neutral) object, then the neutral object will become charged by **conduction**. Charge flows from the charged object to the neutral object. (This is what happens when you feel an electric shock when you touch a metal door handle – the door handle has become charged and the charge travels by conduction to you, a neutral object!)

Figure 2.6 *Charging a person by conduction.*

Activity 2.5: Charging an electroscope by conduction

Charge a metal sphere. Bring it into contact with an electroscope. What happens? Draw a diagram to explain your results.

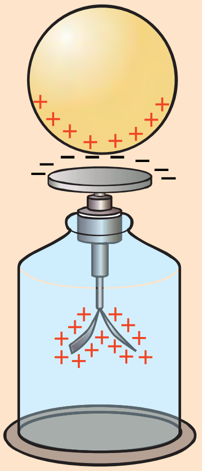

Figure 2.7 *Charging an electroscope by conduction.*

Charging by induction

Figure 2.8 shows a different way of charging a body known as **induction**.

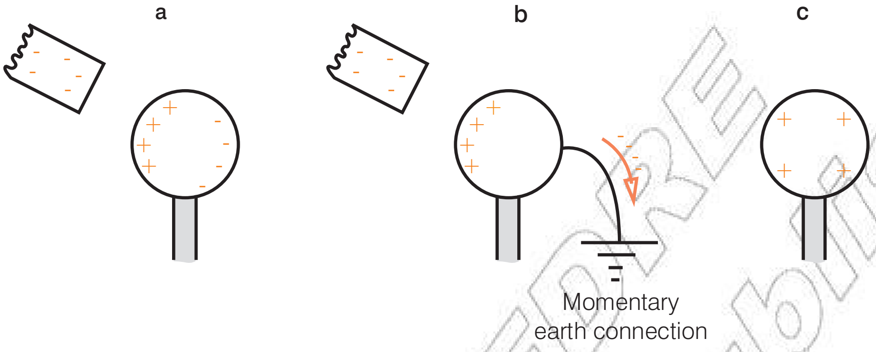

Figure 2.8 *Charging by induction.*

In Figure 2.8a, a negatively charged rod is brought near to a neutral metal sphere held on an insulating support. The negative charges in the metal sphere move to the side of the sphere furthest from the rod, leaving the side of the sphere nearest to the rod positively charged. In Figure 2.8b, while the rod is still nearby, you touch the sphere for a moment then let go. The negative charges now escape further, through you down to earth. In Figure 2.8c, the negative rod is taken away. The negative charges are unable to return from earth, so the sphere is left positively charged. These charges now distribute themselves evenly.

Activity 2.7: Charging by induction

Tear a sheet of newspaper into small pieces, approximately half a centimetre in diameter. Place the bits under a glass plate that is supported by two books (see Figure 2.10).

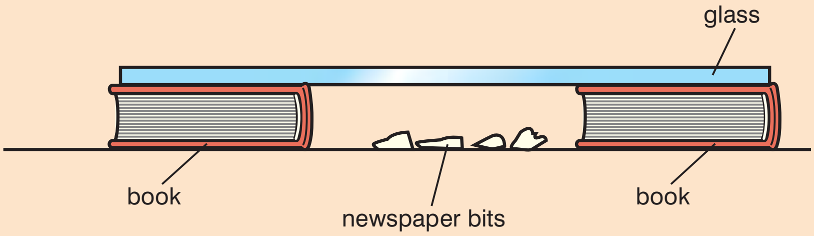

Figure 2.10 *Charging by induction.*

Rub the glass vigorously with a piece of silk and notice how the paper jumps up to the glass. In a small group, discuss what you see. Answer these questions:

- What attracts the paper to the glass?
- Why does it not stay attached to the glass?

Activity 2.6: Charging an electroscope by induction

From the information given about charging by induction, devise and carry out an experiment to charge an electroscope by induction. Draw diagrams to explain what happens.

DID YOU KNOW?

An electroscope is used to detect the presence and magnitude of electric charge. The British physician William Gilbert invented the first electroscope, which was called the *versorium*, around 1600. This was the first electrical measuring instrument.

Figure 2.9 *William Gilbert.*

KEY WORDS

conduction *the flow of charge from a charged object to an uncharged (neutral) object*

induction *a redistribution of electrical charge in an object, caused by the influence of nearby charges*

Figure 2.12 Dr Robert Jemison Van de Graaf and Dr Karl Taylor Compton with a generator.

KEY WORDS

conductor *a material that contains movable electric charges*

DID YOU KNOW?

The American physicist Robert J. Van de Graaf developed the **Van de Graaf generator** at Princeton University. The first model was demonstrated in October 1929 and used a silk ribbon bought at a local shop as the belt to carry the charge. Accelerating electrons are now used to sterilise food and process materials.

Activity 2.8: Using a Van de Graaf generator to make a fluorescent tube glow

Darken the room. Turn on the generator, and slowly move a fluorescent tube towards the generator. Why does the area between the tube, your hand and the generator glow?

Distribution of charges on the surfaces of conductors

Charges on the surface of a **conductor** are able to flow and spread themselves out evenly. The charges on the surface are all the same type and so they repel each other and move as far apart as possible. The result is that they move outwards until they reach the surface. They can get no further than that unless the insulation of the air breaks down to enable them to escape.

The charges on a sphere will distribute themselves evenly over its surface (see Figure 2.11a). If, however, the body has an irregular curvature (see 2.11b) the charge tends to cluster round the sharply curved parts, with the areas of gentle curvature storing far less of the charge. If the metal body has an actual point on it, the accumulation of charge there will be enormous, and the insulation of the air is more likely to break down there so that all the charge is able to escape from the surface. We refer to this is as the action of points.

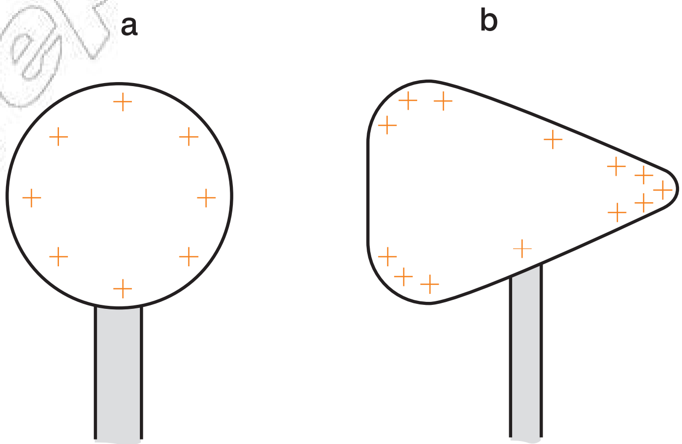

Figure 2.11 Distribution of charges on conductors.

As all the charge sits on the outside, it makes no difference whether the conductor, or metal object, is solid or hollow.

Thunderstorms

Scientists believe that thunderstorms in Ethiopia may sometimes trigger hurricanes as far away as across the Atlantic Ocean.

Thunderclouds form as a result of convection currents (warm air rises and cooler air goes down). Air contains water vapour which we often see as clouds.

As the air cools down, the water vapour in the air condenses. The tiny drops of water that condense experience very rough conditions and, in the process, tend to become charged. The mechanism by which this happens is more than just charging by friction, and we are still not entirely sure of all the details.

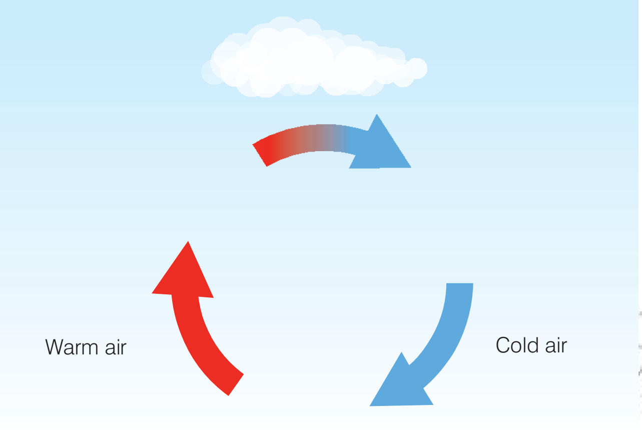

Figure 2.13 *A convection current.*

How lightning is formed

Charged water drops of one sign (positive or negative) may tend to collect in one part of the cloud. The result is lightning: sparks that jump often from one cloud region to another, but sometimes from the cloud to earth.

When a thundercloud passes overhead, if the base of the cloud is positively charged, then it will attract negative electrons in the earth underneath it (see Figure 2.15). Note that the charge carried by the base of the cloud may be negative or positive but the figure assumes that it is positive.

Should a spark jump to earth it will tend to jump the shortest air gap, such as to trees and tall buildings.

Lightning rods

To help to discharge the cloud safely, a lightning conductor is often fitted to the top of a building. This is a metal bar, pointed at the top, the other end of which is buried firmly in the ground. The idea is that it should get struck before the building and conduct the surge of charge harmlessly to the earth.

