Chapter 6
Electric fields

Worksheet

permittivity of free space $\Sigma_0 = 8.85 \quad 10^{-12}$ F m^{-1}
elementary charge $e = 1.6 \quad 10^{-19}$ C

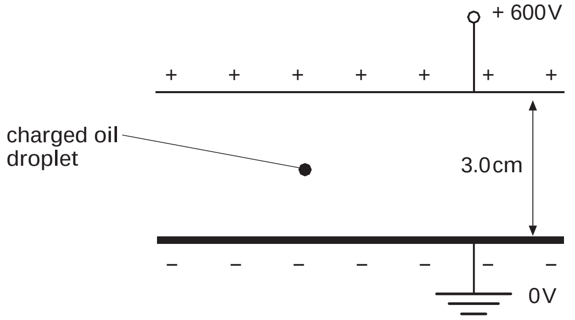
Intermediate level

1 State two possible SI units for electric field strength. [2]

2 A +5.0 10^{-8} C point charge experiences a force of 1.5 10^{-3} N when placed in a uniform electric field. Calculate the electric field strength. [2]

3 Calculate the force experienced by an oil droplet with a charge of 3.2 10^{-19} C due to a uniform electric field of strength 5.0 10^{5} V m^{-1}. [2]

4 The diagram shows two parallel plates separated by 3.0 cm connected to a supply of 600 V.



a Calculate the magnitude and direction of the electric field between the plates. [3]

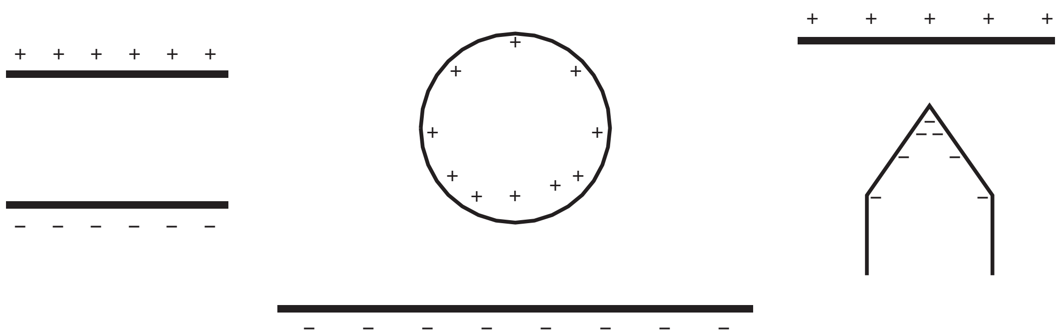
b What is the nature of the electric field between the plates? [2]

c An oil droplet of weight 6.4 10^{-15} N is held stationary between the two plates.

i State whether the charge on the droplet is positive or negative. Explain your answer. [2]

ii Determine the charge on the oil droplet. [2]

5 Draw the electric field patterns for the electrodes shown.



a [2] **b** [2] **c** [2]

6 Calculate the electrical force between a proton and an electron separated by a distance of 5.0 10^{-11} m. [3]

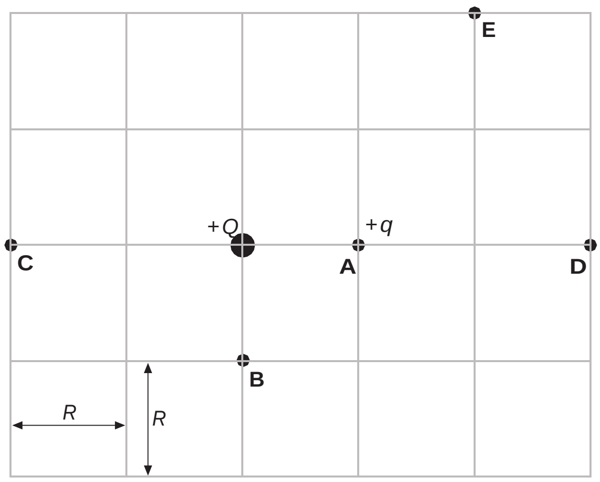
7 The electric field strength E at a distance r from a point charge Q may be written as:

$$E = k\frac{Q}{r^2}$$

What is the value for k? [2]

