Chapter 21

Uniform electric fields

LEARNING INTENTIONS

In this chapter you will learn how to:

- show an understanding of the concept of an electric field
- define electric field strength
- draw field lines to represent an electric field
- calculate the strength of a uniform electric field
- calculate the force on a charge in a uniform electric field
- describe how charged particles move in a uniform electric field.

BEFORE YOU START

- You will have learned about electrostatics in your previous studies and in everyday life. You will also have met the idea of magnetism.
- Make a list of the similarities between electrostatics and magnetism and also a list of the differences.
- Are the two phenomena related or not? If so, how?

ELECTRICITY IN NATURE

The lower surface of a thundercloud is usually negatively charged. When lightning strikes (Figure 21.1), an intense electric current is sent down to the ground below. You may have noticed a ‘strobe’ effect – this is because each lightning strike usually consists of four or five flashes at intervals of 50 milliseconds or so. You will already know a bit about electric (or electrostatic) fields, from your experience of static electricity in everyday life and from your studies in science. In this chapter, you will learn how we can make these ideas more formal. We will look at how electric forces are caused, and how we can represent their effects in terms of electric fields. Then we will find mathematical ways of calculating electric forces and field strengths.

There are about three million lightning strikes on the Earth each day; the energy transferred in one strike is 10 MJ. There is more than enough energy to satisfy the industrial world with all its energy needs. Why is it not harnessed? What problems can you see in harnessing it?

Figure 21.1: Lightning flashes; dramatic evidence of natural electric fields.

21.1 Attraction and repulsion

Static electricity can be useful – it is important in the process of photocopying, in dust precipitation to clean up industrial emissions and in crop-spraying, among many other applications. It can also be a nuisance. Who hasn't experienced a shock, perhaps when getting out of a car or when touching a door handle? Static electric charge has built up and gives us a shock when it discharges.

We explain these effects in terms of **electric charge**. Simple observations in the laboratory give us the following picture:

- Objects are usually electrically neutral (uncharged), but they may become electrically charged, for example, when one material is rubbed against another.
- There are two types of charge, which we call positive and negative.
- Opposite types of charge attract one another; like charges repel (Figure 21.2).
- A charged object may also be able to attract an uncharged one; this is a result of electrostatic induction.

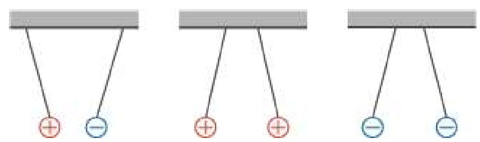

Figure 21.2: Attraction and repulsion between electric charges.

These observations are macroscopic. They are descriptions of phenomena that we can observe in the laboratory, without having to consider what is happening on the microscopic scale, at the level of particles such as atoms and electrons. However, we can give a more subtle explanation if we consider the microscopic picture of static electricity.

Using a simple model, we can consider matter to be made up of three types of particles: electrons (which have negative charge), protons (positive) and neutrons (neutral). An uncharged object has equal numbers of protons and electrons, whose charges therefore cancel out.

When one material is rubbed against another, there is friction between them, and electrons may be rubbed off one material onto the other (Figure 21.3). The material that has gained electrons is now negatively charged, and the other material is positively charged.

If a positively charged object is brought close to an uncharged one, the electrons in the second object may be attracted. We observe this as a force of attraction between the two objects. (This is known as electrostatic induction.)

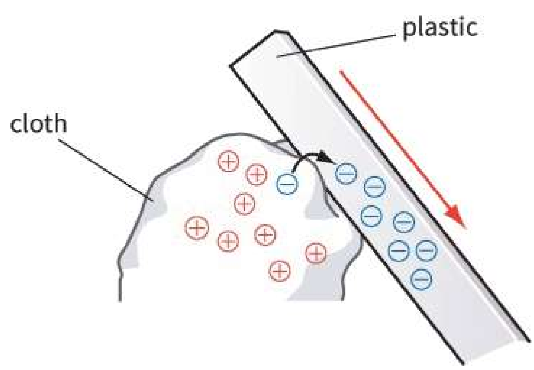

Figure 21.3: Friction can transfer electrons between materials.

It is important to appreciate that it is usually electrons that are involved in moving within a material, or from one material to another. This is because electrons, which are on the outside of atoms, are less strongly held within a material than are protons. They may be free to move about within a material (like the conduction electrons in a metal), or they may be relatively weakly bound within atoms.