Figure 2.16 *A lightning conductor will conduct electric charge from lightning safely away from a building to the earth.*

DID YOU KNOW?

Fluorescent lamps work because there is a flow of electrical current through a gas (usually argon) which has been charged.

KEY WORDS

Van de Graaf generator *a hollow sphere on which an electrostatic charge is accumulated using a moving belt*

Figure 2.14 *Lightning.*

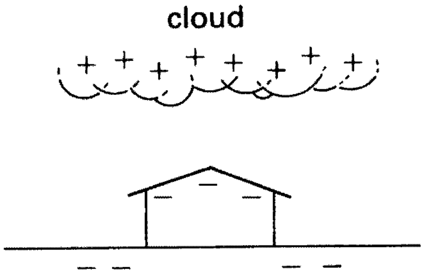

Figure 2.15 *How lightning occurs.*

Activity 2.9: How might tall buildings be protected from damage by lightning?

In a small group, discuss how tall buildings might be protected from damage by lightning.

Safety in storms

It is very rare that people are struck by lightning, and certainly you will not be struck while you are inside a car or an aeroplane – the metal shell around you would divert charge away. You are advised not to shelter under trees because they are particularly likely to get struck, and the spark could jump from the lower branches to you.

Activity 2.10: Why is the inside of a car safe in a storm?

Discuss with a partner why the inside of a car is a safe place to shelter during a storm.

Activity 2.11: Design a safety poster

Use the information above to design a poster to show younger children how to stay safe during a thunderstorm.

Applications of electrostatics

Paint sprays

Electrostatic spray painting is often used to paint car body panels and bike frames. An electrostatic spray painting device sprays charged particles of paint through the air onto a surface. These devices are usually used for covering large surfaces with an even coating of liquid. They can be either automated or hand-held and have interchangeable heads to allow for different spray patterns.

There are three main technologies for charging the fluid (liquid or powders):

- *Direct charging* – an electrode (a charged metal plate) is placed in the paint supply reservoir or in the paint supply conduit.
- *Tribo charging* – this uses the friction of the fluid, which is forced through the barrel of the paint gun. It rubs against the side of the barrel and, in the process, builds up an electrostatic charge.
- *Post-atomisation charging* – the charged fluid comes into contact with an electrostatic field (see page 54) after leaving the spray head. The electrostatic field may be created by electrostatic induction, or by one or more electrodes (electrode ring, mesh or grid).

Figure 2.17 *An electrostatic spray gun in use.*

The charged paint particles repel each other, and so they spread themselves evenly as they leave the spray head. The object being painted is charged in the opposite way (for example, if the paint is positively charged, the object is negatively charged), or grounded. The paint is then attracted to the object, which gives a more even coat than the alternative technique, wet spray painting, and increases the percentage of paint that actually sticks to the object. This method also means that paint covers hard to reach areas. The object is then baked so that the paint sticks properly when the paint powder particles turn into a type of plastic.

Chimney filters

Smoke such as that from a large chimney contains many tiny solid particles, mainly soot. To help to keep the air clean, before reaching the chimney this smoke may be passed between two large upright charged metal plates. In a similar way to how a plastic comb attracts small pieces of paper, the solid specks in the smoke are trapped by sticking to one or other of the plates. From time to time the plates are shaken or scraped to remove the thick layer of dust that has formed on them.

Photocopiers

1. The surface of a cylindrical drum is charged using electrostatics. The drum has a coating of a material that conducts electricity when light shines on it.
2. A bright lamp shines light on the original document, and the white areas of the original document reflect the light onto the surface of the charged drum. The areas of the drum that are exposed to light (those areas that correspond to white areas of the original document) conduct electricity so they discharge. The areas of the drum that are not exposed to light (those areas that correspond to black portions of the original document) remain negatively charged. The result is a stored electrical image on the surface of the drum. (In digital machines, the original document is scanned and digitised and a laser is employed to discharge the drum in a similar fashion.)
3. The toner is positively charged. When it is applied to the drum to produce the image, it is attracted and sticks to the areas that are negatively charged (black areas), just as the balloon in Activity 2.4 stuck to the wall or door.
4. The toner image on the surface of the drum is transferred from the drum onto a piece of paper, which is charged more negatively than the drum.
5. The toner is melted and bonded to the paper by heat and pressure rollers.
6. The drum is wiped clean with a rubber blade and light is used to remove the charge.

When does electrostatic charge cause problems?

Electrostatic charge can be a problem or hazard when there is a sudden discharge. Electrostatic discharge gives a sudden current of electricity between two objects. On page 56, we found out that lightning (which is a form of electrostatic discharge) can be dangerous, especially if you are outside in a thunderstorm. If there is an electrostatic discharge in an area containing liquids or materials which catch fire easily (flammable materials), then the discharge may cause a fire. However, perhaps the main area where electrostatic discharge causes problems is in electronics, where circuits may be damaged by unwanted flows of charge. To protect circuits against this, antistatic devices have been developed. These include antistatic bags, clothing, mats and wrist straps.

Activity 2.12: Design a model chimney filter

In a small group, design a model of chimney filter.

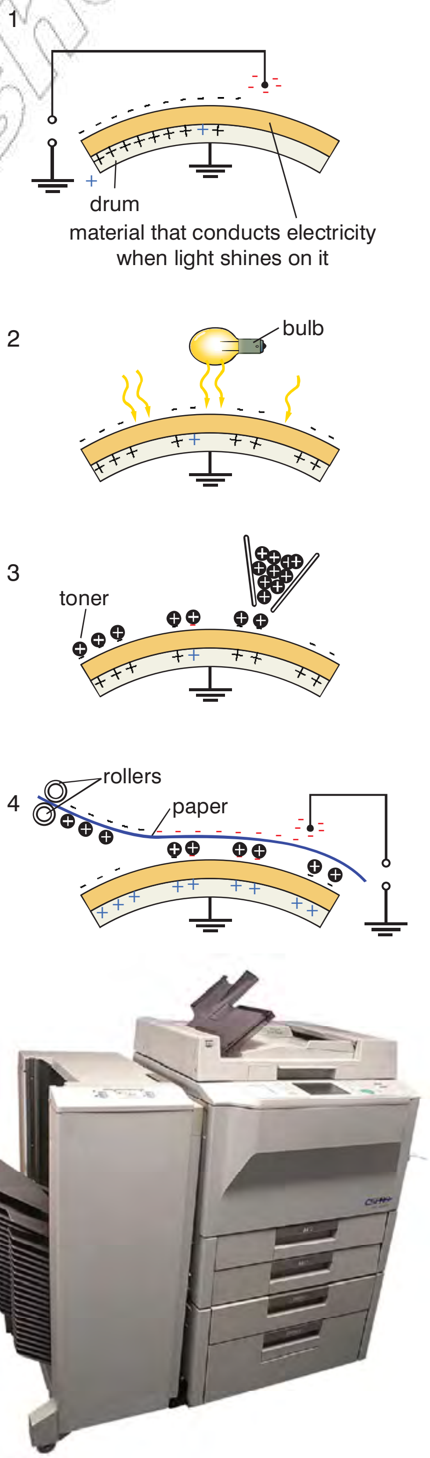

Figure 2.18 How a photocopier works.

Why is static electricity more apparent when the air is dry?

You notice static electricity much more when the air is dry because dry air is a relatively good electrical insulator, so if something is charged the charge tends to stay. When there is moisture in the air, the charged water molecules can remove charge quickly from a charged object.

Activity 2.13: Mind mapping uses and hazards of electrostatics

In a small group, discuss what you have learnt about the uses and hazards of electrostatics. You may like to do some research to find out how electrostatics is used in manufacturing, or more about antistatic devices. Make a summary of your discussion and research using mind maps such as the one in Figure 2.19.

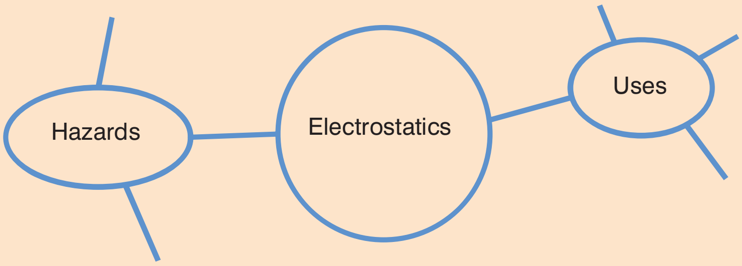

Figure 2.19 *Mind map to show uses and hazards of electrostatics.*

Prepare a presentation for the rest of your class.

Summary

- Charge cannot be created or destroyed, it can only be transferred from one object to another. This is the law of conservation of charge.
- It is possible to charge objects by rubbing, conduction and induction.
- An electroscope can be charged by conduction and induction.
- The distribution of charge on a conductor with a constant surface such as a sphere is uniform (the charges spread out evenly). However, if there is a point on the surface, the charge will form clusters around the point.

