

**REMEMBER**

Before beginning this chapter, you should be able to:

- recognise that charged objects can experience forces of attraction and of repulsion
- apply the concepts of charge ( $Q$ ), current ( $I$ ), voltage ( $V$ ) and energy ( $U$ ) to electrical situations.

**KEY IDEAS**

After completing this chapter, you should be able to:

- describe electricity using a field model
- apply Coulomb's Law to the force between point charges

- describe the electric field around a point charge in terms of its direction and shape
- calculate the strength of the electric field at a point a distance,  $r$ , from a point charge
- describe potential energy changes of an object moving in the electric field of a point charge
- analyse the acceleration and potential energy changes of a charged particle in an uniform electric field.

The concept of the electric field allows us to make use of electricity to provide power and light. It also explains many physical phenomena.



## The long road to Coulomb's Law

You will probably have experienced a small electric shock when you touched a metal rail after walking across carpet. This phenomenon has been observed for thousands of years. Objects such as glass, gemstones and amber (petrified tree resin) can become 'electrified' by friction, when they are rubbed with materials such as animal fur and fabrics, producing a little spark. The Ancient Greek word for amber is *elektron*.

Investigators tried to explain the various manifestations of electricity, but an understanding of the phenomenon was elusive. Both attraction and repulsion were observed, but initially repulsion was considered less important. In 1551 Girolamo Cardano realised that this electrical attraction was different from magnetic attraction. In 1600 William Gilbert, the physician to Elizabeth I, found that other substances such as glass and wax could be 'electrified', but he concluded that metals could not. In 1729 Stephen Gray discovered that electric charge could pass through materials such as the human body and metals. He concluded that some objects are conductors and others insulators. In 1734 Charles du Fay showed that Gilbert was wrong about metals: they could be charged as long as the metal was in a handle of glass. However, du Fay thought there were two fluids, to explain the two types of charge, whereas Benjamin Franklin in 1746 suggested there was only one fluid. Objects with an excess of this fluid were designated positively charged, while negatively charged objects were deficient in the fluid.

Experiments continued, not only to identify what electricity was, but also to determine how strong the electric force was and what affected its strength.

In 1766 Franklin tried an experiment involving a hollow metal sphere with a small hole. He charged up the sphere and then lowered a small cork carrying an electric charge inside the sphere. Nothing happened to it — it was not pushed around, no matter where he placed the test charge. He wrote about this to his friend Joseph Priestley in England. Priestley was aware of Newton's Law of Universal Gravitation, which is an inverse square law ( $F \propto \frac{1}{r^2}$ ). He also knew that Newton had proved mathematically that because of the inverse square law, no net gravitational force exists inside a hollow sphere. That is, at every point inside the sphere, the gravitational force from the mass on one side is balanced by the force from the mass on the other side.

Priestley confirmed Franklin's results and realised that this was strong evidence that the inverse square law applied to electricity. In 1767 he published his finding that electric force was an inverse square law. Unfortunately, his paper went unnoticed by other scientists of his time.

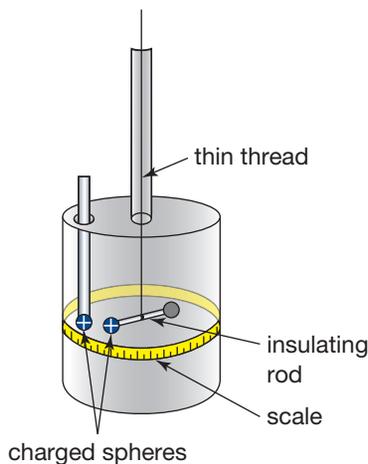
If the force between two charges was an inverse square law, that is,  $F \propto \frac{1}{r^n}$  where  $n = 2$ , could the value of  $n$  be experimentally confirmed?

In 1769 John Robison investigated how the force between charges changed with separation. He determined the value of the power,  $n$ , to be 2.06, very close to 2. In the 1770s Henry Cavendish measured the value as between 1.96 and 2.04, but he never published his results.

In 1788 and 1789 Charles-Augustin de Coulomb published a series of 8 papers on different aspects of his electrical experiments, showing that the electric force satisfied the inverse square law.

**TABLE 5.1** The results of some of Coulomb's experiments

Observed force	Distance	
	Observed	Calculated from the inverse square law
36 units	36 units	36 units
144 units	18 units	18 units
576 units	8.5 units	9 units



Coulomb's torsion balance

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**Electric force**

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Topic 2

Concept 1

Quantity

Charge

Symbol

$Q$

Unit

Coulomb, C

Example

$Q = 5.0 \text{ C}$

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#### Interactivity

Doing the twist  
int-6608

These results are no better than the earlier ones, so why was Coulomb's Law named after him?

Coulomb's papers were excellent examples of scientific writing. They were well organised and thorough. He described his apparatus in detail, and he discussed possible sources of error in his measurements. He also used two different methods to determine the value of  $n$ , obtaining the same result with each.

To investigate the force between two charges, Coulomb designed a torsion balance. His torsion balance had a long silk thread hanging vertically with a horizontal rod attached at the end. On one end of the rod was a small metal-coated sphere. On the other end was a sphere of identical mass to keep the rod level. The metal sphere was given a quantity of charge and a second metal sphere, charged with the same type of charge, was lowered to be in line with the first sphere. The electrical repulsion caused the silk thread to twist slightly. The angle of twist or deflection of the rod was a measure of the strength of the repulsive force.

Coulomb was able to measure the force to an accuracy of less than a millionth of a Newton.