Higher level

8 The diagram shows a point charge $+q$ placed in the electric field of a charge $+Q$.



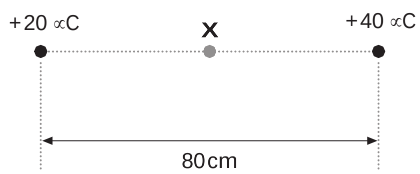
The force experienced by the charge $+q$ at point **A** is F. Calculate the force experienced by this charge when it is placed at points **B**, **C**, **D** and **E**. In each case, explain your answer. [9]

9 A spherical metal dome of radius 15 cm is electrically charged. It has a positive charge of +2.5 ∝C distributed uniformly on its surface.

a Calculate the electric field strength at the surface of the dome. [3]

b Explain how your answer to **a** would change at a distance of 30 cm from the surface of the dome. [2]

10 The diagram shows two point charges. The point **X** is midway between the charges.



a Calculate the electric field strength at point **X** due to:

i the +20 ∝C charge; [3]

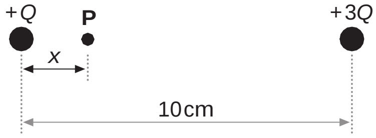
ii the +40 ∝C charge. [2]

b Calculate the resultant field strength at point **X**. [2]

11 Describe some of the similarities and differences between the electrical force due to a point charge and the gravitational force due to a point mass. [6]

Extension

12 The diagram shows two point charges. Calculate the distance x of point **P** from charge $+Q$ where the net electric field strength is zero. [6]



13 Show that the ratio:

$$\frac{\text{electrical force between two protons}}{\text{gravitational force between two protons}}$$

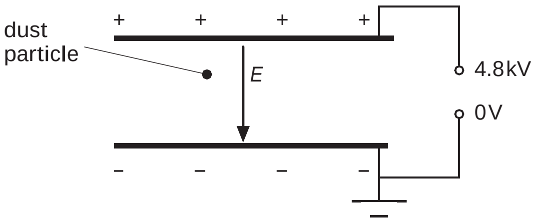
is about 10^{36} and is independent of the actual separation between the protons.
(Mass of a proton = 1.7 10^{-27} kg; gravitational constant G = 6.67 10^{-11} N m^2 kg^{-2}.) [5]

Total: $\overline{\quad}$ / 64 Score: %

Worked examples

Example 1

The diagram shows two parallel plates separated by 3.0 cm and connected to a high-voltage supply. Calculate the electric field strength between the plates. What is the force experienced by a dust particle with a charge of -8.0×10^{-18} C between the plates?



The electric field between the plates is uniform and its strength is given by:

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

Therefore:

$$E = \frac{4.8 \times 10^3}{3.0 \times 10^{-2}} = 1.6 \times 10^5 \text{ V m}^{-1}$$

Since by definition $E = \frac{F}{Q}$, the force F experienced by the charged dust particle is:

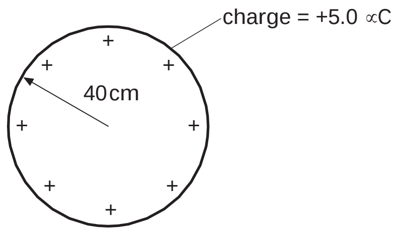
$$F = EQ = 1.6 \times 10^5 \times (-8.0 \times 10^{-18})$$

$$F = -1.28 \times 10^{-12} \text{ N} \approx -1.3 \times 10^{-12} \text{ N}$$

The minus sign means that the force experienced by the dust particle is in the opposite direction to the direction of the electric field.

Example 2

The diagram shows a charged isolated sphere of radius 40 cm. The charge of +5.0 μC is uniformly distributed on the surface of the sphere. What is the electric field strength at the surface of the sphere? Calculate the distance from the centre of the sphere at which the electric field strength is 70 kV m^{-1}.