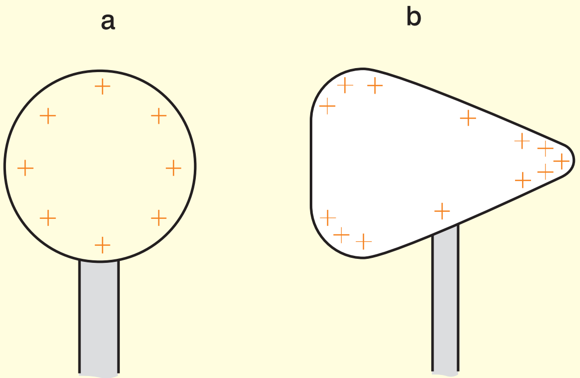

Figure 2.20 *Distribution of charge on conductors of various shapes.*

- Lightning is formed when charged water drops of one sign (positive or negative) collect in one part of the cloud. There is electrostatic discharge (in the form of sparks) which jump often from one cloud region to another, but sometimes from the cloud to earth.
- A lightning rod may be used to protect tall buildings from lightning. This is a metal rod with a point at the top. It attracts the charge from the lightning and conducts it safely to earth rather than it going through the building and causing damage.
- Electrostatics is used in equipment such as paint sprayers and photocopiers. However, it can be a problem in some situations, such as where there are flammable materials, which may catch fire if there is an electrostatic spark, or in sensitive electronic devices. There are various antistatic devices available, which can be used in different situations.

Review questions

1. Why do charged objects soon lose their charge on a damp day?
2. All atoms that make up matter contain tiny charges, both positive and negative. How is it that most objects we meet in daily life appear to be uncharged?
3. Copy Figure 2.21 and show on it how the charges in the uncharged object will distribute themselves in the presence of the positively charged rod.

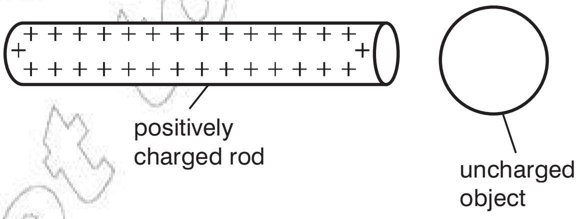

Figure 2.21

4. Why will a plastic comb that has been rubbed attract small pieces of paper?
5. a) Why do plastic objects frequently become covered with dust?
   b) Why is it not necessarily a good idea to rub such objects with a duster?
6. When car manufacturers apply paint to new cars they usually spray it in very fine droplets that are deliberately charged. Why do they do this?
7. a) An inflated toy balloon can be rubbed on your clothing then stuck on the ceiling. Explain why.
   b) Suggest why the balloon eventually drops off the ceiling.

8. Why are metal objects designed to store charge (e.g. the dome of a Van de Graaf generator) made from large hollow metal spheres?
9. Explain the purpose of a lightning conductor, and draw a diagram to show how it does its job.
10. a) List some uses of electrostatics
    b) List some hazards of electrostatics.
11. List some antistatic devices.

2.2 Electric forces and fields

By the end of this section you should be able to:

- Define an electric field.
- Represent diagrammatically the electric field lines around and between two points.
- Distinguish between the electric field inside, outside and between surfaces of a spherical metallic conductor.
- State Coulomb's law.
- Compare Coulomb's law and Newton's law of universal gravitation.
- Calculate the force acting on a charge due to two other charges placed on the same plane (line of action).
- Calculate the force between three charges placed in a line.
- Calculate the electric field strength at a point due to charges placed in a line and at right angles.

KEY WORDS

electric field *a region where an electric charge will experience a force which is due to the presence of other electric charges*

Also see...

The material in this section is related to Unit 4, Section 4.4.

What is an electric field?

Imagine you are a positively charged particle. Whenever you are anywhere near other charges you will find yourself in a world of pushes or pulls. We say you are in an **electric field**.

An electric field is a region where an electric charge will experience a force that is due to the presence of other electric charges.

Clearly a charge will be surrounded by an electric field, because everywhere around it other charges will either be attracted to it or repelled from it, depending on their signs.

Plotting electric field lines

Electric fields can be plotted by indicating the direction of the force on a positive charge, if one happened to be there. Figure 2.22a shows the electric field around a positive charge, and 2.22b shows that round a negative charge.

Figure 2.22 Electric fields around a positive charge, and a negative charge.

Notice two things. First, a negative charge, such as an electron, would move in the opposite way to the direction shown by the arrows. Second, the field is strongest where the lines are closest together.

We can also plot the field around two charges. In Figure 2.23a you can see the field around a pair of opposite charges, while 2.23b shows the completely different situation when both charges are the same sign.

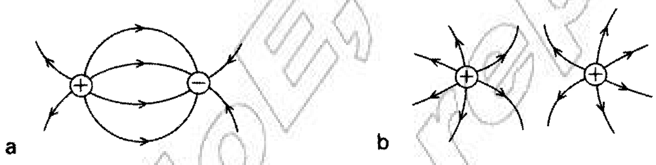

Figure 2.23 Electric fields around a pair of opposite charges, and a pair of charges with the same sign.

Any charge between a pair of charged plates would find itself in a field that was both strong and uniform, as shown in Figure 2.24.

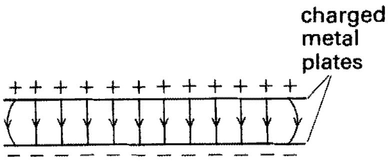

Figure 2.24 The uniform field between a parallel pair of charged plates.

Activity 2.14: Explaining field plots

With a partner, see if you can explain the plots of electric fields shown on this page. Do it by imagining that, in turn, you or your partner are a tiny positively charged particle placed at different points in the field. Think about both the direction of the force you feel and how strong it is.

Also see…

Compare the material on this page to that in Unit 4, Section 4.2.

Electric field inside and outside a spherical metallic conductor

Imagine a spherical, hollow conductor such as the one shown in Figure 2.25.

Activity 2.15: Explaining field patterns

Work with a partner to see whether you can explain the field pattern in Figure 2.25 before reading on!

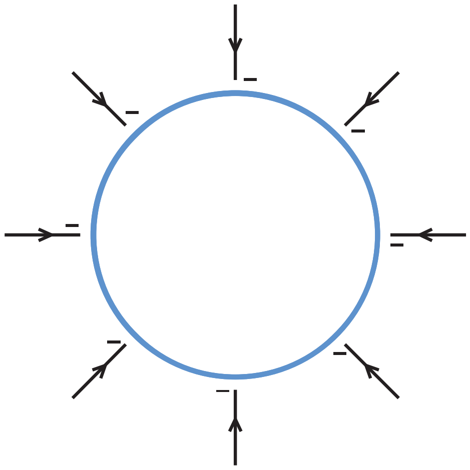

Figure 2.25 Electric field inside and outside a charged hollow spherical metallic conductor.

Inside the conductor there is no charge because the charge has collected on the outer surface. This means that the inside of such a conductor can be used to shield equipment from external electric fields. The outer surface of the conductor will have an electric field that is at right angles to (perpendicular to) the surface.

Electric field strength

An electric charge that finds itself in an electric field will experience a force. There are two factors that determine how large a force F this will be:

- The size of the charge Q, measured in **coulombs**.
- The strength (intensity) of the electric field, which corresponds to the closeness of the field lines.

We define the **electric field strength** (electric field intensity) E by:

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

The units of E will be newtons of force per coulomb of charge – that is, N/C; E is a vector – it has direction as well as magnitude.

Worked example 2.1

A charge of 5 C is in an electric field of 3 N C^{-1}. Find the force acting on the charge.

E (N/C)	F (N)	Q (C)
3	?	5

Rearranging $E = \frac{F}{Q}$ gives $F = QE$. Putting in the values, the force acting on the charge will be

$5\ \text{C} \times 3\ \text{N/C} = 15\ \text{N}$.

(Notice that the units must work out, as well as the numbers.) If it is a positive charge, the force will act in the direction of the arrow on the field lines. The force on a negative charge will be in the opposite direction.

Worked example 2.2

A negative charge of 8 C is in an electric field of 4 N/C. Find the force acting on the charge.
In which direction will it act?

E (N/C)	F (N)	Q (C)
4	?	–8

Rearranging $E = \frac{F}{Q}$ gives $F = QE$. Putting in the values, the force acting on the charge will be

$8\ \text{C} \times 4\ \text{N/C} = 32\ \text{N}$.

Since it is a negative charge, the force will act in the opposite direction to the direction of the arrow on the field lines.

DID YOU KNOW?