PRACTICAL ACTIVITY 21.1

Investigating electric fields

If you rub a strip of plastic so that it becomes charged and then hold it close to your hair, you feel your hair being pulled upwards. The influence of the charged plastic spreads into the space around it; we say that there is an **electric field** around the charge. To produce an electric field, we need unbalanced charges (as with the charged plastic). To observe the field, we need to put something in it that will respond to the field (as your hair responds). There are two simple ways in which you can do this in the laboratory. The first uses a charged strip of gold foil, attached to an insulating handle (Figure 21.4). The second uses grains of a material such as semolina; these line up in an electric field (Figure 21.5), rather like the way in which iron filings line up in a magnetic field (Figure 21.5).

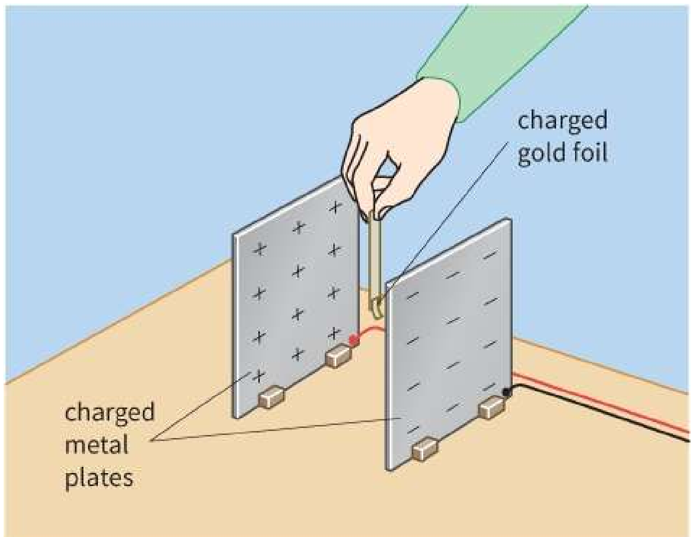

Figure 21.4: Investigating the electric field between two charged metal plates.

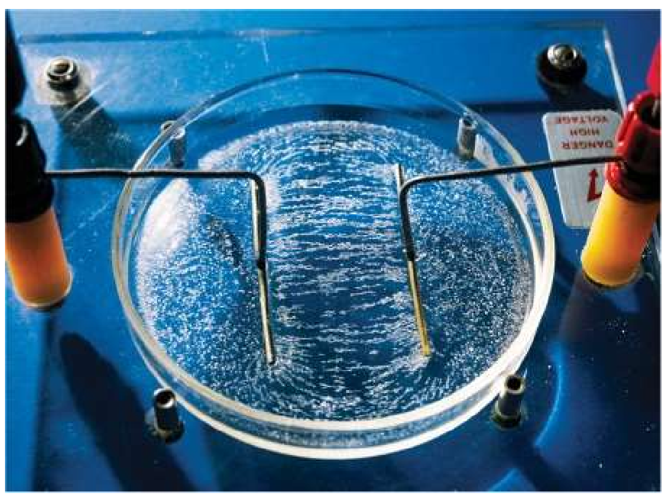

Figure 21.5: Apparatus showing a uniform electric field between two parallel charged plates.

21.2 The concept of an electric field

A charged object experiences a force in an electric field. This is what an electric field is. We say that there is an electric field anywhere where an electric charge experiences a force. An electric field is a **field of force**.

This is a rather abstract idea. You will be more familiar with the idea of a 'field of force' from your experience of magnets. There is a magnetic field around a permanent magnet; another magnet placed nearby will experience a force. You have probably plotted the field lines used to represent the field around a magnet. There is a third type of force field that we are all familiar with, because we live in it. You have already met this force in Chapter 17, the gravitational field. There are many similarities between electric fields and gravitational fields, there are also key differences.

To summarise:

- electric fields – act on objects with electric charge
- magnetic fields – act on magnetic materials, magnets and moving charges (including electric currents)
- gravitational fields – act on objects with mass.

Later, we will see that the electric force and the magnetic force are closely linked. They are generally considered as a single entity, the electromagnetic force.

Representing electric fields

We can draw electric fields in much the same way that we can draw magnetic fields or gravitational fields, by showing **field lines** (sometimes called lines of force). The three most important field shapes are shown in Figure 21.6.

As with magnetic fields, this representation tells us two things about the field: its direction (from the direction of the lines), and how strong it is (from the separation of the lines). The arrows go from positive to negative; they tell us the direction of the force on a positive charge in the field.

- A uniform field has the same strength at all points. Example: the electric field between oppositely charged parallel plates.
- A radial field spreads outwards in all directions. Example: the electric field around a point charge or a charged sphere.