For an isolated charged sphere, the electric field strength is given by:

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

The surface electric field strength is:

$$E = \frac{Q}{4\pi\varepsilon_0 r^2} = \frac{5.0 \times 10^{-6}}{4\pi \times 8.85 \times 10^{-12} \times 0.40^2}$$

$$E = 2.8 \times 10^5 \text{ V m}^{-1} \quad (280 \text{ kV m}^{-1})$$

The electric field created by the sphere is equivalent to that due to a charge of +5.0 μC *at the centre of the sphere.*

At a distance r from the centre of the charged sphere, the electric field strength is 70 kV m^{-1}.

$$70 \times 10^3 = \frac{5.0 \times 10^{-6}}{4\pi\varepsilon_0 r^2}$$

$$r = \sqrt{\frac{5.0 \times 10^{-6}}{4\pi \times 8.85 \times 10^{-12} \times 70 \times 10^3}} = 0.80 \text{ m}$$

Note that electric field strength decreases by a factor of four when the distance is doubled.

Tip

It is vital to substitute correctly into the equations, taking particular care with prefixes like μ (10^{-6}) and k (10^3).

Practical 1

Investigating electric fields

Safety

The usual safety rules apply when using an e.h.t. supply. These experiments are best done as teacher demonstrations. Teachers and technicians should follow their school and departmental safety policies and should ensure that the employer's risk assessment has been carried out before undertaking any practical work.

Aparatus

- e.h.t. supply
- metal sphere (football covered with aluminium foil)
- two large parallel capacitor plates
- polythene strip (or plastic ruler)
- gold leaf
- adhesive tape
- crocodile clip
- connecting leads

Introduction

The nature of the electric field between two charged parallel plates is described in some detail on pages 58 and 59 of *Physics 2*. The short experiments described here give you the opportunity to investigate the factors that affect the electric field strength for two different arrangements of conductors. A charged gold leaf attached to a polythene strip is used to gauge the strength of the electric field at different points around the charged conductors.

Procedure

Charged parallel plates

1 Set the plates with a separation of about 5.0 cm.

2 Connect the plates to a potential difference of 3.0 kV.

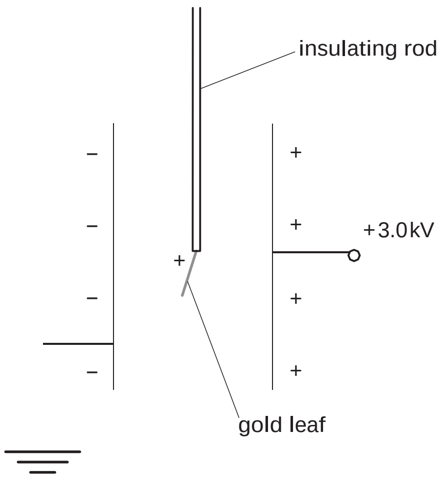
3 Charge the gold leaf by touching it to the positive plate.

4 Use the charged gold leaf to investigate the nature of the electric field between the parallel plates. The electric field between the plates should be uniform. Is it?

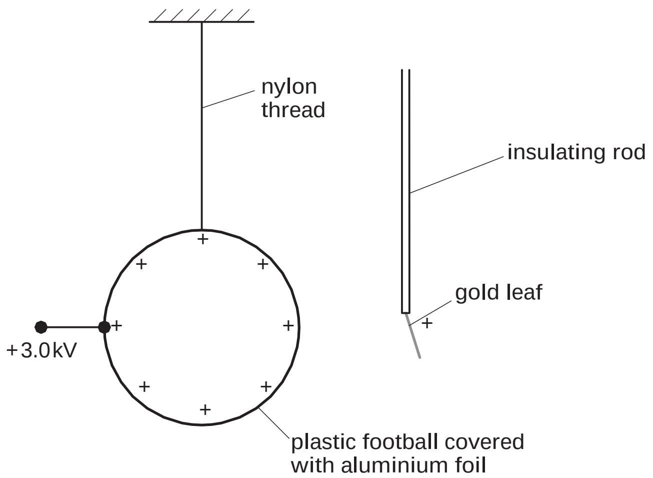
5 Is there an electric field outside the plates?