*Coulomb's Law: The force between two charges at rest is directly proportional to the product of the magnitudes of the charges and inversely proportional to the square of the distance between them.*

$$F \propto \frac{q_1 q_2}{r^2}$$

This expression has no equals sign; it is not an equation or formula. Coulomb was able to measure the force and separation very accurately, but charge was such a new concept that there were no units to measure it. Coulomb was only able to show that halving the size of each charge reduced the size of the force by a quarter.

It was not until the unit for current, the ampere, was defined and precisely measured that a unit for charge could be defined and calculated using the relationship charge = current  $\times$  time ( $Q = I \times t$ ). This unit was called the coulomb after Charles-Augustin de Coulomb. One coulomb of charge equals the amount of charge that is transferred by one ampere of current in one second.

A coulomb of charge is a large quantity of charge. For example, the amount of charge transferred when fur is rubbed against a glass rod is a few millionths of a coulomb. In a typical lightning strike, about 20 coulombs of charge is transferred, whereas in the lifetime of an AA battery, about 5000 coulombs passes through the battery.

When the electron was discovered, its charge was determined as  $1.602 \times 10^{-19}$  coulombs, which means that the total charge of  $6.241 \times 10^{18}$  electrons would equal one coulomb.

Once a unit to measure charge was available, the above relationship for the force between charges could be written as an equation with a proportionality constant,  $k$ :

$$F = \frac{kq_1 q_2}{r^2}$$

where  $k$  is a constant with a value of  $8.988 \times 10^9 \text{ N m}^2 \text{ C}^{-2}$ . (In fact, it only has this value if there is a vacuum between the charges. Air has a similar value, but if the charges are immersed in any other substance, the force is reduced.)

For ease of calculation and remembering, the value of  $k$  is usually approximated to  $9.0 \times 10^9 \text{ N m}^2 \text{ C}^{-2}$ . This constant has no special name, unlike the constant in Newton's Law of Universal Gravitation. It goes by various names, such as 'the electric force constant' and 'Coulomb's constant'.

## Electric fields

Attraction and repulsion between charges occurs without the need for contact. There is 'action at a distance'. To explain such interactions, Michael Faraday (1791–1867) proposed the concept of a 'field'. In the case of an electric charge, there was an electric field in the space around the charge such that if a second charge was placed in that space, it would experience an electrical force. The electric field at that point interacts directly with this second charge to produce a force.

If the first charge is represented by  $Q$  and the second charge is a small test charge,  $q$ , then the force is given by  $F = \frac{kQq}{r^2}$ . The strength of the electric field,  $E$ , is defined by the force on the small test charge divided by the size of the test charge, or force per unit charge, and the unit for electric field is Newtons per coulomb or  $\text{N C}^{-1}$ :

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

$$E = \frac{\left(\frac{kQq}{r^2}\right)}{q}$$

$$E = \frac{kQ}{r^2}$$

This is a similar situation to the expressions for gravitational field.

**TABLE 5.2** Comparison between expressions for electric and gravitational fields

Force and field between masses	Force and field between charges
$F_g = \frac{Gm_1m_2}{r^2}$	$F = \frac{kq_1q_2}{r^2}$
$F_g = mg$	$F = qE$
$g = \frac{GM}{r^2}$	$E = \frac{kQ}{r^2}$

However, electrical interactions are different from gravitational interactions in that electric charges can attract and repel. There are two types of charge, positive and negative, with like charges repelling each other and unlike charges attracting.

### Drawing an electric field

When we draw a gravitational field, the field lines indicate the direction in which a mass would move. But for an electric field, because there are two types of charge, a convention is needed so that we can correctly interpret field diagrams. The convention is that the direction of the field is the direction in which a positive charge would move. This is shown in the following diagrams.

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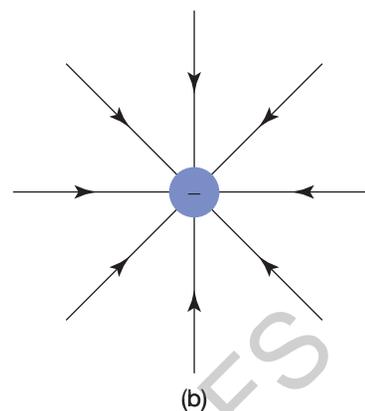
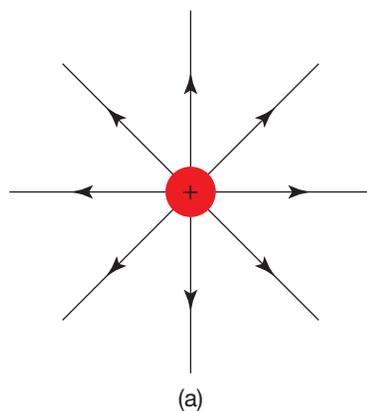
**Field around a point mass and point charge**

AOS 1

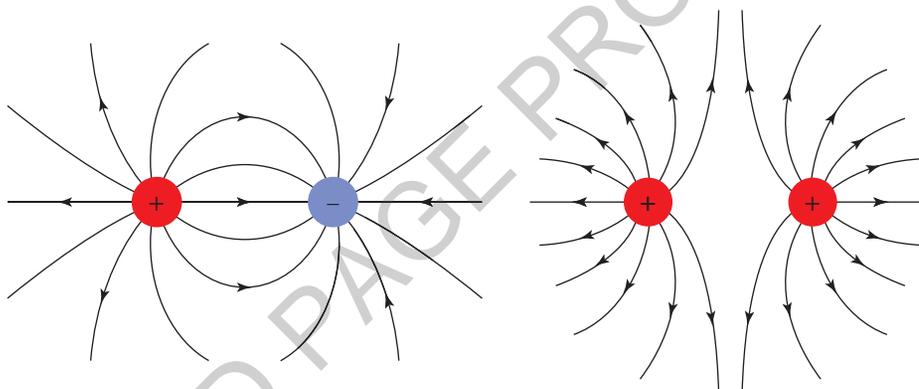
Summary screen and practice questions

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Fields around (a) a positive charge and (b) a negative charge



Fields around (a) a positive and negative charge of equal quantity, and (b) two positive charges of equal value. Close spacing of field lines indicates a strong field. Diverging lines indicate the field is weaker.

