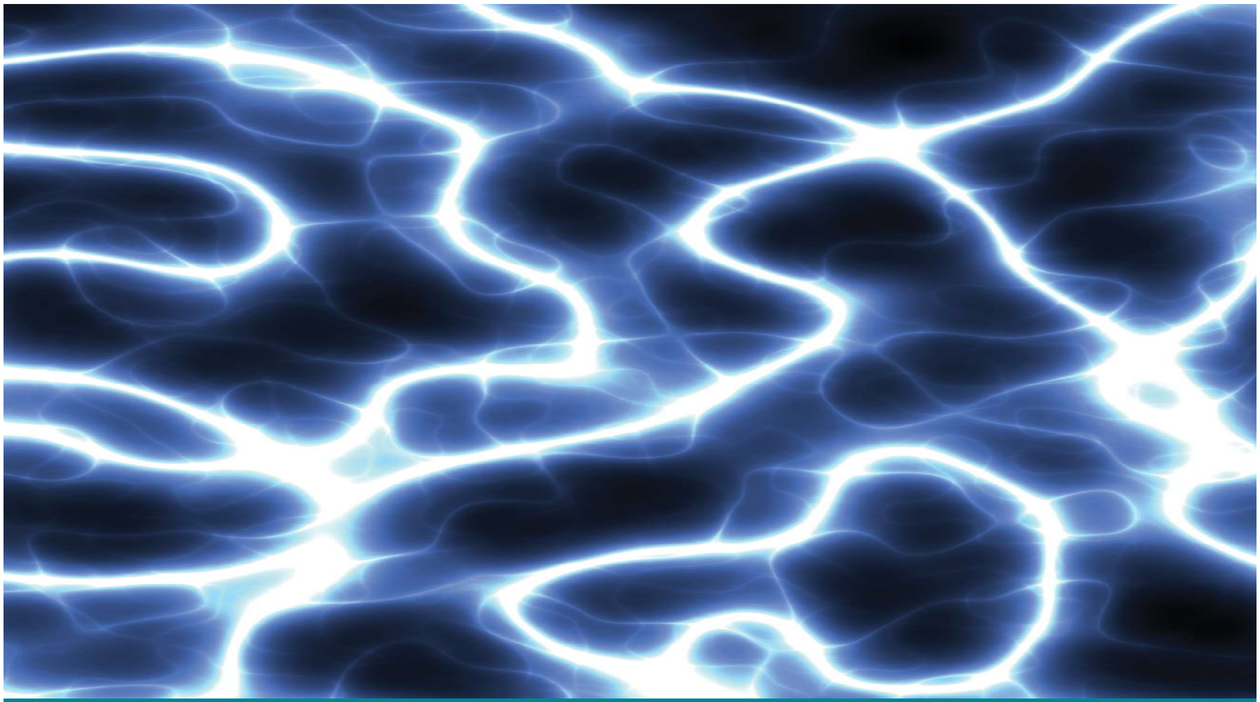


Chapter 22

Coulomb's law

LEARNING INTENTIONS

In this chapter you will learn how to:

- recall and use Coulomb's law
- calculate the field strength for a point charge
- recognise that for the electric field strength for a point outside a spherical conductor, the charge on the sphere may be considered to be a point charge at the centre of the sphere
- define electric potential
- calculate potential due to a point charge
- relate field strength to the potential gradient
- compare and contrast electric and gravitational fields.

BEFORE YOU START

- Cut a piece of paper into very small pieces. Rub a plastic rod (or comb) on your sleeve. Move it towards the pieces of paper. You should observe that the pieces of paper jump up and attach themselves to the comb. Hold the plastic rod still for a few minutes and you should observe something quite surprising.
- Write down what you observe and an explanation as to why this happened. Discuss your results with a fellow learner. Did they observe the same phenomenon? Did they come up with the same explanation?

LIVING IN A FIELD

The scientist in the Figure 22.1 is using a detector to measure the electric field produced by a mobile phone mast. People often worry that the electric field produced by a mobile phone transmitter may be harmful, but detailed studies have yet to show any evidence for this. If you hold a mobile phone close to your ear, the field strength will be far greater than that produced by a nearby mast.

With 5G being rolled out in various countries, what effect will this have on the local environment? Will it mean more masts and relay stations? Will copper cables be able to cope with the speed of the transmission of data needed to make 5G worthwhile? Will the investment needed to introduce 5G cause prices to rise for all customers?

Figure 22.1: Mobile phone masts produce weak electric fields – this scientist is using a small antenna to detect and measure the field of a nearby mast to ensure that it is within safe limits.

22.1 Electric fields

In Chapter 21, we presented some fundamental ideas about electric fields:

- An electric field is a field of force and can be represented by field lines.
- The electric field strength at a point is the force per unit positive charge that acts on a stationary charge:

$$\begin{aligned} \text{field strength} &= \frac{\text{force}}{\text{charge}} \\ E &= \frac{F}{Q} \end{aligned}$$

- There is a uniform field between charged parallel plates:

$$\begin{aligned} \text{field strength} &= \frac{\text{potential difference}}{\text{seperation}} \\ E &= \frac{V}{d} \end{aligned}$$

In this chapter, we will extend these ideas to consider how electric fields arise from electric charges. We will also compare electric fields with gravitational fields (Chapter 17).

22.2 Coulomb's law

Any electrically charged object produces an electric field in the space around it. It could be something as small as an electron or a proton, or as large as a planet or star. To say that it produces an electric field means that it will exert a force on any other charged object that is in the field. How can we determine the size of such a force?

The answer to this was first discovered by Charles Coulomb, a French physicist. He realised that it was important to think in terms of **point charges**; that is, electrical charges that are infinitesimally small so that we need not worry about their shapes. In 1785, Coulomb proposed a law that describes the force that one charged particle exerts on another. This law is remarkably similar in form to Newton's law of gravitation.

Coulomb's law states that any two point charges exert an electrical force on each other that is proportional to the product of their charges and inversely proportional to the square of the distance between them.

We consider two point charges Q_1 and Q_2 separated by a distance r (Figure 22.2). The force each charge exerts on the other is F. According to Newton's third law of motion, the point charges interact with each other and therefore exert equal but opposite forces on each other.

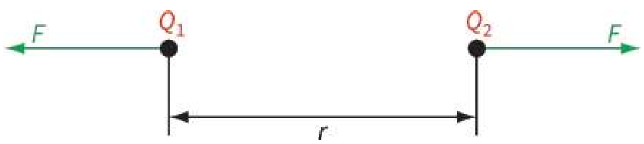


Figure 22.2: The variables involved in Coulomb's law.