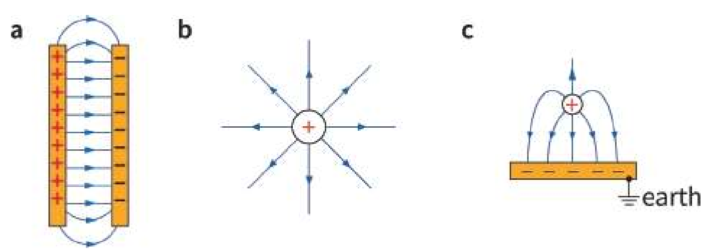

Figure 21.6: Field lines are drawn to represent an electric field. They show the direction of the force on a positive charge placed at a point in the field. **a** A uniform electric field is produced between two oppositely charged plates. **b** A radial electric field surrounds a charged sphere. **c** The electric field between a charged sphere and an earthed plate.

We can draw electric fields for other arrangements. Note the symbol for an earth, which is assumed to be uncharged (in other words, at zero volts).

Questions

1 Which of the three field diagrams in Figure 21.7 represents:

a two positive charges repelling each other?

b two negative charges?

c two opposite charges?

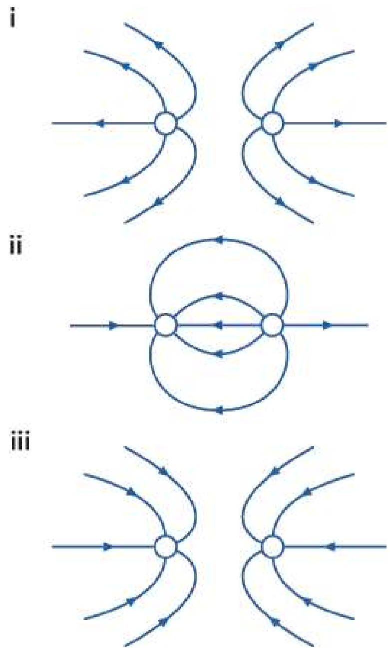

Figure 21.7: Electric fields between charges. For Question 1.

2 Many molecules are described as polar; that is, they have regions that are positively or negatively charged, though they are neutral overall. Draw a diagram to show how sausage-shaped polar molecules like those shown in Figure 21.8 might realign themselves in a solid.

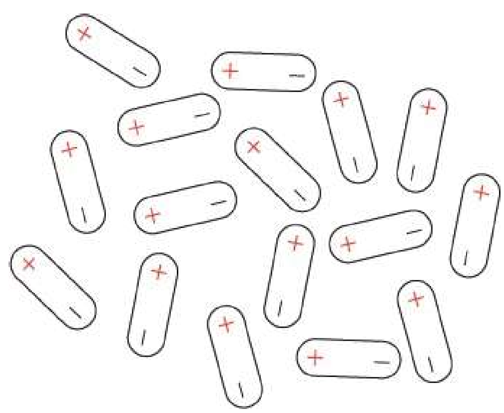

Figure 21.8: Polar molecules. For Question 2.

3 Figure 21.9 shows the electric field pattern between a thundercloud and a building. State and explain where the electric field strength is greatest.

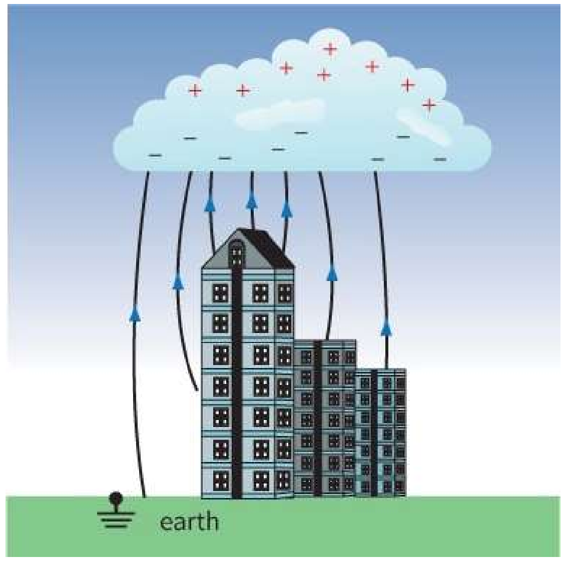

Figure 21.9: Predict where the electric field will be strongest – that's where lightning may strike.

21.3 Electric field strength

The **electric field strength** at a point is defined as the force per unit charge exerted on a stationary positive charge at that point.

To define electric field strength, we imagine putting a positive test charge $+Q$ in the field and measuring the electric force F that it feels (Figure 21.10). It is important to recognise the importance of using a positive test charge, as this determines the direction of an electric field. (If you have used a charged gold leaf to investigate a field, this illustrates the principle of testing the field with a charge.)

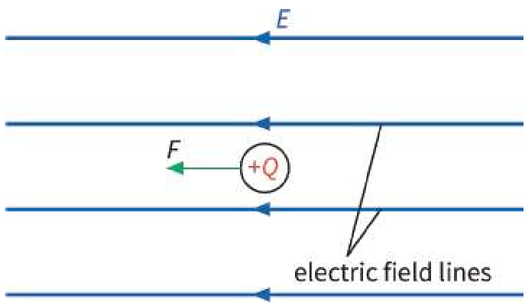

Figure 21.10: A field of strength E exerts force F on charge $+Q$.