### Revision question 5.1

Draw the electrical fields around the following configurations.

- (a) Two separated negative charges
- (b) Two positive charges and two negative charges at the corners of a square with like charges diagonally opposite each other

### Calculating the value of an electric field

The strength of an electric field can be determined from the equation  $E = \frac{kQ}{r^2}$ .

#### Sample problem 5.1

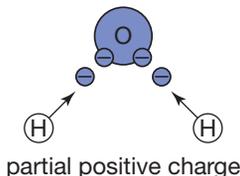
What is the magnitude and direction of the electric field at a point 30 cm left of a point charge of  $+2.0 \times 10^{-5}$  C?

**Solution:** Using  $E = \frac{kQ}{r^2}$ ,

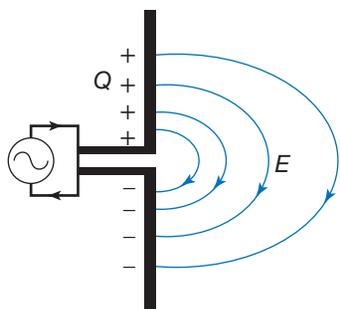
$$\begin{aligned} E &= \frac{9.0 \times 10^9 \text{ Nm}^2 \text{ C}^{-2} \times 2.0 \times 10^{-5} \text{ C}}{(30 \times 10^{-2} \text{ m})^2} \\ &= 2.0 \times 10^6 \text{ NC}^{-1}. \end{aligned}$$

Because the point charge is positive, the direction of the electric field is to the left.

partial negative charge



A water molecule ( $\text{H}_2\text{O}$ ) displays polarity because the shared electrons are attracted more strongly to the oxygen atom than to the hydrogen atoms.



Partial circuit diagram of an antenna

## Revision question 5.2

What is the magnitude and direction of the electric field at a point 50 cm right of a point charge of  $-3.0 \times 10^{-6} \text{ C}$ ?

## Dipole fields

When a positive charge and a negative charge are separated by a short distance, the electric field around them is called a dipole field. This concept is more relevant to magnetic fields, where the ends of a bar magnet have different polarities (north and south). However, electric dipoles do occur in nature.

Electric dipoles mainly occur with the shared electrons in the bonds between atoms in molecules. For example in a molecule of water,  $\text{H}_2\text{O}$ , the oxygen atom more strongly attracts the shared electrons than do each of the hydrogen atoms. This makes the oxygen end of the molecule more negatively charged and the hydrogen end more positively charged. Because of this, the water molecule is called a polar molecule. It is this polarity that makes water so good at dissolving substances.

An antenna can be described as a varying electric dipole. To produce a radio or a TV signal, electrons are accelerated up and down the antenna. At one moment the top may be negative and the bottom positive, then a moment later the reverse is the case.

## AS A MATTER OF FACT

### The structure of DNA and electrical attraction

A DNA molecule is a long chain molecule built from four small molecules: adenine (A), cytosine (C), guanine (G) and thymine (T). These are arranged along the DNA molecule according to a code called the genetic code. Different sequences of A, C, G and T code for different amino acids, which are combined one after the other to produce different protein molecules. Two DNA molecules wrap around each other in a spiral to produce a double-helix chromosome.

The two DNA molecules in the helix are held together by electrical attraction between the polar ends of the four small molecules, A, C, G, and T. The chromosome is able to replicate itself because A and T can only pair up with each other, and likewise C and G can only pair up with each other. If there is an A on one strand, there must be a T immediately opposite on the other strand, and so on.

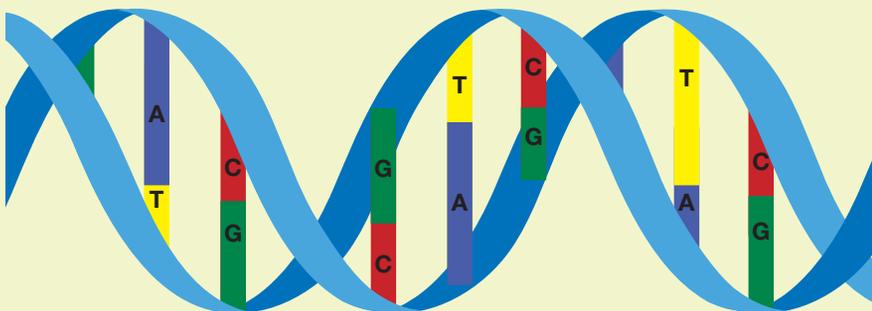
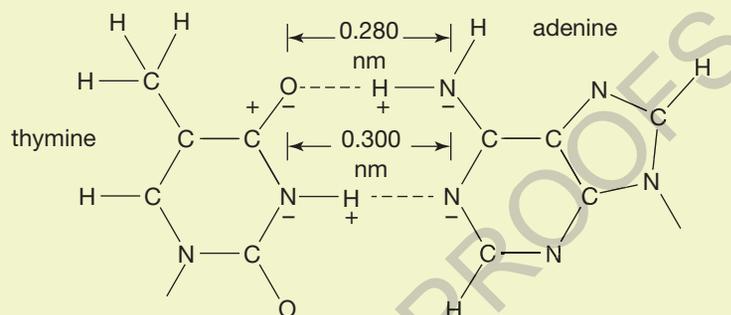


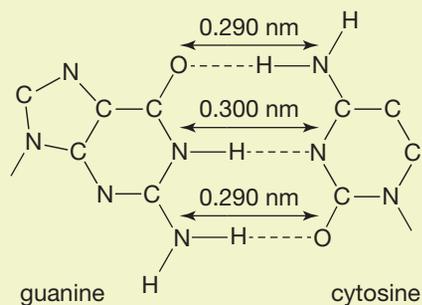
Figure 1 Electrical attraction in a DNA molecule

Figure 2 shows that one of the oxygen atoms in the thymine molecule is slightly negative, and one of the hydrogen atoms in the adenine molecule is slightly positive. Similarly, a hydrogen atom in the thymine molecule is slightly positive, and a nitrogen atom in the adenine molecule is slightly negative. These two slight electrical attractions are enough to hold these two molecules together, and the separations across these weak bonds are comparable in length.