6 Change the separation between the plates. How does the electric field strength depend on the separation between the plates?

7 Change the potential difference between the plates. How does the p.d. between the plates affect the electric field strength?



Charged sphere



1 Use a crocodile clip and a connecting lead to connect the sphere to the positive electrode of the e.h.t. supply.

2 Set the e.h.t. supply to 3.0 kV.

3 Charge the gold leaf by touching it to the positive sphere.

4 The electric field strength should decrease with the distance from the centre of the sphere. Is this the case?

5 What happens to the electric field strength at a given distance as the charge on the sphere is decreased? (Decreasing the setting on the e.h.t. supply decreases the charge on the sphere.)

Practical 2

Investigating Coulomb's law

Safety

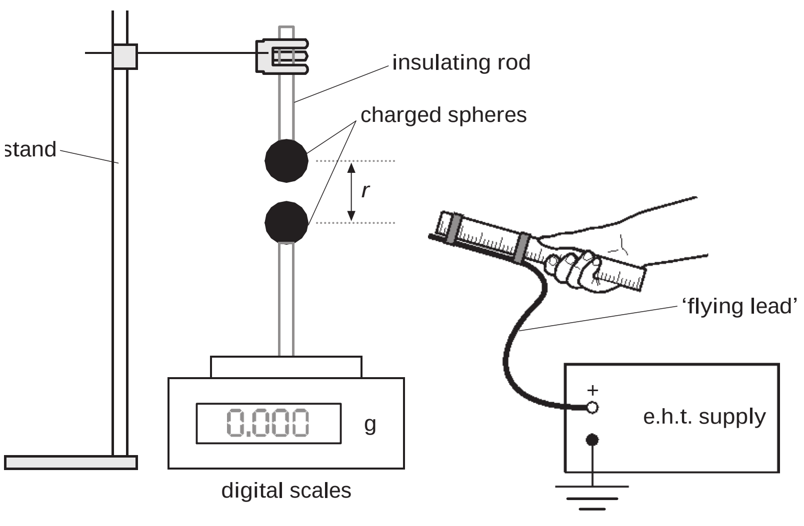
The usual safety rules apply when using an e.h.t. supply. To minimise the risk of electrical shocks, tape the flying lead to an insulating rod or a plastic ruler when charging the spheres. Teachers and technicians should follow their school and departmental safety policies and should ensure that the employer's risk assessment has been carried out before undertaking any practical work.

Apparatus

- digital scales (± 0.001 g)
- 30 cm ruler
- two tennis balls coated with conducting paint
- two insulating rods
- clamp stand
- e.h.t. supply
- flying lead on an insulating rod
- connecting leads

Introduction

The Coulomb's law experiment is described on page 64 of P*hysics 2*. In this experiment you investigate the variation of the force between two charged spheres with their separation. The arrangement of the apparatus is shown in the diagram.



Procedure

1 Place one of the insulating spheres on the digital scales and then zero the balance.

2 Place the other sphere directly above the sphere on the balance and as close as possible to it without the spheres touching.

3 Measure the separation *r* between the centres of the spheres.

4 Set the e.h.t. supply to 5.0 kV.

5 Using a flying lead connected to the positive of the e.h.t. supply, charge each sphere by touching it momentarily with the flying lead.

6 Record the mass *m* displayed on the scales.

7 Calculate the force F between the charged spheres using $F = m$ 9.81, where m is the reading on the scales in kilograms. Repeat the experiment for a range of separations and record your results in a table.

r (m)	**m (g)**	**F (N)**	$\frac{1}{r^2}$ **(m^{-2})**

8 Plot a graph of F against $\frac{1}{r^2}$. This should be a straight line through the origin if Coulomb's law is correct.