From this definition, we can write an equation for E:

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

where E is the electric field strength, F is the force on the charge and Q is the charge.

It follows that the units of electric field strength are newtons per coulomb (N C^{-1}).

KEY EQUATION

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

The strength of a uniform field

You can set up a uniform field between two parallel metal plates by connecting them to the terminals of a high-voltage power supply (Figure 21.11). The strength of the field between them depends on two factors:

- the voltage V between the plates – the higher the voltage, the stronger the field: $E \propto V$
- the separation d between the plates – the greater their separation, the weaker the field: $E \propto \frac{1}{d}$

These factors can be combined to give an equation for E:

$$E = -\frac{V}{d}$$

Worked example 1 shows a derivation of this. Note that the minus sign is often omitted because we are only interested in the magnitude of the field, not its direction. In Figure 21.11, the voltage V increases towards the right while the force F acts in the opposite direction, towards the left. E is a vector quantity.

KEY EQUATION

$$E = \frac{\Delta V}{\Delta d}$$

Strength of a uniform field between two parallel metal plates.

If we look at this formula in a little more detail we can see that the electric field is really equal to the change in the potential (potential difference) divided by the change in distance (distance moved). This is written:

$$E = -\frac{\Delta V}{\Delta d}$$

where the symbol Δ means ‘change of’.

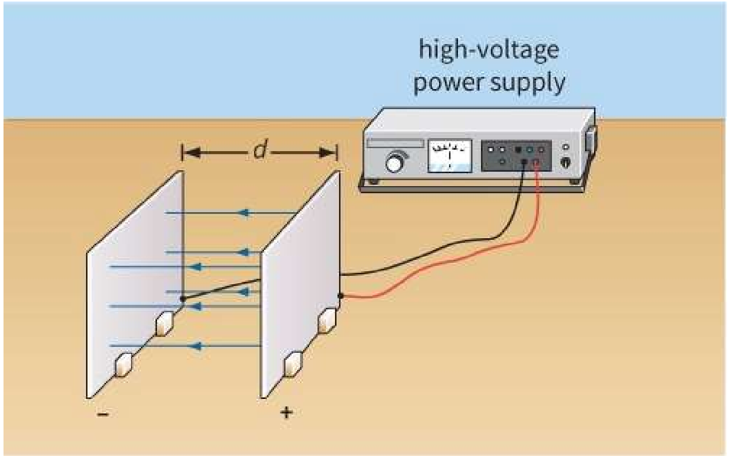

Figure 21.11: There is a uniform field between two parallel, charged plates.

From this equation, we can see that we can write the units of electric field strength as volts per metre (V m^{-1}). Note:

$$1 \text{ V m}^{-1} = 1 \text{ N C}^{-1}$$

Worked example 2 shows how to solve problems involving uniform fields.

WORKED EXAMPLES

1 Two metal plates are separated by a distance *d*. The potential difference between the plates is *V*. A positive charge *Q* is pulled at a constant speed with a constant force *F* from the negative plate all the way to the positive plate. Using the definition for electric field strength and the concept of work done, show that the magnitude of the electric field strength *E* is given by the equation:

$$E = \frac{V}{d}$$

Step 1 We have:

work done on charge = energy transformed

From their definitions, we can write:

work done = force × distance or $W = Fd$

energy transformed = VQ

Step 2 Substituting gives:

$Fd = VQ$

and rearranging gives:

$$\frac{F}{Q} = \frac{V}{d}$$

Step 3 The left-hand side of the equation is the electric field strength *E*. Hence:

$$E = \frac{V}{d}$$

2 Two parallel metal plates separated by 2.0 cm have a potential difference of 5.0 kV. Calculate the electric force acting on a dust particle between the plates that has a charge of 8.0 × 10^{-19} C.

Step 1 Write down the quantities given in the question:

$d = 2.0 \times 10^{-2}$ m

$V = 5.0 \times 10^{3}$ V

$Q = 8.0 \times 10^{-19}$ C

Hint: *When you write down the quantities it is important to include the units and to change them into base units. We have used powers of ten to do this.*

Step 2 To calculate the force *F*, you first need to determine the strength of the electric field:

$$E = \frac{V}{d}$$
$$= \frac{5\times10^3}{2.0\times10^{-2}}$$
$$= 2.5\times10^5\,\mathrm{V\,m^{-1}}$$

Step 3 Now calculate the force on the dust particle:

$F = EQ$

$F = 2.5 \times 10^5 \times 8.0 \times 10^{-19}$

$= 2.0 \times 10^{-13}$ N

Questions

4 Figure 21.12 shows an arrangement of parallel plates, each at a different voltage. The electric field lines are shown in the space between the first pair. Copy and complete the diagram to show the electric field lines in the other two spaces.