According to Coulomb's law, we have:

$$\begin{aligned} \text{force} &\propto \text{product of the charges} \\ F &\propto Q_1 Q_2 \end{aligned}$$

$$\begin{aligned} \text{force} &\propto \frac{1}{\text{distance}^2} \\ F &\propto \frac{1}{r^2} \end{aligned}$$

Therefore:

$$F \propto \frac{Q_1 Q_2}{r^2}$$

We can write this in a mathematical form:

$$F = \frac{k Q_1 Q_2}{r^2}$$

where k is the constant of proportionality.

This constant k is usually given in the form:

$$k = \frac{1}{4\pi\varepsilon_0}$$

where ε_0 is known as the **permittivity of free space** (ε is the Greek letter epsilon). The value of ε_0 is approximately 8.85×10^{-12} F m^{-1}. An equation for Coulomb's law is thus:

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

where F is the force between two charges, Q_1 and Q_2, and r is the distance between their centres.

KEY EQUATION

Coulomb's law:

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

Following your earlier study of Newton's law of gravitation, you should not be surprised by this relationship. The force depends on each of the properties producing it (in this case, the charges), and it is an inverse square law with distance–if the particles are twice as far apart, the electrical force is a quarter of its previous value (Figure 22.3).

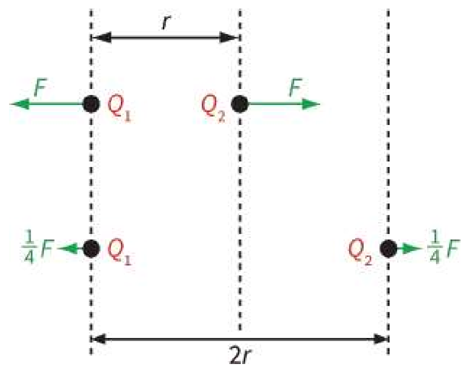


Figure 22.3: Doubling the separation results in one-quarter of the force, a direct consequence of Coulomb's law.

Note also that, if we have a positive and a negative charge, then the force F is negative. We interpret this as an attraction. Positive forces, as between two like charges, are repulsive. In gravity, we only have attraction.

So far, we have considered point charges. If we are considering uniformly charged spheres we measure the distance from the centre of one to the centre of the other – they behave as if their charge was all concentrated at the centre. Hence, we can apply the equation for Coulomb's law for both point charges (e.g. protons, electrons, etc.) and uniformly charged spheres, as long as we use the **centre-to-centre** distance between the objects.

PRACTICAL ACTIVITY 22.1

Investigating Coulomb's law

It is quite tricky to investigate the force between charged objects, because charge tends to leak away into the air or to the Earth during the course of any experiment. The amount of charge we can investigate is difficult to measure, and usually small, giving rise to tiny forces.

Figure 22.4 shows one method for investigating the inverse square law for two charged metal balls (polystyrene balls coated with conducting silver paint). As one charged ball is lowered down towards the other, their separation decreases and so the force increases, giving an increased reading on the balance.

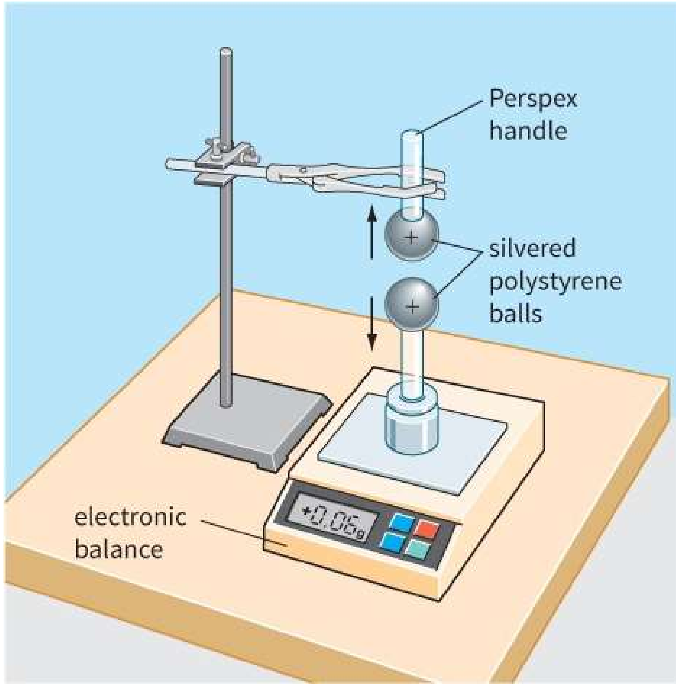


Figure 22.4: Investigating Coulomb's law.

22.3 Electric field strength for a radial field

In Chapter 21, we saw that the electric field strength at a point is defined as the force per unit charge exerted on a positive charge placed at that point, $E = \frac{F}{Q}$.

So, to find the field strength near a point charge Q_1 (or outside a uniformly charged sphere), we have to imagine a small positive test charge Q_2 placed in the field, and determine the force per unit charge on it. We can then use the definition to determine the electric field strength for a point (or spherical) charge.

The force between the two point charges is given by:

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

The electric field strength E due to the charge Q_1 at a distance of r from its centre is thus:

$$\begin{aligned} E &= \frac{\text{force}}{\text{test charge}} \\ &= \frac{Q_1 Q_2}{4\pi\varepsilon_0 r^2 Q_2} \\ &\equiv \frac{Q}{4\pi\varepsilon_0 r^2} \end{aligned}$$

where E is the electric field strength due to a point charge Q, and r is the distance from the point.

The field strength E is not a constant; it decreases as the distance r increases. The field strength obeys an inverse square law with distance–just like the gravitational field strength for a point mass. The field strength will decrease by a factor of four when the distance from the centre is doubled.

Note also that, since force is a vector quantity, it follows that electric field strength is also a vector. We need to give its direction as well as its magnitude in order to specify it completely. Worked example 1 shows how to use the equation for field strength near a charged sphere.

KEY EQUATION

Electric field strength:

$$E = \frac{Q}{4\pi\varepsilon_0 r^2}$$

WORKED EXAMPLE

1 A metal sphere of diameter 12 cm is positively charged. The electric field strength at the surface of the sphere is 4.0×10^5 V m^{-1}. Draw the electric field pattern for the sphere and determine the total surface charge.

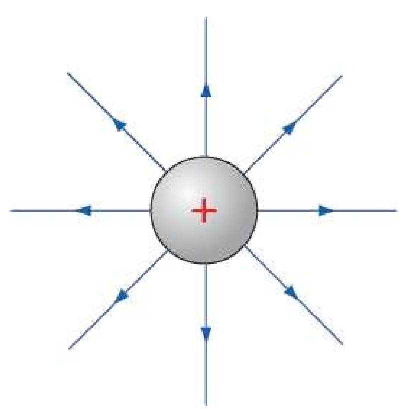


Figure 22.5: The electric field around a charged sphere.