9 How can you use the graph to estimate the charge on each sphere?

Guidance for teachers

Electrostatic experiments are very sensitive and charges are easily discharged through the air or surface moisture on the insulating rods. It is therefore sensible to use a hairdryer for about 2 minutes to remove any surface moisture from the apparatus prior to the experiment.

End-of-chapter test

Answer all questions.

permittivity of free space $\sum_0 = 8.85 \quad 10^{-12}$ F m^{-1}
elementary charge $e = 1.6 \quad 10^{-19}$ C

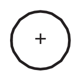
1 **a** Define electric field strength at a point in space. [1]

b The electric field strength close to a charged plate is $5.0 \quad 10^{5}$ V m^{-1}. A droplet of paint carrying a charge of $-4.8 \quad 10^{-19}$ C passes near to the charged plate. Calculate:

i the force the paint droplet experiences due to the electric field; [2]

ii the number of excess electrons on the droplet. [2]

2 The diagram shows the nucleus of a gold atom.



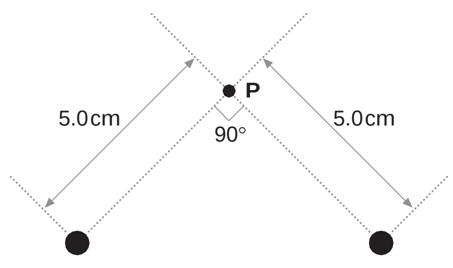
a Draw the electric field pattern for the nucleus. [2]

b The radius of the nucleus is $6.8 \quad 10^{-15}$ m and it has a charge of $+1.3 \quad 10^{-17}$ C. Calculate the magnitude of:

i the electric field strength at the 'surface' of the gold nucleus; [3]

ii the force experienced by an -particle of charge $+3.2 \quad 10^{-19}$ C at a distance of $1.4 \quad 10^{-14}$ m from the centre of the gold nucleus. [3]

3 The diagram shows two identical point charges situated in air.



a Calculate the magnitude of the electric field strength at point **P** due to one of the +20 nC charges. [3]

b On the diagram above, draw the direction of the field at point **P**. [1]

c Show that the resultant electric field is 2 times greater than your answer to **a**. [2]

Total: $\frac{}{19}$ Score: %

Marking scheme

Worksheet

1 The two units are: $\mathrm{V\,m^{-1}}$ [1] and $\mathrm{N\,C^{-1}}$. [1]

2 $E = \dfrac{F}{Q} = \dfrac{1.5 \quad 10^{-3}}{5.0}$ [1]; $E = 3.0 \quad 10^{4}\,\mathrm{V\,m^{-1}}$ [1]

3 $F = EQ = 5.0 \quad 10^{5} \quad 3.2 \quad 10^{-19}$ [1]; $F = 1.6 \quad 10^{-13}\,\mathrm{N}$ [1]

4 **a** $E = \dfrac{V}{d} = \dfrac{600}{3.0 \quad 10^{-2}}$ [1]; $E = 2.0 \quad 10^{4}\,\mathrm{V\,m^{-1}}$ [1]

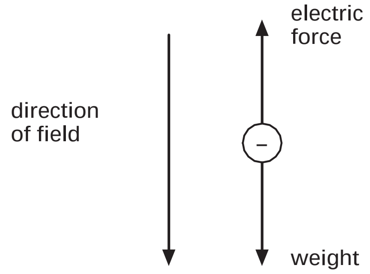
The field acts towards the negative plate. [1]

b The electric field is uniform between the plates (except at the 'edges'). [1]

The electric field is at right-angles to the plate. [1]

c **i** Since the droplet is stationary, the electric force on the droplet must be equal and opposite to its weight. [1]