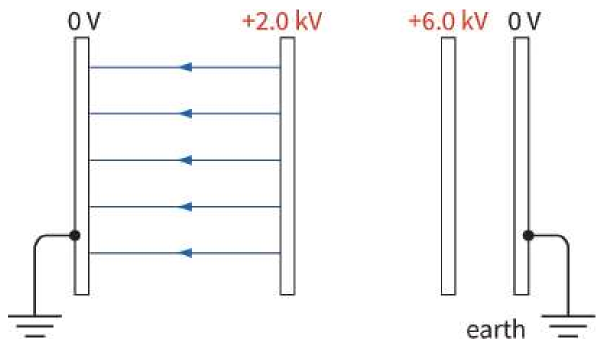

Figure 21.12: An arrangement of parallel plates. For Question 4.

5 Calculate the electric field strength at a point where a charge of 20 mC experiences a force vertically downwards of 150 N.

6 Calculate the electric field strength between two parallel charged plates, separated by 40 cm and with a potential difference between them of 1000 V.

7 An electron is situated in a uniform electric field. The electric force that acts on it is 8×10^{-16} N. What is the strength of the electric field? (Electron charge $e = 1.6 \times 10^{-19}$ C.)

8 Air is usually a good insulator. However, a spark can jump through dry air when the electric field strength is greater than about 40 000 V $\mathrm{cm^{-1}}$. This is called electrical breakdown. The spark shows that electrical charge is passing through the air–there is a current. (Do not confuse this with a chemical spark such as you might see when watching fireworks; in that case, small particles of a chemical substance are burning quickly.)

a A Van de Graaff generator (Figure 21.13) is able to make sparks jump across a 4 cm gap. Estimate the voltage produced by the generator?

b The highest voltage reached by the live wire of a conventional mains supply is 325 V. In theory (but DO NOT try this), how close would you have to get to a live wire to get a shock from it?

c Estimate the voltage of a thundercloud from which lightning strikes the ground 100 m below.

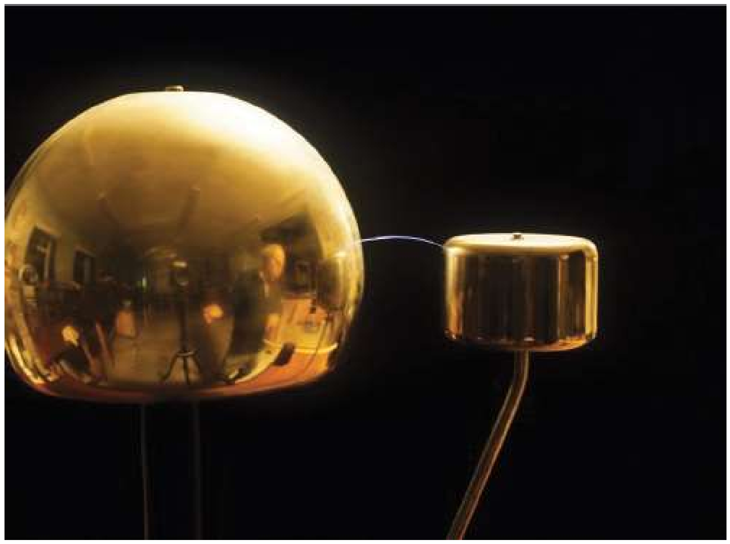

Figure 21.13: A Van de Graaff generator produces voltages sufficient to cause sparks in air.

21.4 Force on a charge

Now we can calculate the force F on a charge Q in the uniform field between two parallel plates. We have to combine the general equation for field strength $E = \frac{F}{Q}$ with the equation for the strength of a uniform field $E = -\frac{V}{d}$.

This gives:

$$F = QE = -\frac{QV}{d}$$

For an electron with charge $-e$, this becomes:

$$F = \frac{eV}{d}$$

Figure 21.14 shows a situation where this force is important. A beam of electrons is entering the space between two charged parallel plates. How will the beam move?

We have to think about the force on a single electron. In the diagram, the upper plate is negative relative to the lower plate, and so the electron is pushed downwards. (You can think of this simply as the negatively charged electron being attracted by the positive plate, and repelled by the negative plate.)

If the electron were stationary, it would accelerate directly downwards. However, in this example, the electron is moving to the right. Its horizontal velocity will be unaffected by the force, but as it moves sideways it will also accelerate downwards. It will follow a curved path, as shown. This curve is a parabola.