**Figure 2** Electrical attraction between thymine and adenine molecules

Guanine and cytosine have a similar arrangement, except that there are three pairs of electrical attraction. Most importantly, the separations of the weak bonds between guanine and cytosine are comparable to each other and also to those of adenine and thymine. Without this matchup of separations, a chromosome could not hold together, nor could it form a double helix.



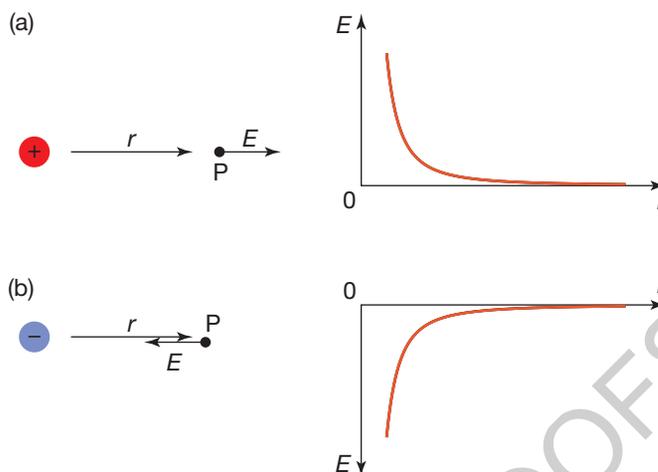
**Figure 3** Electrical attraction between guanine and cytosine molecules

## Graphing the electric field

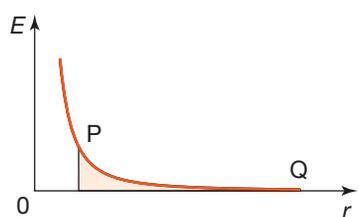
The direction of the electric field is the direction in which a positive test charge would move.

For a central positive charge, the direction of the electric field vector at a point P is in the same direction as the distance vector to the point P. This means the graph of the electric field with distance is above the distance axis.

For a central negative charge, the direction of the electric field vector is in the opposite direction to the radius vector, so the graph of the electric field around a negative charge will be below the distance axis.



Diagrams and field–distance graphs for the electric field around (a) a positive charge and (b) a negative charge



A field–distance graph for a positive charge at P near a central positive charge at Q

## Changes in potential energy and kinetic energy in an electric field

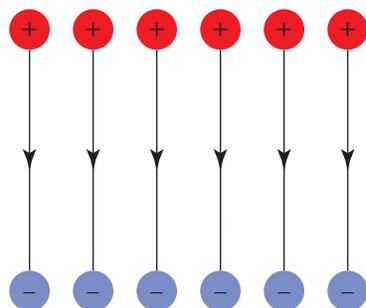
A small positive charge is placed at point Q, some distance from a central positive charge. To move the charge to point P, you will need to push inwards against the repulsive electrical force. At point P the small charge will have electrical potential energy, like a compressed spring. The amount of potential energy it has will be equal to the area under the field–distance graph times its charge. If the small charge was released, all this potential energy would be converted into kinetic energy by the time the charge reached Q.

If instead a small negative charge was placed at Q, it would experience an attractive electrical force, and when the charge reached P, the shaded area would represent its gain in kinetic energy.

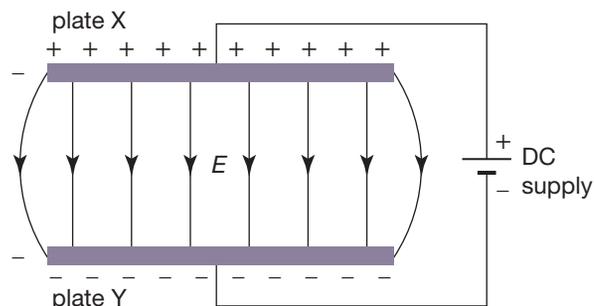
## Uniform electric fields

If a set of positive and negative charges were lined up in two rows facing each other, the lines of electric field in the space between the rows would be evenly spaced, that is, the value of the strength of the field would be constant. This is called a uniform electrical field.

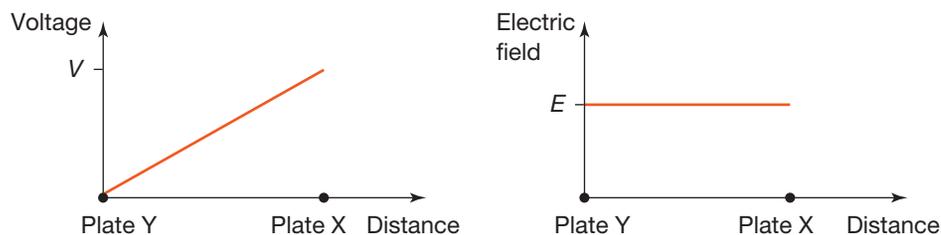
It is also very easy to set up. Just set two metal plates a few centimetres apart, then connect one plate to the positive terminal of a battery and connect the other plate to the negative terminal of the battery. The battery will transfer electrons from one plate, making it positive, and put them on the other, making that one negative. The battery will keep on doing this until the positive plate is so positive that the battery's voltage, or the energy it gives to each coulomb of electrons, is insufficient to overcome the attraction of the positive charged plate. Similarly, the negatively charged plate will become so negative that the repulsion from this plate prevents further electrons being added.