Charles-Augustin de Coulomb, a French physicist, is best known for developing the definition of the **electrostatic force** of attraction and repulsion. This is summarised in Coulomb's law (see page 64). The coulomb is the SI unit of charge and was named after him. During the French Revolution he took part in the determination of weights and measures. He was one of the first members of the French National Institute. As well as his contribution to the understanding of electric fields, Coulomb has contributed to the design of retaining walls!

Figure 2.26 *Charles-Augustin de Coulomb, 1736–1806.*

KEY WORDS

electrostatic force *the force exerted by stationary objects bearing electric charge on other stationary objects bearing electric charge*

Worked example 2.3

E (N/C)	F (N)	Q (C)
?	28	7

Find the electric field strength when a positive charge of 7 C is acted on by a force of 28 N. In which direction will the force act?

Put the given values into $E = \frac{F}{Q}$ so $E = \frac{28}{7}$.

The electric field strength will be 4 N/C.

Since it is a positive charge, the force will act in the direction of the arrow on the field lines.

Worked example 2.4

E (N/C)	F (N)	Q (C)
?	28	7

Find the value, and type, of charge that is acted on by a force of 40 N acting in the opposite direction to the arrow on the field lines in an electric field of strength 10 N C^{-1}.

Rearrange $E = \frac{F}{Q}$ to $Q = \frac{F}{E}$. Put the given values into $Q = \frac{F}{E}$ so $Q = 40/10$. The charge will be 4 C.

Since the force acts in the opposite direction to the the arrow on the field lines, it is a negative charge.

Force between charges

We know that two positive electric charges Q_1 and Q_2 a distance r apart will repel each other. This is because each one lies in the field created by the other (see Figure 2.28).

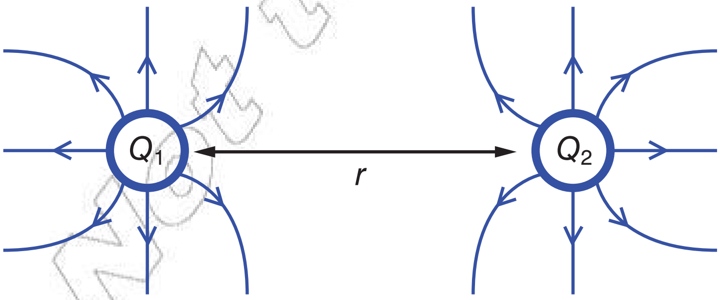

Figure 2.28 Q_1 *lies in the field of* Q_2 *and, since both charges are positive, they will repel each other.*

It has been found by carrying out experiments that:

- The force F between the charges increases if the value of either of the charges is increased.
- The force gets less as the distance between the charges gets larger, and does so by an inverse relationship. The force decreases in relation to the inverse of the distance squared, $\frac{1}{r^2}$.

Reminder: rearranging equations

Remember that you can use a triangle like the one in Figure 2.27 to rearrange the equation connecting three quantities.

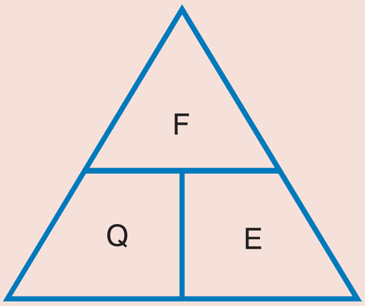

Figure 2.27 To find, for example, Q, cover up Q in the triangle and then you see that $\frac{F}{E}$ *is left. This is the formula you need!*

KEY WORDS

coulomb *unit of electric charge*

electric field strength *the electrostatic force acting on a small positive test charge placed at that point*

Activity 2.16: Comparing Coulomb's law and Newton's law of universal gravitation

With a partner, recall Newton's law of universal gravitation. (Try to do this without looking back to page 41!) Write the two formulae side by side. Compare them. Make a list of things that are similar and things that are different.

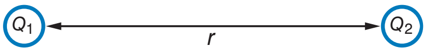

Figure 2.29 *Coulomb's law.*

Also see…

The material on this page may be compared to that in Unit 1, Section 1.4.

KEY WORDS

Coulomb's law *the force between two point charges is directly proportional to the product of the two charges and inversely proportional to the square of the distance between the two*

This means that if the separation doubles, the force reduces to one quarter; if it increases three times, the force reduces to one ninth, and so on.

Coulomb's law states that the force between two point charges is directly proportional to the product of the two charges and inversely proportional to the square of the distance between the two.

We can express this in a formula as $F = \dfrac{k \times Q_1 Q_2}{r^2}$,

where k is a constant. The newton, the coulomb and the metre are already fixed; that constant has to be obtained by measurement. You might expect the constant to be given a symbol such as 'E', perhaps, but instead it is written as $\dfrac{1}{4\pi\varepsilon_0}$. Do not be put off by this: it is still a constant, and nothing more complicated than that.

This gives the final expression as:

$$F = \frac{1}{4\pi\varepsilon_0} \times \frac{Q_1 Q_2}{r^2}$$

Check that you understand why the units for the constant $\dfrac{1}{4\pi\varepsilon_0}$ will be N m^2/C^2. The value of this constant depends on the material in which the charges are placed.

Worked example 2.5

The value of $\dfrac{1}{4\pi\varepsilon_0}$ in a vacuum is 9.0×10^9 N m^2 C^{-2}. What is the force between two charges, 5 C and 7 C, placed 1 metre apart in a vacuum?

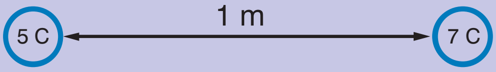

Figure 2.30 *A 5 C charge and a 7 C charge placed 1 metre apart in a vacuum.*

F (N)	*Q*$_1$ (C)	*Q*$_2$ (C)	*r* (m)
?	5	7	1

Use $F = \dfrac{1}{4\pi\varepsilon_0} \times \dfrac{Q_1 Q_2}{r^2}$

Substitute the given values: $Q_1 = 5$ C and $Q_2 = 7$ C, the constant value is 9.0×10^9 N m^2/C and, since $r = 1$, $r^2 = 1$.

So $F = 5 \times 7 \times (9.0 \times 10^9 \text{ N m}^2/\text{C}^2) = 3.15 \times 10^{11}$ N

Activity 2.17: Explaining how results of calculations demonstrate the inverse square relationship

Explain to a partner how the results of the two worked examples on this page demonstrate the inverse square relationship suggested in Coulomb's law.

Try to demonstrate the inverse square relationship suggested in Newton's law of universal gravitation using similar examples. (Take the value of $G = 6.67 \times 10^{-11}$ N m^2/kg^2.)

Worked example 2.6

The value of $\frac{1}{4\pi\varepsilon_0}$ in a vacuum is 9.0×10^9 N m^2 C^{-2}. What is the force between two charges, 5 C and 7 C, placed 2 metres apart in a vacuum?

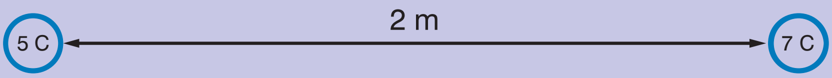

Figure 2.31 *A 5 C charge and a 7 C charge placed 2 metres apart in a vacuum.*

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

Substitute the given values: $Q_1 = 5$ C and $Q_2 = 7$ C, the constant value is 9.0×10^9 N m^2 C^{-2} and, since $r = 2$, $r^2 = 4$.

So $F = \frac{[5 \times 7 \times (9.0 \times 10^9 \text{ N m}^2/\text{C}^2)]}{4} = 7.875 \times 10^{10}$ N

Coulomb's law when there are more than two charges

Electric force has both size and direction. The two electric forces in Figure 2.32 are the same size but opposite in direction. Charges of the same sign exert repulsive forces on one another, while charges of opposite sign attract, so these two charges would repel each other.

Figure 2.32 *Forces of the same size but in opposite directions.*

When more than one charge exerts a force on another charge, the total force on that charge is the sum of the individual forces, taking into account both their sizes and direction.

Worked example 2.7

Three charges are arranged in a line with 2.5 cm between them, as shown in Figure 2.33.

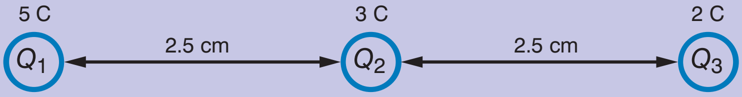

Figure 2.33 *Three charges in a line at 2.5 cm apart.*

Q_1 is 5 C, Q_2 is 3 C and Q_3 is 2 C, $k = 8.99 \times 10^9$ N m^2/C^2.

What is the force exerted on Q_2 by the other two charges?

First draw a good diagram showing the forces acting on the charge. The diagram should also show the directions of the forces.