Step 1 Draw the electric field pattern (Figure 22.5). The electric field lines must be normal to the surface and radial.

Step 2 Write down the quantities given:

electric field strength $E = 4.0 \times 10^5$ V m^{-1}

$$\text{radius } r = \frac{0.12}{2} = 0.06 \text{ m}$$

Step 3 Use the equation for the electric field strength to determine the surface charge:

$$E = \frac{Q}{4\pi\varepsilon_0 r^2}$$

$$Q = 4\pi\varepsilon_0 r^2 \times E$$

$$= 4\pi \times 8.85 \times 10^{-12} \times (0.06)^2 \times 4.0 \times 10^5$$

$$= 1.6 \times 10^{-7}\text{C}$$

$$\equiv 0.16\mu\text{C}$$

Questions

You will need the following data to answer the following questions. (You may take the charge of each sphere to be situated at its centre.)

$\varepsilon_0 = 8.85 \times 10^{-12}$ F m^{-1}

1 A metal sphere of radius 20 cm carries a positive charge of +2.0 μC.

a What is the electric field strength at a distance of 25 cm from the centre of the sphere?

b An identical metal sphere carrying a negative charge of −1.0 μC is placed next to the first sphere. There is a gap of 10 cm between them. Calculate the electric force that each sphere exerts on the other.

Remember to calculate the centre-to-centre distance between the two spheres.

c Determine the electric field strength midway along a line joining the centres of the spheres.

2 A Van de Graaff generator produces sparks when the field strength at its surface is 4.0×10^4 V cm^{-1}. If the diameter of the sphere is 40 cm, what is the charge on it?

22.4 Electric potential

When we discussed gravitational potential (Chapter 17), we started from the idea of potential energy. The potential at a point is then the potential energy of unit mass at the point. We will approach the idea of electrical potential in the same way. However, you may be relieved to find that you already know something about the idea of electrical potential, because you know about voltage and potential difference. This topic shows how we formalise the idea of voltage, and why we use the expression ‘potential difference’ for some kinds of voltage.

Electric potential energy

When an electric charge moves through an electric field, its potential energy changes. Consider this example: if you want to move one positive charge closer to another positive charge, you have to push it (Figure 22.6). This is simply because there is a force of repulsion between the charges. You have to do work in order to move one charge closer to the other.

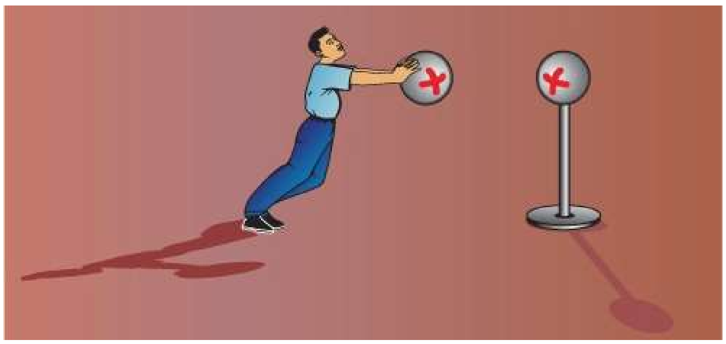


Figure 22.6: Work must be done to push one positive charge towards another.

In the process of doing work, energy is transferred from you to the charge that you are pushing. Its potential energy increases. If you let go of the charge, it will move away from the repelling charge. This is analogous to lifting up a mass; it gains gravitational potential energy as you lift it, and it falls if you let go.

Energy changes in a uniform field

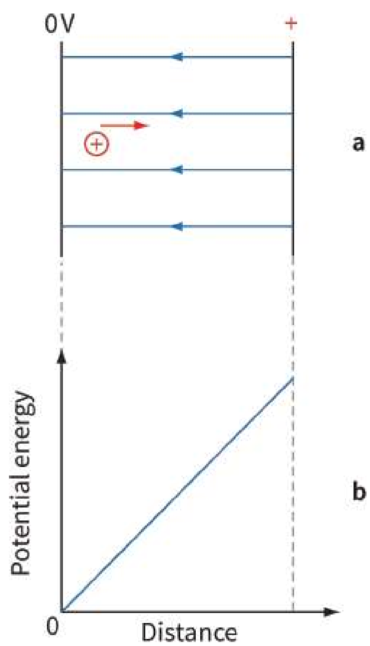


Figure 22.7: Electrostatic potential energy changes in a uniform field.

We can also think about moving a positive charge in a uniform electric field between two charged parallel plates. If we move the charge towards the positive plate, we have to do work. The potential energy of the charge is therefore increasing. If we move it towards the negative plate, its potential energy is decreasing (Figure 22.7a).

Since the force is the same at all points in a uniform electric field, it follows that the energy of the charge increases steadily as we push it from the negative plate to the positive plate. The graph of potential energy against distance is a straight line, as shown in Figure 22.7b.

We can calculate the change in potential energy of a charge Q as it is moved from the negative plate to the positive plate very simply. Potential difference is defined as the energy change (joules) per unit charge (coulombs) between two points (recall from Chapter 8 that one volt is one joule per coulomb). Hence, for charge Q, the work done in moving it from the negative plate to the positive plate is:

$$W = QV$$

We can rearrange this equation as:

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

This is really how voltage V is defined. It is the energy per unit positive charge at a point in an electric field. By analogy with gravitational potential, we call this the electric potential at a point. Now you should be able to see that what we regard as the familiar idea of voltage should more correctly be referred to as electric potential. The difference in potential between two points is the potential difference (p.d.) between them.

Just as with gravitational fields, we must define the zero of potential (this is the point where we consider a charge to have zero potential energy). Usually, in a laboratory situation, we define the Earth as being at a potential of zero volts. If we draw two parallel charged plates arranged horizontally, with the lower one earthed (Figure 22.8), you can see immediately how similar this is to our idea of gravitational fields. The diagram also shows how we can include equipotential lines in a representation of an electric field.

We can extend the idea of electric potential to measurements in electric fields. In Figure 22.9, the power supply provides a potential difference of 10 V. The value of the potential at various points is shown. You can see that the middle resistor has a potential difference across it of (8 − 2) V = 6 V.