A uniform electric field



An electric field between two plates



Electric field strength equals the gradient of the voltage–distance graph.

If a space contains a uniform field, that means that if a charge was placed in that space it would experience a constant electric force,  $F = Eq$ . The direction of the force on a positive charge will be in the direction of the field, and the force on a negative charge will be opposite to the field direction. Also, because the force is constant, the acceleration will be constant. As we will see later, the situation with a charged particle in the space between the plates in the figure above is similar to the vertical motion under gravity. Indeed, if a charged particle is injected with speed into the field from one side, its subsequent motion is similar to projectile motion.

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**Electric fields**

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**Change in potential energy**

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### What is the strength of a uniform electric field?

In the situation of an electric field between two plates, it is not easy to apply Coulomb's Law, as there are many charges on each plate interacting with each other. An alternative approach is needed — one that uses the concept of energy.

The emf of a battery, or its voltage, is the amount of energy that the battery gives to each coulomb of charge. A battery of  $V$  volts would use up  $V$  joules of energy transferring one coulomb of electrons from the top plate through the wires to the bottom plate. Once on the negative plate, this coulomb of electrons would have  $V$  joules of electrical potential energy.

If this coulomb of electrons could be released from the negative plate, it would be accelerated by the constant force of the electric field between the plates, gaining kinetic energy like a stone falling in a gravitational field. And as in a gravitational field, the gain in kinetic energy equals the loss in electrical potential energy.

The gain in kinetic energy of one coulomb of charge =  $V$  joules.

The gain in kinetic energy for  $q$  coulombs of charge =  $qV$  joules.

This is the relationship  $W = qV$ .

$$\text{Work done on } q \text{ coulombs of charge } (W) = \frac{\text{quantity of charge } (q)}{\text{charge } (q)} \times \text{voltage drop or potential difference } (V)$$

However, work done ( $W$ ) also has a definition of motion:

$$\text{Work done } (W) = \text{force } (F) \times \text{displacement } (d)$$

$$W = Fd$$

But the force, if it is an electrical force, is given by  $F = qE$ , so  $W = qE \times d$ , where  $d$  in this instance is the separation of the plates.

Equating the two expressions for work done,

$$qE \times d = q \times V$$

Cancelling the charge,  $q$ , gives

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

This provides an alternative unit for electric field of volts per metre or  $\text{V m}^{-1}$ . So, like gravitational field strength, electric field strength has two equivalent units: either newtons per coulomb or volts per metre. Using volts per metre makes it very easy to determine the strength of a uniform electric field.

### Sample problem 5.2

What is the strength of the electric field between two plates 5.0 cm apart connected to a 100 V DC supply?

**Solution:**  $V = 100 \text{ V}$ ,  $d = 5.0 \text{ cm} = 5.0 \times 10^{-2} \text{ m}$ ,  $E = ?$

$$\begin{aligned} E &= \frac{V}{d} \\ &= \frac{100 \text{ V}}{5.0 \times 10^{-2} \text{ m}} \\ &= 2000 \text{ V m}^{-1} \end{aligned}$$

### Revision question 5.3

- Calculate the strength of the electric field between a storm cloud 1.5 km above ground and the ground itself if the voltage drop or potential difference is 30 000 000 V. Assume a uniform field.
- How would the strength of the electric field change if the storm cloud was higher?

In developing the expression for the strength of a uniform electric field, the relationship  $W = Vq$  was used. The implication of  $W = Vq$  is that the energy gained by a charge in moving across the gap between the plates only depends on the voltage drop or the potential difference across them. It does not depend on the separation of the plates. This does not seem right, because if the plates are further apart, the electric field is weaker by  $E = \frac{V}{d}$ , so the force and the acceleration will be less.

The explanation is that although the force may be less when the plates are further apart, the force acts on the charge over a greater distance. If the separation is doubled, the field strength and therefore the force is halved, but it acts over twice the distance.

Work done = force  $\times$  displacement

$$W = Fd$$

Using the definition of an electric field,  $F = qE$ , this becomes

$$W = qE \times d.$$

Using the alternative formula for electric field strength,  $E = \frac{V}{d}$ , this becomes

$$W = q \times \left( \frac{V}{d} \right) \times d.$$

Simplifying,

$$W = qV.$$

### An electric field as a particle accelerator

An electric field can be used to increase the speed and kinetic energy of charged particles. This is the case in all of the devices in the following table.

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Unit 3

Work done by a uniform field

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Concept summary

Topic 2

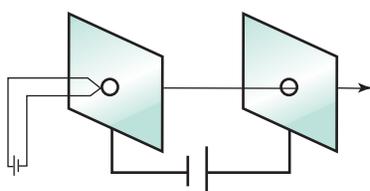
and practice

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**TABLE 5.3** Devices that use electric fields to accelerate charged particles

Device	Operation	Purpose
Mass spectrometer	Accelerate positive ions of different mass, which then enter a uniform magnetic field and curve around to hit a screen in different spots	To measure the abundance of different elements and isotopes in a sample
Electron microscope	Accelerate electrons, which then pass through electric and magnetic lenses to produce an image	To use an electron beam to examine very small objects
Synchrotron	Accelerate electrons close to the speed of light, then feed them into a storage ring	To produce intense and very narrow beams of mainly X-rays to examine the fine structure of substances such as proteins
Large Hadron Collider	Accelerate protons or lead ions close to the speed of light, then let them collide	To test the predictions of theories of particle physics, e.g. the existence of the Higgs boson



The electrons on the hot filament are attracted across to the positive plate and pass through the hole that is in line with the beam.