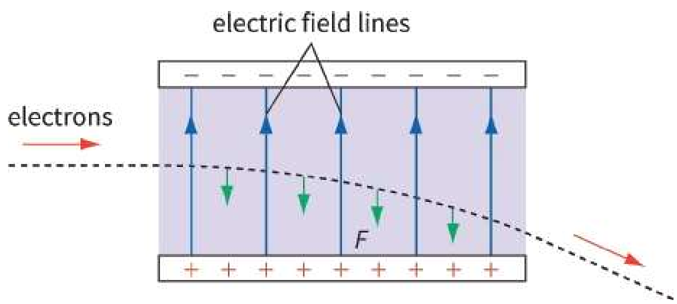

Figure 21.14: The parabolic path of a moving electron in a uniform electric field.

Note that the force on the electron is the same at all points between the plates, and it is always in the same direction (downwards, in this example).

This situation is equivalent to a ball being thrown horizontally in the Earth's uniform gravitational field (Figure 21.15). It continues to move at a steady speed horizontally, but at the same time it accelerates downwards. The result is the familiar curved trajectory shown. For the electron described, the force of gravity is tiny–negligible compared to the electric force on it.

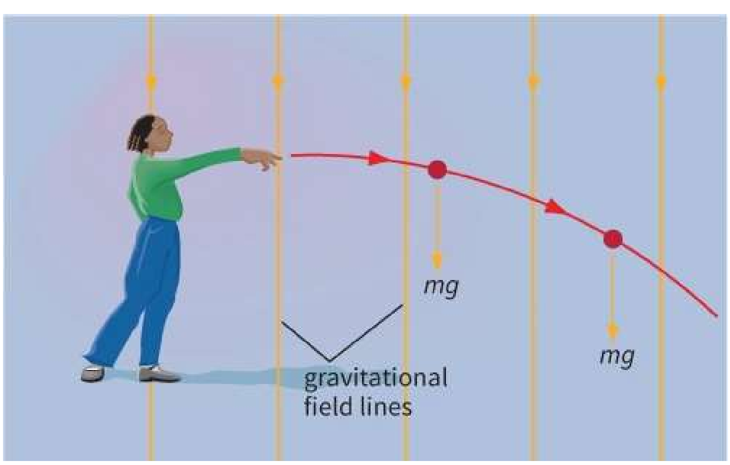

Figure 21.15: A ball, thrown in the uniform gravitational field of the Earth, follows a parabolic path.

Questions

9 In Figure 21.16, two parallel plates are shown, separated by 25 cm.

a Copy the diagram and draw field lines to represent the field between the plates.

b What is the potential difference between points A and B?

c What is the electric field strength at C, and at D?

d Calculate the electric force on a charge of +5 μC placed at C. In which direction does the force act?

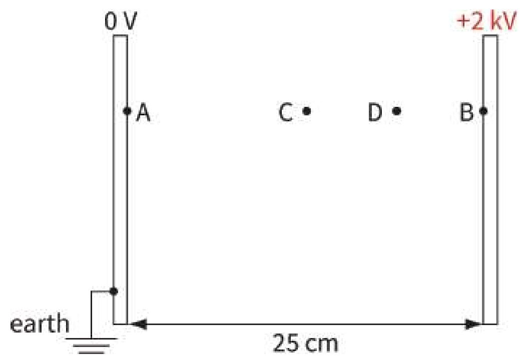

Figure 21.16: Two parallel, charged plates.

10 A particle of charge +2 μC is placed between two parallel plates, 10 cm apart and with a potential difference of 5 kV between them. Calculate the field strength between the plates, and the force exerted on the charge.

11 We are used to experiencing accelerations that are usually less than 10 m s^{-2}. For example, when we fall, our acceleration is about 9.81 m s^{-2}. When a car turns a corner sharply at speed, its acceleration is unlikely to be more than 5 m s^{-2}. However, if you were an electron, you would be used to experiencing much greater accelerations than this. Calculate the acceleration of an electron in a television tube where the electric field strength is 50 000 V cm^{-1}. (Electron charge $-e = -1.6 \times 10^{-19}$ C; electron mass $m_e = 9.11 \times 10^{-31}$ kg.)

12 a Use a diagram to explain how the electric force on a charged particle could be used to separate a beam of electrons (e^-) and positrons (e^+) into two separate beams. (A positron is a positively charged particle that has the same mass as an electron but opposite charge. Positron–electron pairs are often produced in collisions in a particle accelerator.)

b Explain how this effect could be used to separate ions that have different masses and charges.

REFLECTION

When charged particles pass through a uniform electric field they are deflected.

On what factors does the deflection depend? How could this be used to compare masses of different ions? What variables must be kept the same or constant in order to give a fair comparison?

What would you do differently if you were to approach this same problem again?

SUMMARY

An electric field is a field of force, created by electric charges, and can be represented by electric field lines.