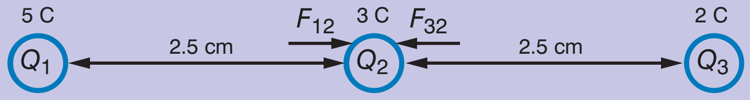

Figure 2.34 *Forces acting on a charge with their direction shown.*

Consider the forces exerted on Q_2 by the other two:

$$\text{from } Q_1\text{: } F_{12} = \frac{kQ_1Q_2}{r^2} = \frac{8.99 \times 10^9 \times 5 \times 3}{(0.025)^2} = 2.1576 \times 10^{14}$$

$$\text{from } Q_3\text{: } F_{32} = \frac{kQ_3Q_2}{r^2} = \frac{8.99 \times 10^9 \times 2 \times 3}{(0.025)^2} = 8.6304 \times 10^{13}$$

The total force on Q_2 is therefore $2.1576 \times 10^{14} + 8.6304 \times 10^{13} = 3 \times 10^{14}$ (to 1 significant figure)

Note that if Q_1 and Q_3 are at right angles to Q_2 as shown in Figure 2.35, you find the forces between the charges in the same way as in the example above but the lines of action of the forces do not coincide so you have to add the horizontal components of the total force and the vertical components of the total force. Note: F_{12v} is the vertical component of the force between Q_1 and Q_2.

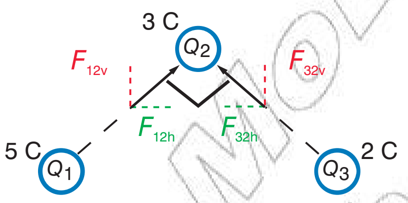

Figure 2.35 *Finding the forces between charges.*

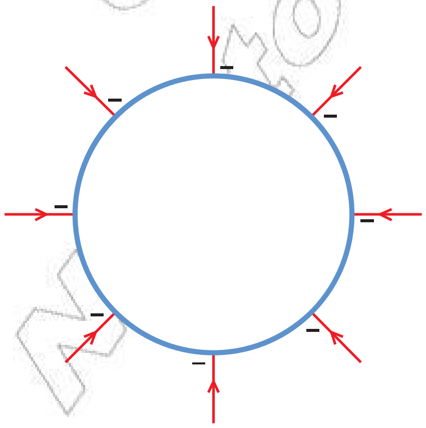

Figure 2.36 *An electric field on the inside and outside surfaces.*

Summary

- An electric field is a region where an electric charge will experience a force because other charges are present.
- The electric field on the inside and outside surfaces of a spherical metallic conductor is as shown in Figure 2.36.
- Coulomb's law states that the force between two point charges is directly proportional to the product of the two charges and inversely proportional to the square of the distance between them.
- We can express this in a formula as $F = \frac{k \times Q_1Q_2}{r^2}$, where k is a constant.
- Coulomb's law and Newton's law of universal gravitation are both inverse square relationships.
- You can calculate the force between three charges placed in a line.

Review questions

1. Explain, as if to a friend, the meaning of the term 'electric field'.
2. Draw the pattern of the electric field around:
   a) a positive charge
   b) a negative charge.

   Explain what the arrows mean and explain at which points the strength of the field is greatest.
3. Repeat question 2 for the electric field:
   a) around a positive and a negative charge
   b) around two negative charges
   c) between two oppositely charged flat metal plates.
4. What is the name of the unit we use to measure electric charge? Give its correct abbreviation.
5. How big a force will a charge of +2 C experience if placed in an electric field of strength 18 N/C?
6. In question 5, what can you say about the force if the charge was one of −2 C instead?
7. A charge is placed in an electric field of 48 N/C and it experiences a force of 12 N. How great must the charge be?
8. Two point charges, one of 3.0 C and the other of 2.0 C, are placed 5.0 m apart. Calculate the force which acts between them. (Take $\frac{1}{4\pi\varepsilon_0}$ to be 9.0×10^9 N m^2 /C^2.)
9. The answer to question 8 is an *enormous force* – a coulomb is a huge unit for static charge, and we do not normally encounter point charges of anything like that size. Repeat the calculation but this time take the charges as 3.0 pC (p = pico- = $\times 10^{-12}$) and 2.0 μC.

2.3 Electric potential

By the end of this section you should be able to:

- Define electric potential and its SI unit.
- Distinguish between absolute potential and potential difference.
- Show that 1 N/C = 1 V/m.
- Explain equipotential lines and surfaces.
- Draw equipotential lines and surfaces in an electric field.
- Define the term electric potential energy.

DID YOU KNOW?

Alessandro Volta (1745–1827) was an Italian physicist known especially for the development of the first electric cell. Volta made contributions for chemistry: in 1776–77 he discovered methane by collecting the gas from marshes. He devised experiments such as the ignition of methane by an electric spark in a closed vessel.

Volta began to study, around 1791, the 'animal electricity' noted by Luigi Galvani when two different metals were connected in series with a frog's leg and to one another. He replaced the frog's leg by brine-soaked paper, and detected the flow of electricity.

In 1800, he invented the voltaic pile, an early electric battery, which produced a steady electric current.

Figure 2.37 Alessandro Volta.

Electric potential and its SI unit

Electric potential at a point in space is potential energy divided by charge that is associated with a static (one that does not vary with time) electric field. Its SI unit is the volt, in honour of Alessandro Volta.

You know from earlier in this unit that objects may possess electric charge. An electric field exerts a force on charged objects, accelerating them in the direction of the force, in either the same or the opposite direction of the electric field. If the charged object has a positive charge, the force and acceleration will be in the direction of the field. This force has the same direction as the electric field vector, and its magnitude is given by the size of the charge multiplied with the magnitude of the electric field.

The electric potential created by a point charge q, at a distance r from the charge (relative to the potential at infinity), can be shown to be

$$V = \frac{1}{4\pi\varepsilon_0} \times \frac{q}{r}$$

where ε_0 is the electric constant.

Absolute potential and potential difference

To define absolute potential you need a reference point (for example, infinity). Then you can say that:

electric potential at a point = work done per unit charge in bringing a small object from infinity to a point in an electric field

To define electric potential difference between two points P and Q, you need to assume the absolute electric potential at P is V_P and the absolute electric potential at Q is V_Q. Then the electric potential difference is:

$$V_P - V_Q$$

How to show that that two quantities are equivalent

You can show that two quantities are equivalent by using their units.

From the definition of V we can find its units in terms of N, m and C.

$$V = \frac{1}{4\pi\varepsilon_0} \times \frac{q}{r}$$

We know that the units for the constant term are N m^2/C^{-2}.

The units for $\frac{q}{r}$ are C/m. So the units for V are $\frac{\text{N m}^2\,\text{C}}{\text{C}^2\,\text{m}}$.

This can be simplified, using the laws of indices, to N m/C.

If we divide this by m, to give V/m, we get N/C. So 1 V/m = 1 N/C.

Equipotential lines and surfaces

The term 'equi' means equal. Equipotential therefore means 'equal potential'. Equipotential lines are lines showing where the electric potential is the same value. Equipotential surfaces are surfaces that have the same electric potential.

Equipotential lines and surfaces in an electric field

You have already seen a diagram like that in Figure 2.38. The electric field strength along the lines marked in blue is the same at all points along the line. These are therefore lines of equipotential.

Electric potential energy

Potential energy is energy that a body possesses because of its position. If you have a spring and you compress it, you have to do work to make the compression. The work you do is transferred to the spring as potential energy. In a similar way, when a positive charge (say) is moved towards another positive charge, they will repel each other, so work has to be done to push them towards each other. When there is no longer any work being done, the charges will be able to repel each other (the natural state). Electric potential energy is the energy a charge possesses because it is in the region of other charges.

Note that you can convert one form of energy (e.g. electric potential energy) to another form (e.g. kinetic energy, which is energy relating to movement) but energy cannot be created or destroyed. Energy is conserved in a system.

Summary

- Electric potential at a point in space is potential energy divided by charge that is associated with a static (one that does not vary with time) electric field. Its SI unit is the volt, in honor of Alessandro Volta.
- To define absolute potential you need a reference point (for example, infinity). Then you can say that:
  electric potential at a point = work done per unit charge in bringing a small object from infinity to a point in an electric field
- To define electric potential difference between two points P and Q, you need to assume the absolute electric potential at P is V_P and the absolute electric potential at Q is V_Q. Then the electric potential difference is:

  $V_P - V_Q$
- You can show that 1 N/C = 1 V/m.
- Equipotential lines are lines showing where the electric potential is the same value. Equipotential surfaces are surfaces that have the same electric potential.
- You can draw equipotential lines and surfaces in an electric field.
- Electric potential energy is the energy a charge possesses because it is in the region of other charges.

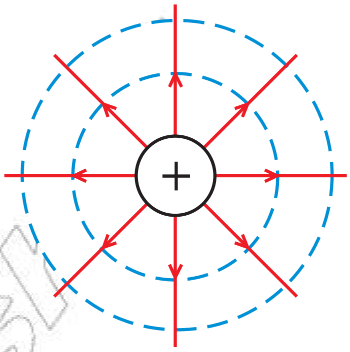

Figure 2.38 *Equipotential lines are shown in blue.*

Activity 2.18: Drawing equipotentials

Using Figures 2.22b, 2.23a and 2.23b on page 61, draw diagrams showing equipotential lines around
a) a negative charge,
b) two opposite charges,
c) two positive charges.