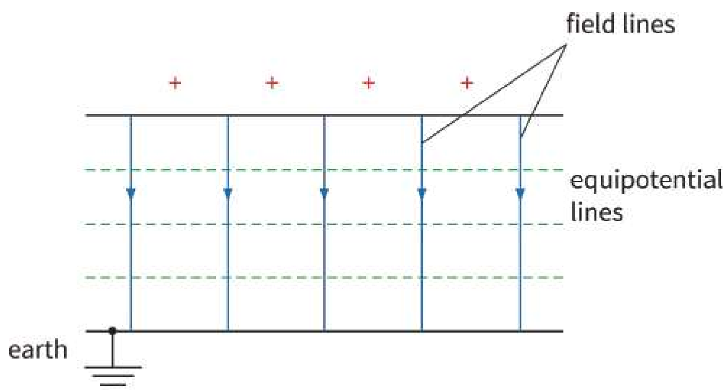


Figure 22.8: Equipotential lines in a uniform electric field.

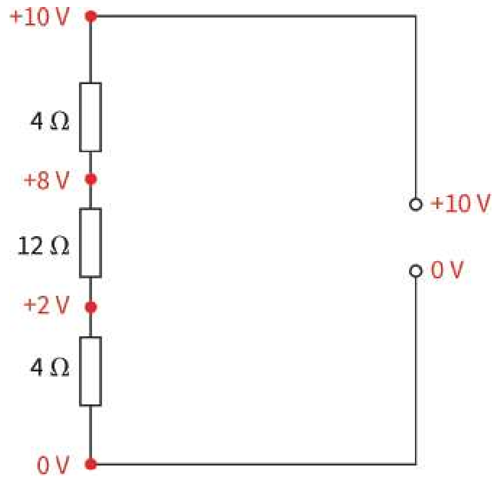


Figure 22.9: Changes in potential (shown in red) around an electric circuit.

Energy in a radial field

Imagine again pushing a small positive test charge towards a large positive charge. At first, the repulsive force is weak, and you have only to do a small amount of work. As you get closer, however, the force increases (Coulomb's law), and you have to work harder and harder.

The potential energy of the test charge increases as you push it. It increases more and more rapidly the closer you get to the repelling charge. This is shown by the graph in Figure 22.10. We can write an equation for the potential V at a distance r from a charge Q:

$$V = \frac{Q}{4\pi\varepsilon_0 r}$$

where V is the potential near a point charge Q, ε_0 is the permittivity of free space and r is the distance from the point.

(This comes from the calculus process of integration, applied to the Coulomb's law equation.)

You should be able to see how this relationship is similar to the equivalent formula for gravitational potential in a radial field:

$$\phi = -\frac{GM}{r}$$

Note that we do not need the minus sign in the electric equation as it is included in the charge. A negative charge gives an attractive (negative) field whereas a positive charge gives a repulsive (positive) field.

We can show these same ideas by drawing field lines and equipotential lines. The equipotentials get closer together as we get closer to the charge (Figure 22.11).

KEY EQUATION

$$V = \frac{Q}{4\pi\varepsilon_0 r}$$

Electric potential in a radial field due to a point charge.

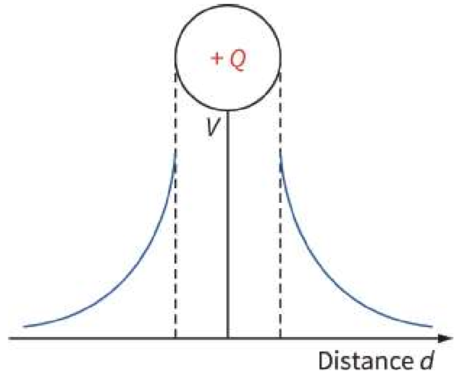


Figure 22.10: The potential changes according to an inverse law near a charged sphere.

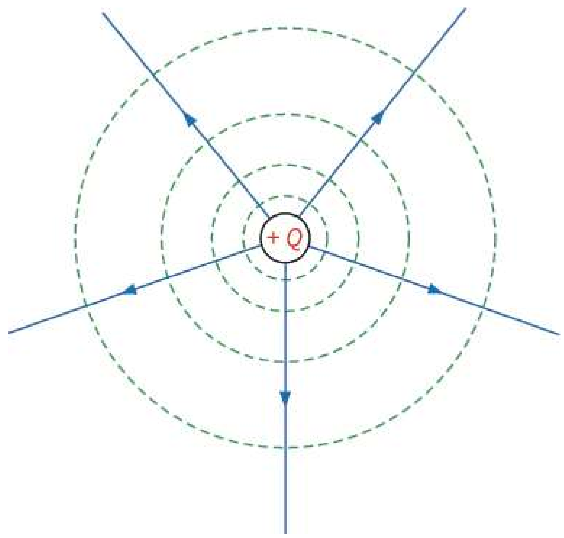


Figure 22.11: The electric field around a positive charge. The dashed equipotential lines are like the contour lines on a map; they are spaced at equal intervals of potential.

To arrive at this result, we must again define our zero of potential. Again, we say that a charge has zero potential energy when it is at infinity (some place where it is beyond the influence of any other charges). If we move towards a positive charge, the potential is positive. If we move towards a negative charge, the potential is negative.

This allows us to give a definition of electric potential: The **electric potential** at a point is equal to the work done per unit charge in bringing unit positive charge from infinity to that point.

Electric potential is a scalar quantity. To calculate the potential at a point caused by more than one charge, find each potential separately and add them. Remember that positive charges cause positive potentials and negative charges cause negative potentials.

Electrical potential energy

We have already defined electric potential energy between two points A and B as the work done in moving positive charge from point A to point B. This means that the potential energy change in moving point charge Q_1 from infinity towards a point charge Q_2 is equal to the potential at that point due to Q_2 multiplied by Q_1. In symbol form:

$$W = VQ_2$$

The potential V near the charge Q_2 is:

$$V = \frac{Q_2}{4\pi\varepsilon_0 r}$$

Thus the potential energy of the pair of point charges W (shown as E_p in the equation) is:

$$E_p = \frac{Qq}{4\pi\varepsilon_0 r}$$

KEY EQUATION

$$E_p = \frac{Qq}{4\pi\varepsilon_0 r}$$

Potential energy of a pair of point charges.

WORKED EXAMPLE

2 An α-particle approaches a gold nucleus and momentarily comes to rest at a distance of 4.5×10^{-14} m from the gold nucleus. Calculate the electric potential energy of the particles at that instant. (Charge on the α-particle = 2*e*; charge on the nucleus = 79*e*.)

Step 1 Convert the charges to coulombs.