The strength of the field is the force acting per unit positive charge on a stationary positive charge at a point in the field:

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

In a uniform field (e.g. between two parallel charged plates), the force on a charge is the same at all points; the strength of the field is given by:

$$E = -\frac{\Delta V}{\Delta x}$$

An electric charge moving initially at right-angles to a uniform electric field follows a parabolic path.

EXAM-STYLE QUESTIONS

1 A pair of charged parallel plates are arranged horizontally in a vacuum.

The upper plate carries a negative charge and the lower plate is earthed.

An electron enters the space between the plates at right angles to the electric field.

In which direction is the electric field between the plates and in which direction is the force on the electron? **[1]**

	Electric field strength	**Force on the electron**
A	downwards towards the lower plate	downwards towards the lower plate
B	downwards towards the lower plate	upwards towards the upper plate
C	upwards towards the upper plate	downwards towards the lower plate
D	upwards towards the upper plate	upwards towards the upper plate

Table 21.1

2 A pair of charged parallel plates are 2.0 cm apart and there is a potential difference of 5.0 kV across the plates.

A charged ion between the plates experiences a force of 1.2×10^{-13} N due to the field.

What is the charge on the ion? **[1]**

A 1.6×10^{-19} C

B 4.8×10^{-19} C

C 2.5×10^{-15} C

D 4.0×10^{-6} C

3 Figure 21.4 shows apparatus used to investigate the field between a pair of charged, parallel plates.

a Explain why the piece of gold foil deflects in the manner shown. **[1]**

b State and explain what would be observed if the gold foil momentarily touched the negatively charged plate. **[2]**

[Total: 3]

4 A charged dust particle in an electric field experiences a force of 4.4×10^{-13} N. The charge on the particle is 8.8×10^{-17} C. Calculate the electric field strength. **[2]**

5 Calculate the potential difference that must be applied across a pair of parallel plates, placed 4 cm apart, to produce an electric field of 4000 V m^{-1}. **[2]**

6 A potential difference of 2.4 kV is applied across a pair of parallel plates. The electric field strength between the plates is 3.0×10^4 V m^{-1}.

a Calculate the separation of the plates. **[2]**

b The plates are now moved so that they are 2.0 cm apart. Calculate the electric field strength produced in this new position. **[2]**

[Total: 4]

7 A variable power supply is connected across a pair of parallel plates. The potential difference across the plates is doubled and the distance between the plates is decreased to one-third of the original. State by what factor the electric field changes. Explain your reasoning. **[3]**

8 This diagram shows a positively charged sphere hanging by an insulating thread close to an earthed metal plate.

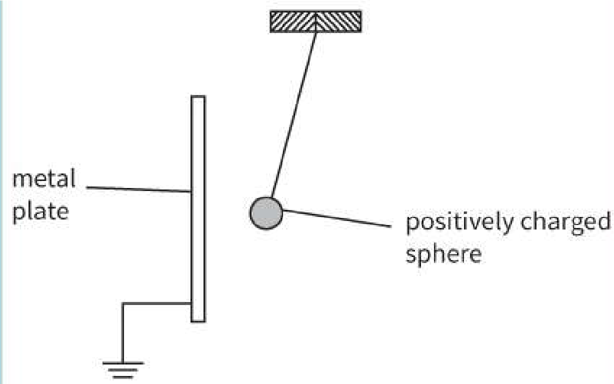

Figure 21.17

a Copy the diagram and draw five lines to show the electric field near the plate and the sphere. **[3]**

b Explain why the sphere is attracted towards the metal plate. **[2]**

c The sphere is now replaced with a similar negatively charged sphere.

i Explain what would be observed when the sphere is brought near to the earthed metal plate. **[2]**

ii Describe any changes to the electric field that would occur. **[1]**

[Total: 8]

9 This diagram shows a proton as it moves between two charged parallel plates. The charge on the proton is $+1.6 \times 10^{-19}$ C.

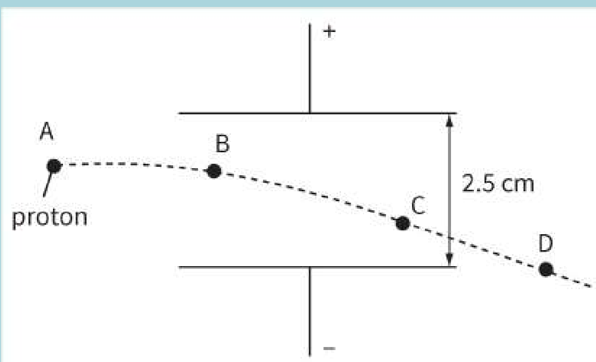

Figure 21.18

a Copy the diagram and draw the electric field between the parallel plates. **[2]**

The force on the proton when it is at position B is 6.4×10^{-14} N.

b In which direction does the force on the proton act when it is at position B? **[1]**

c What will be the magnitude of the force on the proton when it is at position C? **[1]**

d Calculate the electric field strength between the plates. **[2]**

e Calculate the potential difference between the plates. **[2]**

[Total: 8]

10 a Define what is meant by the electric field strength at a point. **[2]**

In a particle accelerator, a proton, initially at rest, is accelerated between two metal plates, as shown.