KEY WORDS

electric potential *potential energy divided by charge that is associated with a static electric field. Its SI unit is the Volt*

Review questions

1. Define electric potential and its SI unit.
2. Distinguish between absolute potential and potential difference.
3. Show that 1 N/C = 1 V/m.
4. Explain equipotential lines and surfaces.
5. Draw equipotential lines between two negative charges in an electric field.
6. Define the term electric potential energy.

2.4 Capacitors and capacitances

By the end of this section you should be able to:

- Describe the structure of a simple capacitor.
- Define the term capacitance and its SI unit.
- Apply the definition of capacitance to solve numerical problems.
- Use a circuit symbol to represent a capacitor.
- Explain the charging and discharging of a capacitor.
- Define the term dielectric and explain what is meant by a dielectric material.
- Identify combination of capacitors in series, parallel and series–parallel.
- Explain the effect of inserting a dielectric in the gap between the plates of a parallel plate capacitor.
- Derive an expression for the effective capacitance of capacitors connected in series and parallel.
- Draw an electric circuit diagram for a simple capacitor, series and parallel connections of two or more capacitors using symbols.
- Solve problems on combination of capacitors.
- Define parallel plate capacitor.
- Describe the factors that affect the capacitance of a parallel plate capacitor.
- Calculate the capacitance of a parallel plate capacitor.
- Find an expression for the electric potential energy stored in a capacitor.
- Calculate the energy stored in a capacitor using one of three possible formulae.
- State some uses of capacitors in everyday life.

The structure of a simple capacitor

A capacitor is a small device designed to store more charge at a lower potential. The commonest way of doing this is to use two parallel plates, a tiny distance apart and separated by an insulator (which may be air or may be a dielectric material – see page 73).

Capacitance and its SI unit

If we place some charge on an insulated metal sphere, the sphere's voltage will rise; put some more charge on, and its voltage will rise further.

Presumably a larger sphere will hold more charge before its potential has risen by 1 V. We measure this by using a quantity called capacitance, *C*. If a charge *Q* results in a rise of *V* in the potential, we define the capacitance of the sphere by:

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

This is the charge needed for each volt rise in the sphere potential. The units will be coulombs per volt, C/V, which we call farads, F.

The farad is a very large unit of capacitance – it is rare for an extra coulomb of charge to result in a rise in potential of no more than 1 V. We often use the microfarad (μF, $\times 10^{-6}$ F) or even the picofarad (pF, $\times 10^{-12}$ F).

Worked example 2.8

The metal dome at the top of a Van de Graaf generator will have a capacitance of around 10 pF (1×10^{-11} F). The insulation of air will typically break down when subjected an electric field of around 3000 V/mm. Suppose that the charged dome will produce sparks to earth across an air gap of about 33 mm. That suggests that the potential of the sphere is something like 3000 V/mm × 33 mm, which gives 100 000 V.

C (F)	*Q* (C)	*V* (V)
1×10^{-11}	?	1×10^{5}

The charge held on the dome can be found using

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

Rearranging, $Q = CV$

$= 1 \times 10^{-11}$ F (C/V) $\times 1 \times 10^{5}$ V

$= 1 \times 10^{-6}$ C (1 μC)

Figure 2.39 *A selection of capacitors.*

Worked example 2.9

A 150 pF capacitor holds 6.0×10^{-9} C of charge. What will the p.d. be between its terminals?

C (F)	*Q* (C)	*V* (V)
150×10^{-12}	6×10^{-9}	?

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

We want to find *V*. Rearrange to give

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

Substitute values

$V = \frac{6.0 \times 10^{-9}}{150 \times 10^{-12}} = 40$ V

Larger spheres

A larger sphere will have a bigger capacitance, so you will need to give it a greater amount of charge before its potential rises by 1 V. However, a sphere with a capacitance of 1 F would be vast – its radius would be around 2000 times that of the Earth.

Activity 2.19: Charging and discharging capacitors

Charge a large capacitor for a few minutes by connecting it to a battery, as shown in Figure 2.41.

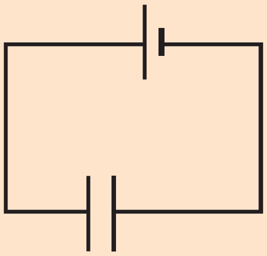

Figure 2.41 *Circuit showing capacitor connected to a battery.*

Then add a bulb to the circuit, as shown in Figure 2.24.

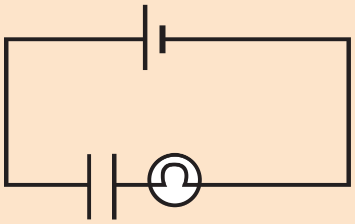

Figure 2.42 *Circuit with bulb.*

What happens? Try to draw a graph showing light intensity versus time. Discuss what was stored and what was drained before reading on.

Also see...

See page 94 for more on Ohm's law.

The circuit symbol for a capacitor

Figure 2.40 shows the usual circuit symbol for a capacitor.

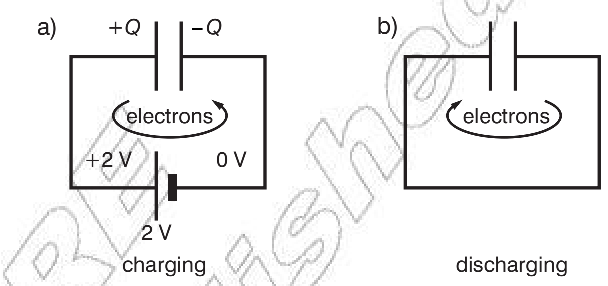

Figure 2.40 *Circuit symbol for a capacitor.*

In Figure 2.40a, the battery is moving electrons from the plate +Q, so it is left with a positive charge. The electrons move round the wires to the −Q plate, which is left with a negative charge. When the potential difference between the plates is the same as that across the battery (2 V), no more charge can flow because the capacitor is balancing the battery.

How much charge is being stored on the capacitor? It might be argued that for example, with +Q on one plate and −Q on the other as shown above, the total amount stored is 2Q. More plausibly, perhaps, somebody else might say +Q and −Q means a total charge of zero. However, neither is correct. Look at Figure 2.40b which shows the capacitor emptying. What happens is that 'Q' coulombs of electrons flow off one plate, pass round the circuit in the form of a momentary current and go on to the other plate. The charge stored is Q.

The formula for capacitance is still $C = \frac{Q}{V}$ but the terms now take on a slightly different meaning: Q is the charge held on one of the plates, and V is the potential difference between them.

Charging and discharging a capacitor

When a capacitor discharges through a resistor (or a bulb), the capacitor acts like a battery to drive a current through the resistor, but, unlike a battery, its voltage drops rapidly as its charge drains away. Think of a capacitor charged up to a voltage V_0 which is then emptied through a resistor R. When it is first connected, the discharging current is determined entirely by the resistor (since $I = \frac{V}{R}$ for it) – the higher the value of the resistor, the more slowly the capacitor will empty.

Figure 2.43 indicates how the charge remaining on the capacitor will decrease with time; the vertical axis actually shows the voltage across its plates, but this also provides a measure of the charge left.

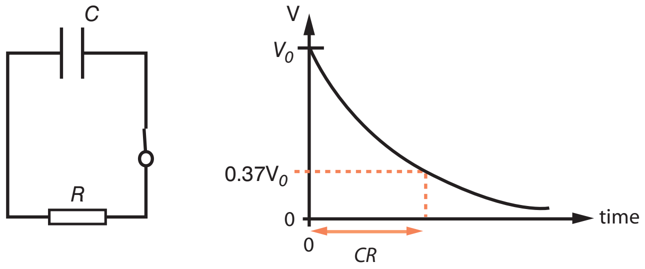

Figure 2.43 *Charge decreasing over time.*

As the capacitor empties, so the voltage across its plates drops. This decreasing voltage across the resistor *R* results in a reducing discharge current, so the capacitor empties ever more slowly. The resulting curve is what we call exponential decay.

We can work out how long it takes for the voltage to drop to 0.37 of its starting value (by which time the capacitor has almost two-thirds emptied). We do this by multiplying *C* by *R*. This gives what we call the time constant of the circuit.

Working out *CR* gives a time in seconds. This means that F Ω, farads multiplied by ohms, must be seconds. It seems unlikely, but it is certainly a good exercise to try. From the definition of capacitance, be sure you can see why the farad is coulombs per volt, C/V. The ohm is derived from $R = \frac{V}{I}$, and so is volts per ampere, V/A. Multiply them together and the unit reduces to C/A. Realise that the coulomb is the ampere second, A s, and you are there.