α-particle charge = $2 \times 1.6 \times 10^{-19}$ C

charge on the gold nucleus = $79 \times 1.6 \times 10^{-19}$ C

Step 2

$$\begin{aligned} W &= \frac{Q_1 Q_2}{4\pi\varepsilon_0 r} \\ &= \frac{2\times1.6\times10^{-19}\times79\times1.6\times10^{-19}}{4\pi\times8.85\times10^{-12}\times4.5\times10^{-14}} \\ &= 8.1\times10^{-13}\,\text{J} \end{aligned}$$

Electric potential difference near a charged sphere

We have already seen that the electric potential ΔV at a distance r from a point charge Q is given by the equation:

$$\Delta V = \frac{Q}{4\pi\varepsilon_0 r}$$

The potential difference between two points, one at a distance r_1 and the second at a distance r_2 from a charge Q is:

$$\begin{aligned} \Delta V &= \frac{Q}{4\pi\varepsilon_0 r_1} - \frac{Q}{4\pi\varepsilon_0 r_2} \\ &= \frac{Q}{4\pi\varepsilon_0}\left[\frac{1}{r_1} - \frac{1}{r_2}\right] \end{aligned}$$

This reflects the similar formula for the gravitational potential energy between two points near a point mass.

KEY EQUATION

$$\Delta V = \frac{Q}{4\pi\varepsilon_0}\left[\frac{1}{r_1} - \frac{1}{r_2}\right]$$

Potential difference between two points from a charge.

Field strength and potential gradient

We can picture electric potential in the same way that we thought about gravitational potential. A negative charge attracts a positive test charge, so we can regard it as a potential 'well'. A positive charge is the opposite–a 'hill' (Figure 22.12). The strength of the field is shown by the slope of the hill or well:

field strength = −potential gradient

The minus sign is needed because, if we are going up a potential hill, the force on us is pushing us back down the slope, in the opposite direction.

KEY IDEA

electric field strength = −potential gradient

Figure 22.12: A ‘potential well’ near a negative charge, and a ‘potential hill’ near a positive charge.

This relationship applies to all electric fields. For the special case of a uniform field, the potential gradient E is constant. Its value is given by:

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

where V is the potential difference between two points separated by a distance d.

(This is the same as the relationship $E = \frac{V}{d}$ quoted in Chapter 21.)

Worked example 3 shows how to determine the field strength from a potential–distance graph.

WORKED EXAMPLE

3 The graph (Figure 22.13) shows how the electric potential varies near a charged object. Calculate the electric field strength at a point 5 cm from the centre of the object.

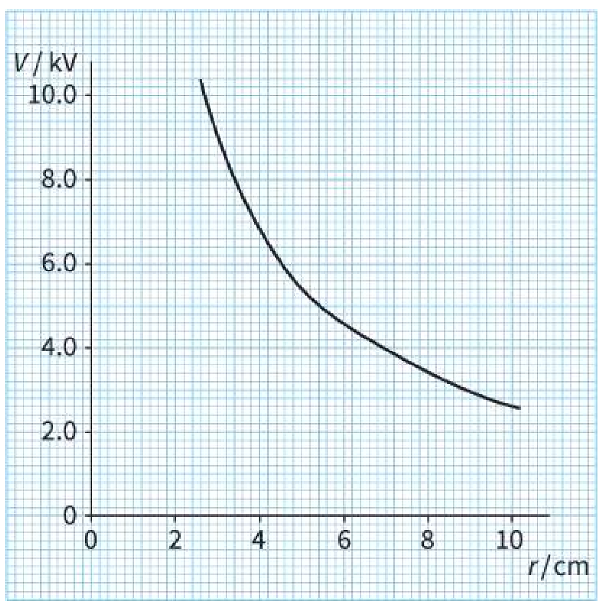


Figure 22.13: Variation of the potential V near a positively charged object.

Step 1 Draw the tangent to the graph at the point 5.0 cm. This is shown in Figure 22.14.

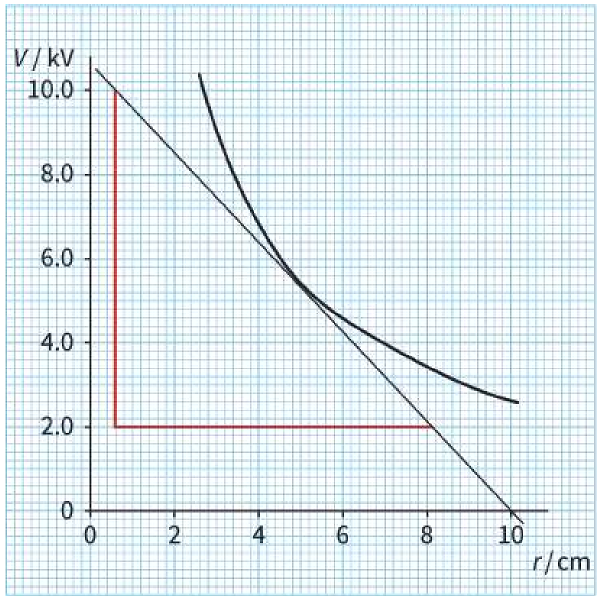


Figure 22.14: Drawing the tangent to the V–r graph to find the electric field strength E.

Step 2 Calculate the gradient of the tangent:

$$\begin{aligned} \text{gradient} &= \frac{\Delta V}{\Delta r} \\ &= \frac{10.0-2.0}{0.6-8.2} \\ &= -1.05 \text{kVcm}^{-1} \\ &\equiv -1.05 \times 10^5 \text{V m}^{-1} \\ &\approx -1.0 \times 10^5 \text{V m}^{-1} \end{aligned}$$

The electric field strength is therefore $+1.0 \times 10^5$ V m^{-1} or $+1.0 \times 10^5$ N C^{-1}.

Remember E = −potential gradient.

Questions

3 **a** What is the electrical potential energy of a charge of +1 C placed at each of the points A, B, C, D between the charged, parallel plates shown in Figure 22.15?

b What would be the potential energy of a +2 C charge at each of these points? (C is halfway between A and B, D is halfway between C and B.)

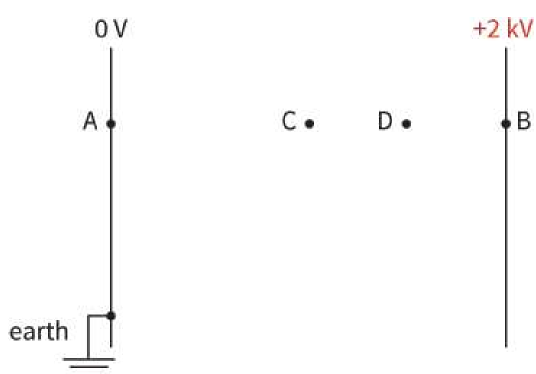


Figure 22.15: A uniform electric field. For Question 3.

4 A Van de Graaff generator has a spherical dome of radius 10 cm. It is charged up to a potential of 100 000 V (100 kV). How much charge is stored on the dome? What is the potential at a distance of 10 cm from the dome?