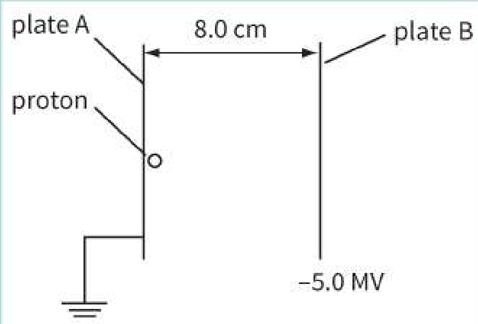

Figure 21.19

b Calculate the force on the proton due to the electric field. **[3]**

c Calculate the work done on the proton by the electric field when it moves from plate A to plate B. **[2]**

d State the energy gained by the proton. **[1]**

e Assuming that all this energy is converted to kinetic energy of the proton, calculate the speed of the proton when it reaches plate B. **[3]**

(Charge on a proton = $+1.6 \times 10^{-19}$ C; mass of a proton = 1.7×10^{-27} kg.)

[Total: 11]

11 a This diagram shows the structure of a spark plug in an internal combustion engine. The magnified section shows the end of the spark plug, with some of the lines of force representing the electric field.

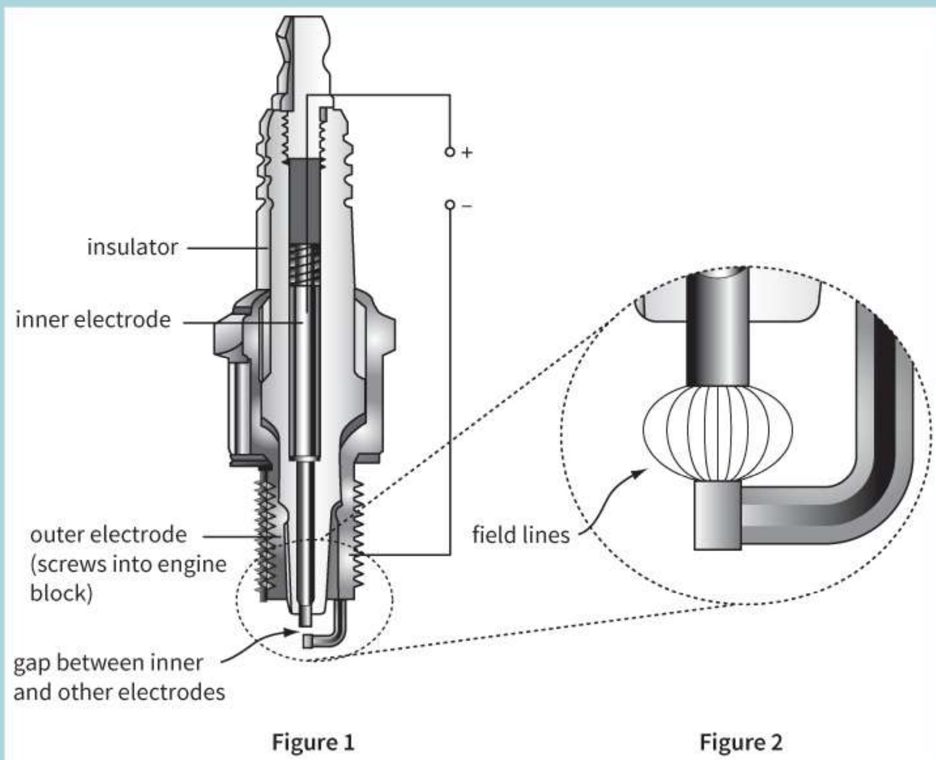

Figure 21.20

i Copy the field lines from the diagram. On your copy, draw arrows on the lines of force to show the direction of the field. **[1]**

ii What evidence does the diagram give that the field is strongest near the tip of the inner electrode? **[1]**

b The gap between the inner and outer electrodes is 1.25 mm and a field strength of 5.0×10^6 N C^{-1} is required for electrical breakdown. Estimate the minimum potential difference that must be applied across the inner and outer electrodes for a spark to be produced. (You may treat the two electrodes as a pair of parallel plates.) **[2]**

c When an electron is accelerated through a potential drop of approximately 20 V it will have sufficient energy to ionise a nitrogen atom. Show that an electron must move 4.0 μm to gain this energy. **[2]**

[Total: 6]