When a capacitor is charged through a resistor, we have the opposite to the discharge situation. Here the capacitor charges rapidly at the start, but then continues at an ever-declining rate. It is a kind of 'upside down' exponential curve. When the voltage between the plates of the capacitor equals that of the battery, the charging ceases.

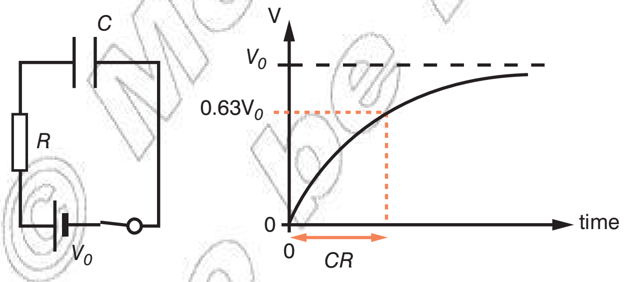

***Figure 2.44** Capacitor charging through a resistor.*

This time when the time constant has elapsed, the capacitor is almost two-thirds full. Such a circuit can be used as the basis for a timing circuit. When the voltage across the capacitor reaches a certain value, it causes something else to occur – a light to come on, for instance. If a control is provided by which you can adjust the time delay, you will be altering a variable resistor to change the value of *R*.

Dielectric materials

A **dielectric** is the electrically insulating material between the metallic plates of a capacitor that increases the capacitance of the capacitor (so a greater charge can be stored at a given voltage). The advantage of using a dielectric is that it stops the two charged plates coming into contact with each other.

The dielectric in a capacitor is often a solid material with high **permittivity** (permittivity is a measure of how an electric field affects, and is affected by, a dielectric medium, and relates to a material's ability to transmit (or 'permit') an electric field).

KEY WORDS

dielectric *electrically insulating material*

permittivity *a measure of how an electric field affects, and is affected by, a dielectric medium*

Challenge...

Work in a small group to derive the given formulae for capacitors in series and in parallel.

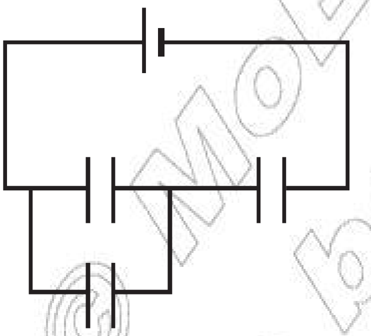

Figure 2.46 *Combining parallel and series capacitors.*

Activity 2.20: Charging and discharging series and parallel combinations of capacitors

Repeat Activity 2.19, but this time use combinations of capacitors in series and in parallel. Add a resistor to the circuit. Investigate the variation in discharge times. Try to explain your observations.

Combination of capacitors in series, parallel and series–parallel

Sometimes you may wish to combine two or more capacitors, to make one of a different value. The formulae are as follows.

Capacitors in parallel (as shown in Figure 2.45a)

$C_{total} = C_1 + C_2$

Capacitors in series (as shown in Figure 2.45b)

$$\frac{1}{C_{total}} = \frac{1}{C_1} + \frac{1}{C_2}$$

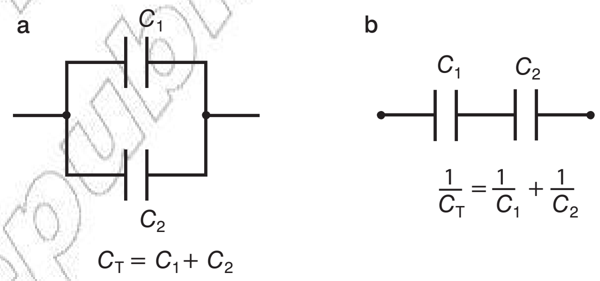

Figure 2.45 *Parallel capacitors and series capacitors.*

It is also possible to organise capacitors as shown in Figure 2.46, in which case you work out the capacitance of the parallel combination first and then take that capacitance as C_1 in the formula for series capacitors.

Worked example 2.10

Two capacitors of values 4 μF and 2 μF are placed a) in parallel, b) in series. Draw a diagram to show these circuits. Work out the effective capacitance of each combination.

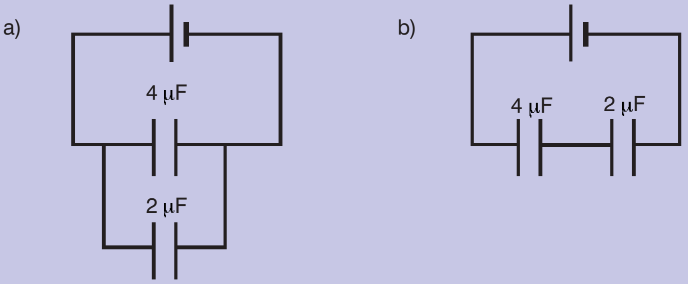

Figure 2.47 *Capacitors in parallel use and series use.*

a) Capacitors in parallel use $C_{total} = C_1 + C_2$

$C_{total} = 4\ \mu F + 2\ \mu F = 6\ \mu F$

b) Capacitors in series use

$$\frac{1}{C_{total}} = \frac{1}{C_1} + \frac{1}{C_2}$$

$$\frac{1}{C_{total}} = \frac{1}{4\ \mu F} + \frac{1}{2\ \mu F} = \frac{3}{4}\ \mu F$$

So $C_{total} = \frac{4}{3}\mu F$

Parallel plate capacitor and the factors that affect its capacitance

A parallel plate capacitor has two plates that are parallel to each other. If a capacitor has two plates each of area A separated by a distance d, then it is possible to calculate what its capacitance C will be by using the relationship:

$C_0 = \frac{\varepsilon_0 A}{d}$ if the distance d is not filled by any dielectric material

If there is a dielectric material,

$$C = \frac{\varepsilon A}{d}$$

The symbol ε is a constant that varies according to the dielectric which is used to separate the plates.

Looking at the expression, in addition to a suitable dielectric, what are needed for a large capacitance are two plates of large area placed exceedingly close together. One way to achieve this is to use a very long strip of thin metal foil for each of the plates. The two strips are separated by a similar-shaped strip, perhaps of thin waxed paper (which acts as the dielectric). The assembly is then rolled up tightly to fit into a plastic case with two leads, one going to each plate.

Activity 2.21

If possible, look for the capacitors in a broken radio. See if you can find the dielectric material.

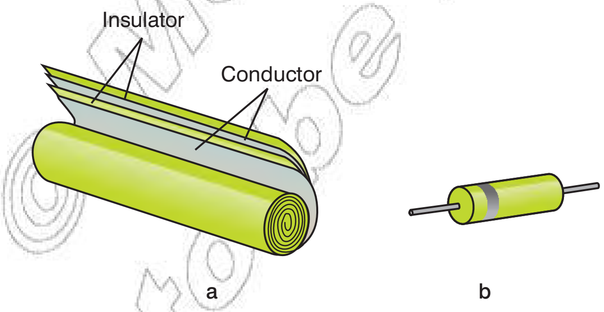

Figure 2.48 *Parallel plate capacitor.*

Another type of capacitor is the electrolytic capacitor, where the three layers are deposited by an electroplating technique, which helps to make them very thin – so the plates are close together and the whole device is compact. (If you wonder how you can deposit an insulator by electroplating, the answer is you cannot. The dielectric has to be slightly conducting, which means that the charge will soon leak off the capacitor. With some applications in electronics the charge needs be stored for only a brief interval, in which case that is not important.)

The electric potential energy stored in a capacitor

If a capacitor holds a charge Q at a potential V, then the energy it contains is given by:

Energy $= \frac{1}{2}QV$

An alternative form of the same expression, including $C = \frac{Q}{V}$ as well, is:

Energy $= \frac{1}{2}CV^2$

Worked example 2.11

A 20 μF capacitor is charged to 12 V. How much energy does it contain?

Energy = $\frac{1}{2}CV^2$ =

$\frac{1}{2} \times 20 \times 10^{-6} \times 122$ = 1.4×10^{-3} J (1.4 mJ)

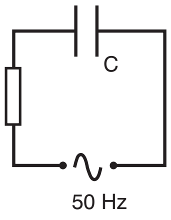

Figure 2.49 Capacitor powered by 50 Hz alternating voltage supply.

This is only a tiny amount of energy. Clearly capacitors are not suitable for storing large amounts of energy.

However, a capacitor can be useful for the flash circuit in a camera. The flash needs a big current just for an instant – not much charge is needed in total, but it must all be supplied quickly. The little battery in the camera cannot supply such a large current, but what it does is to slowly fill up a capacitor; it is the capacitor then that empties to generate the flash for an instant. The capacitor is behaving rather like the tank in a flushing toilet. A small water pipe is used to slowly fill up the cistern, then when it flushes the whole tankful empties in a very short time to give a momentary rapid flow of water.