5 **a** How much work is done in moving a +1 C charge along the following paths shown in Figure 22.16: from E to H; from E to F; from F to G; from H to E?

b How do your answers differ for a:

i −1 C charge?

ii +2 C charge?

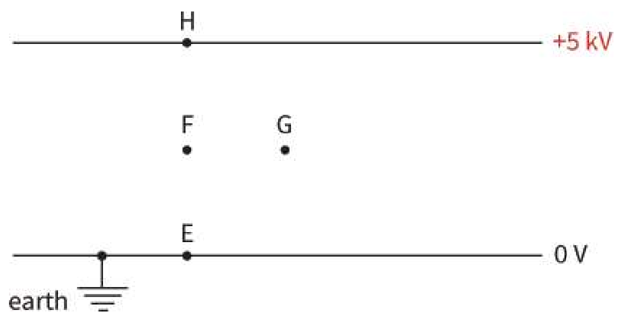
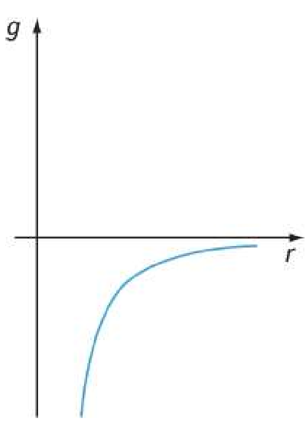
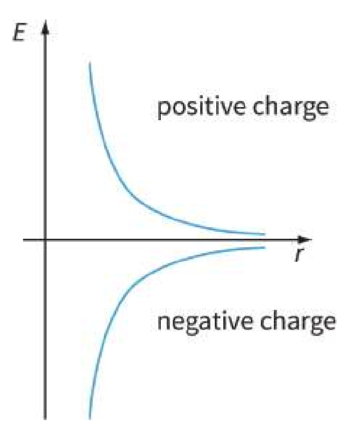


Figure 22.16: A uniform electric field. For Question 5.

22.5 Gravitational and electric fields

There are obvious similarities between the ideas we have used in this chapter to describe electric fields and those we used in Chapter 17 for gravitational fields. This can be helpful, or it can be confusing! The summary given in Table 22.1 is intended to help you to sort them out.

An important difference is this: electric charges can be positive or negative, so they can attract or repel. There are no negative masses, so there is only attraction in a gravitational field.

Gravitational fields	**Electric fields**
Origin arise from masses	**Origin** arise from electric charges
Vector forces only gravitational attraction, no repulsion	**Vector forces** both electrical attraction and repulsion are possible (because of positive and negative charges)
All gravitational fields field strength $g = \frac{F}{m}$ field strength is force per unit mass	**All electric fields** field strength $E = \frac{F}{Q}$ field strength is force per unit positive charge
Units F in N, g in N kg^{-1} or m s^{-2}	**Units** F in N, E in N C^{-1} or V m^{-1}
Uniform gravitational fields parallel gravitational field lines g = Constant	**Uniform electric fields** parallel electric field lines $E = \frac{V}{d}$ = constant
Spherical gravitational fields radial field lines force given by Newton's law: $F = \frac{GMm}{r^2}$ field strength is therefore: $g = \frac{GM}{r^2}$ (Gravitational forces are always attractive, so we show g on a graph against r as negative.) force and field strength obey an inverse square law with distance 	**Spherical electric fields** radial field lines force given by Coulomb's law: $F = \frac{Q_1 Q_2}{4\pi\varepsilon_0 r^2}$ field strength is therefore: $E = \frac{Q}{4\pi\varepsilon_0 r^2}$ (A negative charge gives an attractive field; a positive charge gives a repulsive field.) force and field strength obey an inverse square law with distance 
Gravitational potential	**Electric potential**

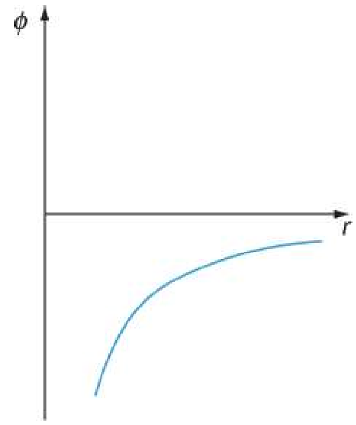
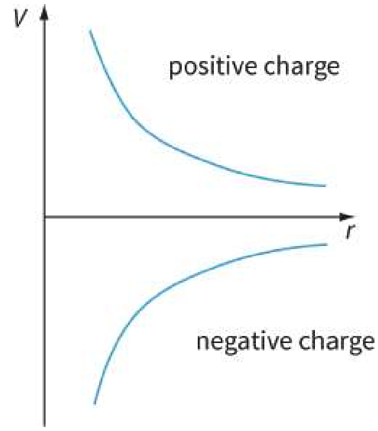
given by: $\phi = \frac{GM}{r}$ potential obeys an inverse relationship with distance and is zero at infinity potential is a scalar quantity and is always negative  	given by: $V = \frac{Q}{4\pi\varepsilon_0 r}$ potential obeys an inverse relationship with distance and is zero at infinity potential is a scalar quantity 

Table 22.1: Gravitational and electric fields compared.

Question

You will need the following data to answer the question.

proton mass = 1.67×10^{-27} kg

proton charge = $+1.60 \times 10^{-19}$ C

$\varepsilon_0 = 8.85 \times 10^{-12}$ F m^{-1}

$G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}

6 Two protons in the nucleus of an atom are separated by a distance of 10^{-15} m. Calculate the electrostatic force of repulsion between them, and the force of gravitational attraction between them. (Assume the protons behave as point charges and point masses.) Is the attractive gravitational force enough to balance the repulsive electrical force? What does this suggest to you about the forces between protons within a nucleus?

REFLECTION

In Question 6, we showed that in the atomic nuclei the electric force is much larger than the gravitational force. Is this also true in the formation of atoms? Yet, in the formation of stars and planetary systems, the gravitational force rules.

Discus and explain why there is this difference.

What did this discussion and explanation reveal about you as a learner?