The first part of all of these devices is an **electron gun**, a device that is designed to produce electrons and then give them an initial acceleration.

The diagram shows two metal plates with a small hole cut in the middle of each plate. The plates have been connected to a DC power supply. In the hole of the negative plate is a filament of wire, like the filament in an incandescent light globe, connected to a low voltage. When the current flows in this circuit, the filament glows red hot. The electrons are, in a sense, ‘boiling at the surface’ of the filament. The electric field can easily pull the electrons off the surface of the filament.

The hole in the positive plate is in a direct line with the filament, so as the electrons are accelerated across the space between the plates, they go straight through the hole to the next part of the machine. This design is called an **electron gun**. It produces the electrons that generate the picture in a television tube, and it also produces the electrons for a synchrotron.

### Sample problem 5.3

An electron is accelerated from one plate to another. The voltage drop between the plates is 100 V.

- How much energy does the electron gain as it moves from the negative plate to the positive plate?
- How fast will the electron be travelling when it hits the positive plate, if it left the negative plate with zero velocity?

Use mass of electron =  $9.1 \times 10^{-31}$  kg, charge on electron =  $1.6 \times 10^{-19}$  C.

**Solution:**

$$\begin{aligned} \text{(a) } W &= Vq \\ &= 100 \text{ V} \times 1.6 \times 10^{-19} \text{ C} \\ &= 1.6 \times 10^{-17} \text{ J} \end{aligned}$$

Energy gained is  $1.6 \times 10^{-17}$  J.

- Energy is gained as kinetic energy.

$$\begin{aligned} E_k &= \frac{1}{2}mv^2 \\ 1.6 \times 10^{-17} \text{ J} &= \frac{1}{2} \times 9.1 \times 10^{-31} \text{ kg} \times v^2 \\ v^2 &= \frac{2 \times 1.6 \times 10^{-17} \text{ J}}{9.1 \times 10^{-31} \text{ kg}} \\ v &= 5.9 \times 10^6 \text{ m s}^{-1} \end{aligned}$$

The speed of the electron is  $5.9 \times 10^6 \text{ m s}^{-1}$  or  $5900 \text{ km s}^{-1}$ , which is about 2% of the speed of light.

## Revision question 5.4

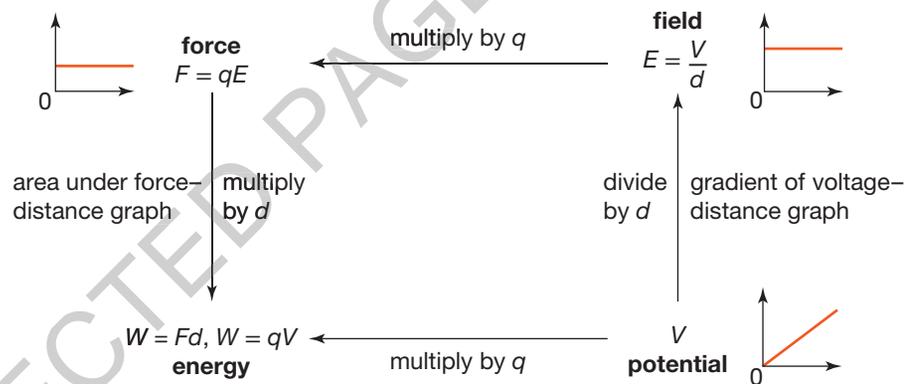
Repeat sample problem 5.3 but with a voltage drop of 1000 V.

Beyond an accelerating voltage of 1000 V, special relativity comes into play (as discussed in chapter 3). In relativistic situations, as the speed comes closer to the speed of light, the method shown above for determining the speed of the electron increasingly gives the wrong answer.

## Linking the concepts together

In this chapter, the four concepts of force, field, energy and potential have been used to explain electrical interactions and to calculate the values of various physical quantities. The significance of these concepts and their relationships is not only that the same concepts can be used for other fields, but that the relationships between the concepts are the same in different types of fields.

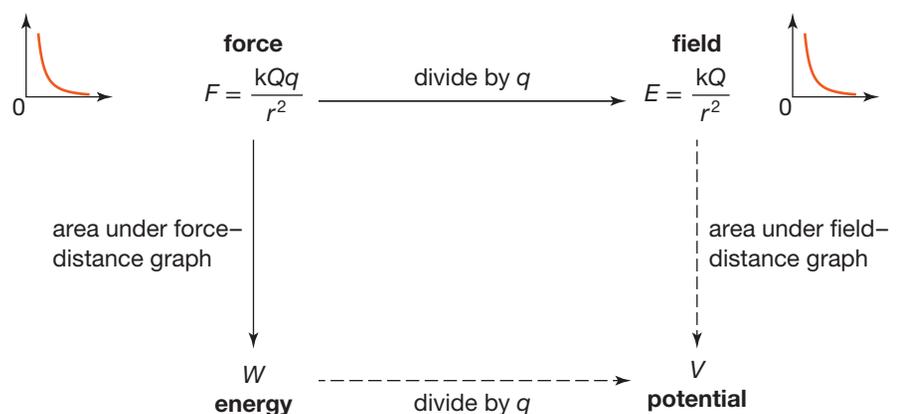
The relationships are best illustrated in a diagram. For example, consider a uniform electric field. If you start with the potential,  $V$ , in the bottom right corner, each of the other three quantities can be determined by the mathematical operations beside each arrow.



The relationships between force, field strength, energy and potential in a uniform electric field

Note that the descriptions for the down arrow on the left are the opposite mathematical operation to the descriptions for the up arrow on the right. 'Divide' is the opposite of 'multiply', and 'gradient' is the opposite of 'area under the graph'.