Why is the energy not given by QV? After all, we have Q coulombs of charge being stored at a potential of V volts for each coulomb – so why the extra factor of a half?

To see the answer, it is necessary to consider what happened when the charge first went on to the capacitor, a little at a time. The first piece of charge went on to an uncharged capacitor, and so did not have to be 'lifted' through any volts. Successive charges had to be 'lifted' through an increasing voltage, but it was only the final piece that had to be 'lifted' through the full V volts.

Applying those ideas:

the energy stored on the capacitor =

the total charge × the *average* voltage through which it had to be 'lifted' (which is just $\frac{1}{2}V$)

$= Q \times \frac{1}{2}V = \frac{1}{2}QV.$

It is a bit like building a brick wall which is to be 2 m high. The first bricks have to be lifted through no height at all, and it is only the final ones that have to be lifted through the full 2 m. The average brick has to be lifted by 1 m.

Capacitors in everyday life

In direct current circuits (see Unit 3) a capacitor provides a break in the circuit. Apart from a momentary charging current when you switch on, nothing will happen.

In alternating current circuits (see Unit 3) capacitors do useful things, however.

Look at Figure 2.49, which shows a capacitor in a circuit that is being powered by a 50 Hz alternating voltage supply. This means than the voltage rises to a maximum, dies away, builds up to a maximum in the other direction, then dies away again – and repeats this cycle 50 times every second.

The capacitor is continually charging up, emptying, charging up the other way round then emptying again – and does this 50 times every second. As far as the power supply and the rest of the circuit are concerned, it is just as if there was a complete circuit.

To sum up, therefore, capacitors block direct currents but appear to allow alternating currents to pass. That is one important use in electronic circuits.

In a public address system, for example, the signal is an alternating current. This has to be passed on from one amplifier stage to the next (see Figure 2.50).

The output of the first stage is at a different voltage to the input of the next stage. Just joining them with a wire would have caused both stages to stop working. The capacitor provides the solution.

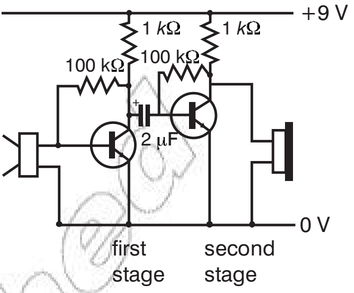

Figure 2.50 *Alternating current in a public address system.*

Summary

- A capacitor is a small device designed to store more charge at a lower potential. The commonest way of doing this is to use two parallel plates, a tiny distance apart and separated by an insulator.
- If we place some charge on an insulated metal sphere, the sphere's voltage will rise; put some more charge on, and its voltage will rise further.
- Presumably a larger sphere will hold more charge before its potential has risen by 1 V. We measure this by using a quantity called capacitance, C. If a charge Q results in a rise of V in the potential, we define the capacitance of the sphere by:
  $$C = \frac{Q}{V}$$
- This is the charge needed for each volt rise in the sphere's potential. The units will be coulombs per volt, C/V, which we call farads, F.
- You can apply the definition of capacitance to solve numerical problems.
- The circuit symbol to represent a capacitor is as shown in Figure 2.51.
- You can use this symbol to draw an electric circuit diagram for a simple capacitor and series and parallel connections of two or more capacitors.
- When a capacitor discharges through a resistor (or a bulb), the capacitor acts like a battery to drive a current through the resistor, but unlike a battery its voltage drops rapidly as its charge drains away.
- When a capacitor is charged through a resistor we have the opposite to the discharge situation. Here the capacitor charges rapidly at the start, but then continues at an ever-declining rate. It is a kind of 'upside down' exponential curve. When the voltage between the plates of the capacitor equals that of the battery, the charging ceases.
- A dielectric is the electrically insulating material between the metallic plates of a capacitor and increases the capacitance of the capacitor (so a greater charge can be stored at a given voltage). The advantage of using a dielectric is that it stops the two charged plates coming into contact with each other. The dielectric in a capacitor is often a solid material with high permittivity (permittivity is a measure of how an electric field affects, and is affected by, a dielectric medium, and relates to a material's ability to transmit (or 'permit') an electric field).
- Sometimes you may wish to combine two or more capacitors, to make one of a different value. The formulae are as follows:

  Capacitors in parallel (as shown in Figure 2.51a)

  $$C_{total} = C_1 + C_2$$

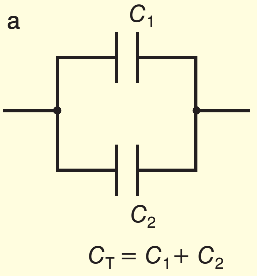

Figure 2.51a

- Capacitors in series (as shown in Figure 2.51b)

  $$\frac{1}{C_{total}} = \frac{1}{C_1} + \frac{1}{C_2}$$

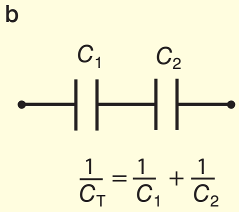

Figure 2.51b

Summary

- It is also possible to organise capacitors as shown below, in which case you work out the capacitance of the parallel combination first and then take that capacitance as C_1 in the formula for series capacitors.

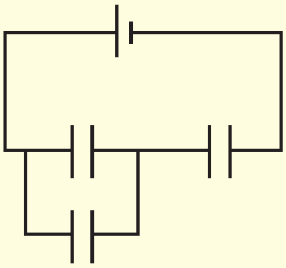

Figure 2.52

- You can use the above expressions to solve problems on combination of capacitors.
- A parallel plate capacitor has two plates that are parallel to each other. If a capacitor has two plates each of area A separated by a distance d, then it is possible to calculate what its capacitance C will be by using the relationship:

  $$C = \frac{\varepsilon A}{d}$$

  The symbol ε is a constant that varies according to the dielectric which is used to separate the plates.
- From the expression, the factors that affect the capacitance of a parallel plate capacitor are the dielectric material, the area of the plates, and the distance between the plates.
- You can calculate the capacitance of a parallel plate capacitor using the above formula.
- The electric potential energy stored in a capacitor can be found using

  $$\text{Energy} = \tfrac{1}{2}QV$$

  $$\text{or energy} = \tfrac{1}{2}CV^2$$
- You can calculate the energy stored in a capacitor using one of these formulae.
- Some uses of capacitors in everyday life include in a camera flash, to provide a break in a direct current circuit, to allow alternating currents to pass, to link two stages of an amplifier, and as the basis for a timing circuit.

Review questions

1. Describe the structure of a simple capacitor.
2. Define the term capacitance and its SI unit.
3. A 2.0 μF capacitor is charged from a 6.0 V battery.
   a) How much charge will it hold?
   b) How much energy is stored on it?
   c) Where has that energy come from?
   d) If the capacitor is then discharged, where does the energy go to?
4. a) Take a 2.0 μF and a 5.0 μF capacitor and connect them in parallel. Draw the circuit diagram. What is the capacitance of the combination?
   b) Repeat part a), but this time connect capacitors in series.
5. Explain the charging and discharging of a capacitor.

6. Define the term dielectric and explain what is meant by a dielectric material.
7. Explain the effect of inserting a dielectric in the gap between the plates of a parallel plate capacitor.
8. Define a parallel plate capacitor and describe the factors that affect its capacitance.
9. You want to make a 5.0 μF capacitor. For the dielectric you use waxed paper of thickness 0.4 mm and $\varepsilon = 7.1 \times 10^{-12}$ F/m. What area plates will be required?
10. State an expression for the electric potential energy stored in a capacitor.
11. A photographic flash unit has a 100 μF capacitor which is charged up by a small 22.5 V battery. How much energy may be discharged into the flash bulb?

End of unit questions

1. Describe how you can test how charged bodies attract or repel one another.
2. Why is the inside of a car a safe place to shelter in a storm?
3. a) Find the force acting on a charge of 4 C in an electric field of 5 N/C.
   b) State Coulomb's law.
   c) State the similarities between Coulomb's law and Newton's law of universal gravitation.
4. What is an equipotential?
5. a) What is a capacitor?
   b) State some uses of capacitors in everyday life.
   c) Two capacitors of 5 μF and 10 μF could be arranged either in series of in parallel. Which arrangement gives the highest capacitance? Explain your answer.
   d) If two capacitors, A and B, have the same area and dielectric constant, but the distance between the plates of A is twice the distance between the plates of B, which has the higher capacitance? Explain your answer.
6. An electron travels at a horizontal velocity of 5×10^6 m/s in a vacuum between two charged plates 100 mm long and 20 mm apart, to which a p.d. of 30 V is applied. The charge on an electron is 1.5×10^{-19} C and the mass of an electron is 9.1×10^{-31} kg.
   a) What size force will the electron experience while it passes through the plates?
   b) What acceleration will this give to the electron?
   c) If the positive plate is the lower one, in which direction will the electron accelerate?
   d) How long will it take for the electron to pass through the plates?