SUMMARY

Coulomb's law states that two point charges exert an electrical force on each other that is proportional to the product of their charges and inversely proportional to the square of the distance between them.
The equation for Coulomb's law is: $F = \frac{Q_1 Q_2}{4\pi\varepsilon_0 r^2}$
A point charge Q gives rise to a radial field. The electric field strength is given by the equation: $$E = \frac{Q}{4\pi\varepsilon_0 r^2}$$
The electric potential at a point is defined as the work done per unit positive charge in bringing charge from infinity to the point.
For a point charge, the electric potential is given by: $V = \frac{Q}{4\pi\varepsilon_0 r}$
The electric potential energy of two point charges is: $W = \frac{Q_1 Q_2}{4\pi\varepsilon_0 r}$

EXAM-STYLE QUESTIONS

1 How does the potential V change with the distance r from a point charge? **[1]**

A $V \propto r$

B $V \propto r^2$

C $V \propto r^{-1}$

D $V \propto r^{-2}$

2 The electric field strength 20 cm from an isolated point charge is 1.9×10^4 N C^{-1}.

What is the electric field strength 30 cm from the charge? **[1]**

A 8.4×10^3 N C^{-1}

B 1.3×10^4 N C^{-1}

C 2.9×10^4 N C^{-1}

D 4.3×10^4 N C^{-1}

3 On a copy of this diagram, draw the electric fields between the charged objects. **[5]**

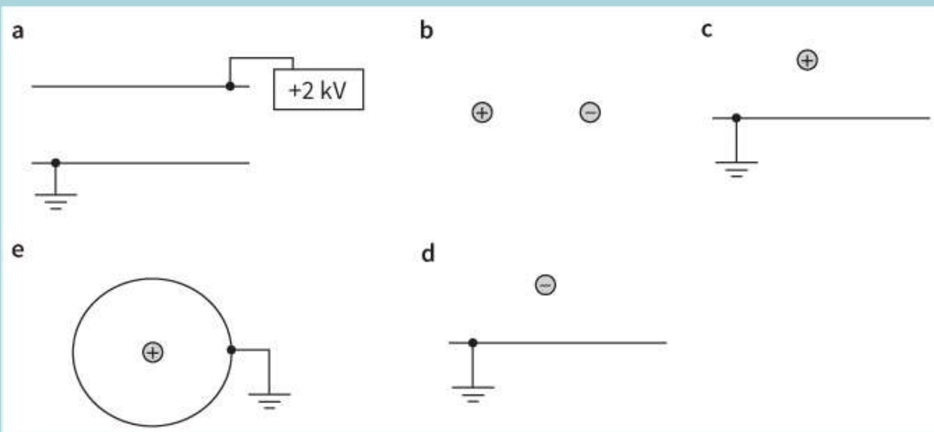


Figure 22.17

4 Two parallel plates are 4 cm apart and have a potential difference of 2.5 kV between them.

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

b A small piece of dust carrying a charge of +2.4 nC moves into the space between the plates.

i Calculate the force on the dust particle. **[2]**

ii The mass of the dust particle is 4.2 mg. Calculate the acceleration of the particle towards the negative plate. **[2]**

[Total: 6]

5 A small sphere carries a charge of 2.4×10^{-9} C. Calculate the electric field strength at a distance of:

a 2 cm from the centre of the sphere **[2]**

b 4 cm from the centre of the sphere. **[2]**

[Total: 4]

6 A conducting sphere of diameter 6.0 cm is mounted on an insulating base. The sphere is connected to a power supply that has an output voltage of 20 kV.

a Calculate the charge on the sphere. **[3]**

b Calculate the electric field strength at the surface of the sphere. **[2]**

[Total: 5]

7 The nucleus of a hydrogen atom carries a charge of $+1.60 \times 10^{-19}$ C.

Its electron is at a distance of 1.05×10^{-10} m from the nucleus.

Calculate the ionisation potential of hydrogen. **[3]**

(Hint: This is equal to the work per unit charge needed to remove the electron to infinity.)

8 **a** Define electric field strength. **[2]**

b Two charged conducting spheres, each of radius 1.0 cm, are placed with their centres 10 cm apart, as shown.

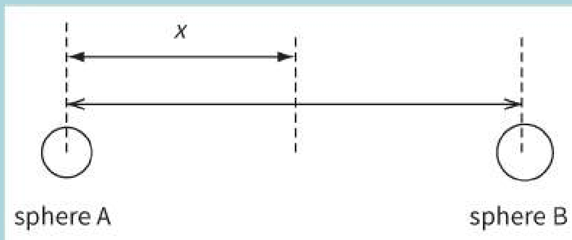


Figure 22.18

Sphere A carries a charge of $+2.0 \times 10^{-9}$ C.

The graph shows how the electric field strength between the two spheres varies with distance *x*.

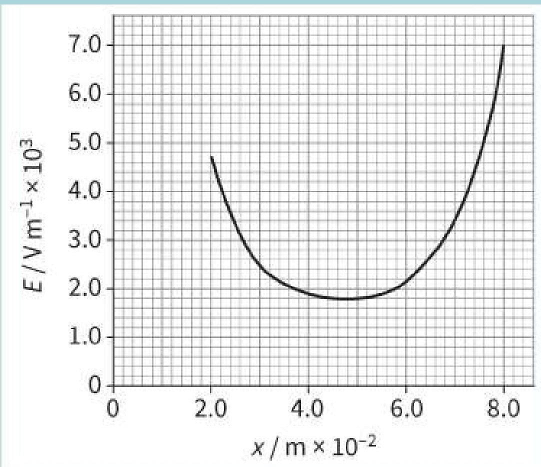


Figure 22.19

i Determine the field strength 5.0 cm from the centre of sphere A **[2]**

ii Use your result to **i** to calculate the charge on sphere B. **[3]**

c **i** Sphere B is now removed. Calculate the potential at the surface of sphere A. **[2]**

ii Suggest and explain how the potential at the surface of sphere A would compare before and after sphere B was removed. **[2]**

[Total: 11]

9 An α-particle emitted in the radioactive decay of radium has a kinetic energy of 8.0×10^{-13} J.

a **i** Calculate the potential difference that an α-particle, initially at rest, would have to be accelerated through to gain this energy. **[2]**

ii Calculate the speed of the α-particle at this kinetic energy. **[3]**

b This diagram shows the path of an α-particle of this energy as it approaches a gold nucleus head-on.

Figure 22.20

i State the speed of the α-particle at its point of closest approach to the gold nucleus. **[1]**

ii Write down the kinetic energy of the α-particle at this point. **[1]**

iii Write down the potential energy of the α-particle at this point. **[1]**

c Use your answer to part **b iii** to show that the α-particle will reach a distance of 4.5×10^{-14} m from the centre of the gold nucleus. **[2]**

d Suggest and explain what this information tells us about the gold nucleus. **[2]**

(Mass of an α-particle = 6.65×10^{-27} kg; charge on an α-particle = $+2e$; charge on a gold nucleus = $+79e$.)

[Total: 12]

10 a Define electric potential at a point. **[2]**

b This graph shows the electrical potential near an antiproton.