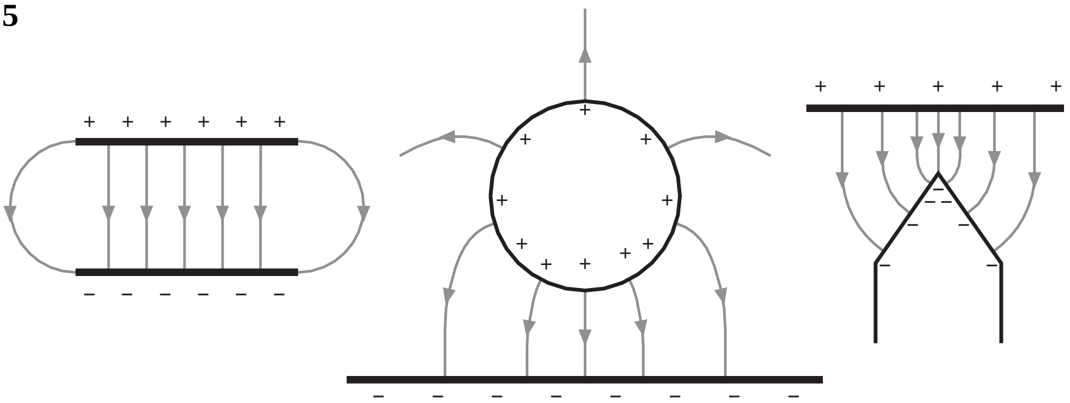
The electric force must act upwards, so the charge on the droplet must be negative. [1]



ii $E = \dfrac{F}{Q}$

$Q = \dfrac{F}{E} = \dfrac{6.4 \quad 10^{-15}}{2.0 \quad 10^{4}}$ [1]; $Q = 3.2 \quad 10^{-19}\,\mathrm{C}$ [1]

5



a **b** **c**

Correct field patterns [1] 3

Correct field directions. [1] 3

6 $F = \dfrac{Q_1 Q_2}{4 \ \Sigma_0 r^2}$ [1];

$F = \dfrac{1.6 \quad 10^{-19} \quad 1.6 \quad 10^{-19}}{4 \quad 8.85 \quad 10^{-12} \quad (5.0 \quad 10^{-11})^2}$ [1]

(magnitude of charge on both proton and electron = e)

$F \quad 9.2 \quad 10^{-8}\,\mathrm{N}$ [1]

7 $E = \dfrac{Q}{4 \ \Sigma_0 r^2}$ so $k = \dfrac{1}{4 \ \Sigma_0} = \dfrac{1}{8.85 \quad 10^{-12}}$ [1]

4

$k = 8.99 \quad 10^{9}\,\mathrm{m\,F^{-1}} \quad 9.0 \quad 10^{9}\,\mathrm{m\,F^{-1}}$ [1]

8 The force between the charges obeys an inverse square law with distance, that is:

$F \propto \frac{1}{r^2}$ [1]

Point **B**: The distance is the same.

The force between the charges = F [1]

Point **C**: The distance is doubled.

The force between the charges decreases by a factor of 4. [1]

The force between the charges is $\frac{F}{4}$. [1]

Point **D**: The distance is trebled.

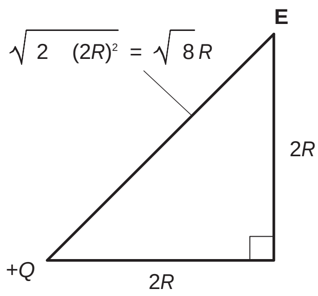
The force between the charges decreases by a factor of $3^2 = 9$. [1]

The force between the charges is $\frac{F}{9}$. [1]

Point **E**: The distance between the charges is $\sqrt{8}R$. [1]

The force between the charges decreases by a factor of $(\sqrt{8})^2 = 8$ [1]

The force between the charges is $\frac{F}{8}$. [1]



9 **a** $E = \frac{Q}{4\ \Sigma_0 r^2}$ [1]

$E = \frac{2.5\ \ 10^{-6}}{4\ \ 8.85\ \ 10^{-12}\ \ 0.15^2}$ [1]; $E = 9.99\ \ 10^5\ \mathrm{V\,m^{-1}}\ \ 1.0\ \ 10^6\ \mathrm{V\,m^{-1}}$ [1]

b The distance from the **centre** of the dome increases by a factor of 3.