The same analysis can be applied to the electric field around a point charge. This time, start with force and Coulomb's Law.



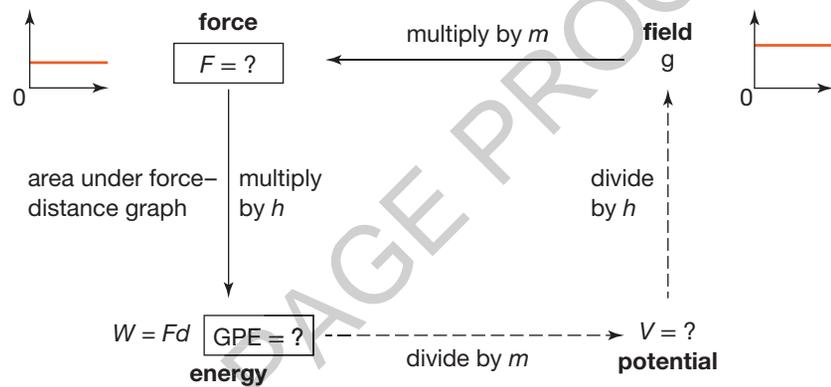
The relationships between force, field strength, energy and potential in an electric field around a point charge

The course covered by this textbook considers energy in non-uniform electric fields, such as the field around a point charge, in only a qualitative manner. Further study of electric fields will cover expressions for electrical potential energy and electric potential near a point charge.

These two diagrams for a uniform field and a non-uniform field also have their parallels in gravitation. The only change is to replace charge,  $q$  with mass,  $m$ .

### Revision question 5.5

As a revision exercise for gravitation, as well as to check on your understanding of the above diagrams, complete the following diagram for a uniform gravitational field, starting with  $g$ , the gravitational field strength.



The relationships between force, field strength, energy and potential in a uniform gravitational field

*Note:* The concept of gravitational potential is not of much use for calculations in a uniform gravitational field. This is because, unlike electrical technology, gravitation does not have a 'gravitational battery' that can deliver energy in joules per kilogram in the way a battery can supply joules per coulomb.



# Chapter review

## Summary

- Electric interactions between charges can be described with a field model.
- The electric field strength,  $E$ , at a distance  $r$  from an object with charge  $Q$  is given by the formula  $E = \frac{kQ}{r^2}$ , where  $k$  is the electric force constant. The electric force on an object with charge  $q$  is given by  $F = qE$  or  $F = \frac{kQq}{r^2}$ . This equation is referred to as Coulomb's Law.
- The electric field lines around a point charge describe the direction and shape of the field.
- The electric force between two charges can be attractive or repulsive, depending on whether the two charges are unlike or alike respectively. When two charges are held close together, there is potential energy stored in the electric field, and this potential energy is converted to kinetic energy when the charges are free to move.
- A uniform electric field exists between two metal plates connected to a DC supply. The strength of the electric field,  $E$ , is given by the voltage drop or potential difference across the plates,  $V$ , over the plate separation,  $d$ :  $E = \frac{V}{d}$ . This uniform field produces a constant force on a charge and thus a constant acceleration.
- The energy transferred to a charge  $q$  in moving from one plate to the other is given by  $W = Vq$ .

## Questions

### Electric force between point charges

1. What is the experimental evidence for there being two types of charge?
2. A and B are metal spheres  $x$  metres apart. Each has a charge of  $+q$  coulombs. The force they exert on each other is  $5.0 \times 10^{-4}$  newtons. Determine the magnitude of the force in each of the following situations. (Consider the situations separately.)
  - (a) The separation of A and B is increased to  $2x$  metres.
  - (b) A charge of  $+2q$  coulombs is added to B. Are the forces on A by B and on B by A still equal in magnitude?
  - (c) A charge of  $-3q$  coulomb is added to A.
  - (d) The distance is halved and the charges are changed to  $+0.5q$  on A and  $4q$  on B.
3. Find the force of repulsion between two point charges with charges of  $5.0$  microcoulombs ( $\mu\text{C}$ ) and  $7.0$  microcoulombs ( $\mu\text{C}$ ) if they are  $20$  cm apart.
4. If the force between two charges was  $400$  mN, how far apart would they need to be moved for the force to reduce by one-eighth?
5. How far apart would two charges, each of  $1.0$  coulomb, need to be to each experience an electric force of  $10$  N?
6. Two charged spheres are  $5.0$  cm apart, with one holding twice the amount of charge of the other. If the force between is  $1.5 \times 10^{-4}$  newtons, how much charge does each sphere have?
7. Two small spheres are placed with their centres  $20$  cm apart. The charges on each are  $+4.0 \times 10^{-8}$  C and  $+9.0 \times 10^{-8}$  C. Where between the two spheres would a test charge experience zero net force?
8. Coulomb's Law is very similar to Newton's Law of Universal Gravitation. How do these two laws differ? Compare electric charge and gravitational mass.
9. How many electrons would need to be removed from a coin to give it a charge of  $+10 \mu\text{C}$ ?
10. The radius of a hydrogen atom is  $5.3 \times 10^{-11}$  m. What is the strength of the electric force between the nucleus and the electron?
11. The nucleus of an iron atom has 26 protons, and the innermost electron is  $1.0 \times 10^{-12}$  m away from the nucleus. What is the strength of the electric force between the nucleus and the electron?
12. The nucleus of a uranium atom has 92 protons, and the innermost electron is about  $5.0 \times 10^{-13}$  m away from the nucleus. What is the strength of the electric force between the nucleus and the electron?
13. How close must two electrons be for the electric repulsion force to equal the gravitational attraction force? How close must two protons be?
14. A proton is made up of two 'up' quarks of charge  $+\frac{2e}{3}$  and one 'down' quark of charge  $-\frac{1e}{3}$ . The diameter of a proton is about  $8.8 \times 10^{-16}$  m. Using the diameter as the maximum value for the separation of the two 'up' quarks, calculate the size of the electrical repulsion force between them.
15. What equal positive charge would the Earth and the Moon need to have for the electrical repulsion to balance the gravitational attraction? Why don't you need to know separation of the two objects?