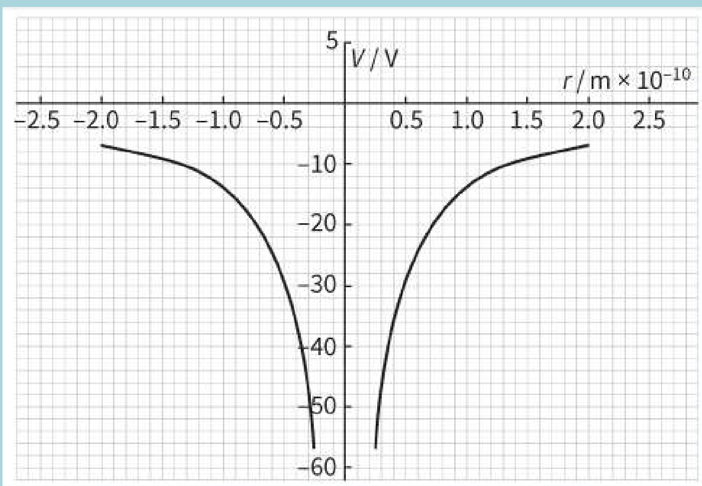


Figure 22.21

i Determine the potential at a distance 0.53×10^{-10} m from the antiproton. **[2]**

ii Determine the potential energy a positron would have at this distance. **[2]**

c Use the graph to determine the electric field at this distance from the antiproton. **[2]**

[Total: 8]

11 This diagram shows a conducting sphere of radius 0.80 cm carrying a charge of $+6.0 \times 10^{-8}$ C resting on a balance.

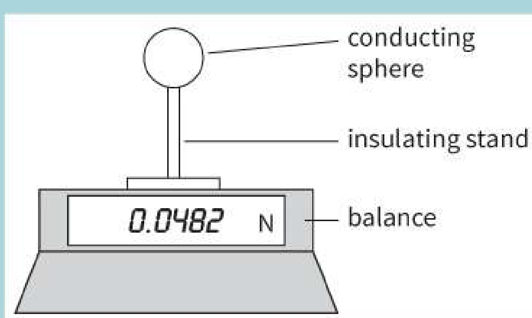


Figure 22.22

a Calculate the electric field at the surface of the sphere. **[2]**

b An identical sphere carrying a charge of -4.5×10^{-8} C is held so that its centre is 5.0 cm vertically above the centre of the first sphere.

i Calculate the electric force between the two spheres. **[2]**

ii Calculate the new reading on the balance. **[1]**

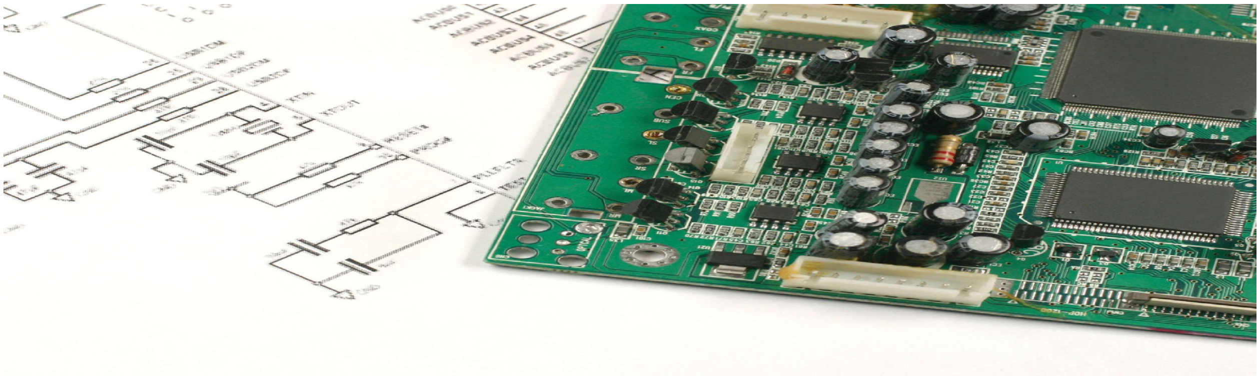
c The second sphere is moved vertically downwards through 1.5 cm. Calculate the work done against the electric field in moving the sphere. **[3]**

[Total: 8]

SELF-EVALUATION CHECKLIST

After studying the chapter, complete a table like this:

I can	See topic…	Needs more work	Almost there	Ready to move on
understand the nature of the electric field	22.1			
represent and interpret an electric field using field lines	22.4			
recall and use Coulomb's law: $F = \frac{Q_1 Q_2}{4\pi\varepsilon_0 r^2}$	22.2			
understand that electric field g is defined as the electric force per unit coulomb	22.5			
derive from Coulomb's law of gravitation: $$E = \frac{Q}{4\pi\varepsilon_0 r^2}$$	22.3			
recall and use the equation: $E = \frac{Q}{4\pi\varepsilon_0 r^2}$	22.3			
recall and use: $E = \frac{\Delta \mathrm{V}}{\Delta d}$	22.4			
define electric potential at a point, V, as the work done in bringing unit charge from infinity to that point	22.4			
recognise that the electric potential at infinity is zero	22.4			
recognise that the electric potential increases as you move closer to a positively charged object	22.4			
recognise that the electric potential decreases as you move closer to a negatively charged object	22.4			
recall and use the formula: gravitational potential $V = \frac{Q}{4\pi\varepsilon_0 r}$	22.4			
use the formula: $\Delta V = \frac{Q}{4\pi\varepsilon_0}\left[\frac{1}{r_1} - \frac{1}{r_2}\right]$	22.4			
understand that the electric potential energy of two point masses is equal to: $W = \frac{Q_1 Q_2}{4\pi\varepsilon_0 r}$	22.4			



Chapter 23

Capacitance

LEARNING INTENTIONS

In this chapter you will learn how to:

- define capacitance and state its unit, the farad
- solve problems involving charge, voltage and capacitance
- deduce the electric potential energy stored in a capacitor from a potential–charge graph
- deduce and use formulae for the energy stored by a capacitor
- derive and use formulae for capacitances in series and parallel
- recognise and use graphs showing variation of potential difference, current and charge as a capacitor discharges.
- recall and use the time constant for a capacitor–resistor circuit
- use the equation for the discharge of a capacitor through a resistor.

BEFORE YOU START

- In order to avoid an electric shock, electrical engineers regularly connect various points to Earth, even though the equipment is disconnected from the mains supply.
- What does this suggest to you is happening? How can you get a shock when the equipment is not connected to the mains? Discuss with a partner and be prepared to share your thoughts with the rest of the class.

CAPACITORS

Most electronic devices, such as radios, computers and MP3 players, make use of components called capacitors. These are usually quite small, but Figure 23.1 shows a giant capacitor, specially constructed to store electrical energy at the Fermilab particle accelerator in the United States.