16. What is the charge in coulombs of  $10 \text{ kg}$  of electrons?
17. One example of alpha decay is uranium-238 decaying to thorium-234. The thorium nucleus has 90 protons and the alpha particle has two protons. At a moment just after the ejection of the alpha particle, their separation is about  $9.0 \times 10^{-15} \text{ m}$ . What is the size of the electrical repulsion force between them, and what is the acceleration of the alpha particle at this point?
18. What is the size of the electric force between a positive sodium ion ( $\text{Na}^+$ ) and a negative chloride ion ( $\text{Cl}^-$ ) in a NaCl crystal if their spacing is  $2.82 \times 10^{-10} \text{ m}$ ?
19. An electric force of  $1.5 \text{ N}$  acts upwards on a charge of  $+3.0 \mu\text{C}$ . What is the strength and direction of the electric field?
20. An electric force of  $3.0 \text{ N}$  acts downwards on a charge of  $-1.5 \mu\text{C}$ . What is the strength and direction of the electric field?
21. A proton is suspended so that it is stationary in an electric field. Using the value of  $g = 10 \text{ m s}^{-2}$ , determine the strength of the electric field.
22. Use the statement 'the electric force exerted by a charged object A on a charged object B is proportional to the charge on B' and Newton's Third Law to show that the electric force between the two charges is proportional to the **product** of the charges.

### Electric fields of point charges

23. Electric field lines can never cross. Why?
24. If a charged particle is free to move, will it move along an electric field line?
25. Two charged objects, A and B, are held a short distance apart. Which object is the source of the electric field that acts on B?
26. One of the units for gravitational field is that of acceleration. Is that also true for electric field? If not, why not?
27. Sketch the electric field around two positive charges, A and B, where the charge on A is twice that on B.
28. Sketch the electric field around a positively charged straight plastic rod. Assume the charge is distributed evenly. Sketch the electric field as if the rod had a curve in it. If the plastic rod was bent into a closed circle, what would be the strength of the electric field in the middle?
29. A negative test charge is placed at a point in an electric field. It experiences a force in an easterly direction. What is the direction of the electric field at that point?
30. Two small spheres, A and B, are placed with their centres  $10 \text{ cm}$  apart. P is  $2.5 \text{ cm}$  from A. What is the direction of the electric field at P in the following situations?
- (a) A and B have the same positive charge.
- (b) A has a positive charge, B has a negative charge and the magnitudes are the same.
31. Determine the strength of the electric field  $30 \text{ cm}$  from a charge of  $120 \mu\text{C}$ .
32. What is the strength of the electric field  $1.0 \text{ mm}$  from a proton?

### Uniform electric fields

33. Two metal plates, X and Y, are set up  $10 \text{ cm}$  apart. The X plate is connected to the positive terminal of a  $60 \text{ V}$  battery and the Y plate is connected to the negative terminal. A small positively charged sphere is suspended midway between the plates and it experiences a force of  $4.0 \times 10^{-3} \text{ newtons}$ .
- (a) What would be the size of the force on the sphere if it was placed  $7.5 \text{ cm}$  from plate X?
- (b) The sphere is placed back in the middle and the plates are moved apart to a separation of  $15 \text{ cm}$ . What is the size of the force now?
- (c) The plates are returned to a separation of  $10 \text{ cm}$  but the battery is changed. The force is now  $6.0 \times 10^{-3} \text{ newtons}$ . What is the voltage of the new battery?
34. Electrons from a hot filament are emitted into the space between two parallel plates and are accelerated across the space between them.
- (a) Which battery supplies the field to accelerate the electrons?
- (b) How much energy would be gained by an electron in crossing the space between the plates?
- (c) How would your answer to (b) change if the plate separation was halved?
- (d) How would your answer to (b) change if the terminals of the  $6 \text{ V}$  battery were reversed?
- (e) How would your answer to (b) change if the terminals of the  $100 \text{ V}$  battery were reversed?
- (f) How would the size of the electric field between the plates, and thus the electric force on the electron, change if the plate separation was halved?
- (g) Explain how your answers to (c) and (f) are connected.
35. (a) Calculate the acceleration of an electron in a uniform electric field of strength  $1.0 \times 10^6 \text{ N C}^{-1}$ .
- (b) Starting from rest, how long would it take for the speed of the electron to reach 10% of the speed of light? (Ignore relativistic effects.)
- (c) What distance would the electron travel in that time?

(d) If the answer to (c) was the actual spacing of the plates producing the electric field, what was the voltage drop or potential difference across the plates?

36. In an inkjet printer, small drops of ink are given a controlled charge and fired between two charged plates. The electric field deflects each drop and thus controls where the drop lands on the page.

Let  $m$  = the mass of the drop,  $q$  = the charge of the drop,  $v$  = the speed of the drop,  $l$  = the horizontal length of the plate crossed by the drop, and  $E$  = electric field strength.

- (a) Develop an expression for the deflection of the drop. *Hint:* This is like a projectile motion question.
- (b) With the values  $m = 1.0 \times 10^{-10}$  kg,  $v = 20$  m s<sup>-1</sup>,  $l = 1.0$  cm and  $E = 1.2 \times 10^6$  N C<sup>-1</sup>, calculate the charge required on the drop to produce a deflection of 1.2 mm.