The electric field strength decreases by a factor of $3^2 = 9$. [1]

Therefore: $E = \frac{1.0\ \ 10^6}{9} = 1.1\ \ 10^4\ \mathrm{V\,m^{-1}}$ [1]

10 **a** **i** $E = \frac{Q}{4\ \Sigma_0 r^2}$ [1]

$E = \frac{20\ \ 10^{-6}}{4\ \ 8.85\ \ 10^{-12}\ \ 0.40^2}$ $\left(r = \frac{80}{2} = 40\ \mathrm{cm}\right)$ [1]

$E = 1.124\ \ 10^6\ \mathrm{V\,m^{-1}}\ \ 1.1\ \ 10^6\ \mathrm{V\,m^{-1}}$ [1]

ii $E = \frac{40\ \ 10^{-6}}{4\ \ 8.85\ \ 10^{-12}\ \ 0.40^2}$ [1]

$E = 2.248\ \ 10^6\ \mathrm{V\,m^{-1}}\ \ 2.2\ \ 10^6\ \mathrm{V\,m^{-1}}$ [1]

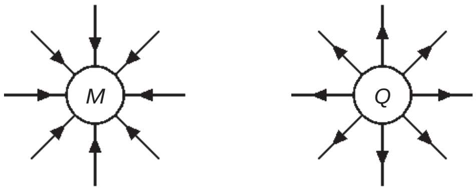
(The electric field doubles because the charge is doubled, $E \propto Q$.)

b Net field strength, $E = 2.2\ \ 10^6 - 1.1\ \ 10^6 = 1.1\ \ 10^6\ \mathrm{V\,m^{-1}}$ [1]

The field acts to the **left**. [1]

11 **Similarities**

- Both produce **radial** fields. [1]



mass   positive charge

- Both obey an **inverse square law** with distance, that is:

  $F \propto \frac{1}{r^2}$ [1]

- The field strengths are defined as force **per** unit (positive) charge or mass. [1]
- Both produce **action at a distance**. [1]

Differences

- Electrical forces can be either **attractive** or **repulsive**, whereas gravitational forces are always **attractive**. [1]
- Gravitational forces act between **masses**, whereas electrical forces act between **charges**. [1]

12 The electric field strength due to the charge $+Q$ is equal in magnitude but opposite in direction to the electric field strength due to the charge $+3Q$. [1]

Therefore:

$\frac{Q}{4\ \Sigma_0 x^2} = \frac{3Q}{4\ \Sigma_0\ (R-x)^2}$ (where R is the distance between the charges = 10 cm) [1]

$\frac{1}{x^2} = \frac{3}{(R-x)^2}$ [1]; so $\frac{R-x}{x} = \sqrt{3}$ [1]

$x(1+\sqrt{3}) = R$ so $x = \frac{R}{1+\sqrt{3}} = 0.37R$ [1]

$x = 0.37 \quad 10 = 3.7$ cm [1]

13 Ratio $= \frac{e^2 / 4\ \Sigma_0 r^2}{Gm^2 / r^2}$ (where m = mass of proton and r = separation) [2]

ratio $= \frac{e^2}{4\ \Sigma_0 G m^2}$ [1]

The r^2 terms cancel and so this ratio is independent of the separation. [1]

ratio $= \frac{(1.6 \quad 10^{-19})^2}{4 \quad 8.85 \quad 10^{-12} \quad 6.67 \quad 10^{-11} \quad (1.7 \quad 10^{-27})^2}$ [1]

ratio $\quad 1.2 \quad 10^{36}$

Marking scheme

End-of-chapter test

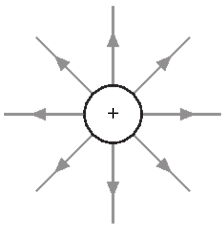
1 **a** Electric field strength at a point in space is equal to the force experienced **per** unit **positive** charge. [1]

b **i** $F = EQ = 5.0 \quad 10^5 \quad 4.8 \quad 10^{-19}$ [1]

$F = 2.4 \quad 10^{-13}$ N [1]

ii Number $= \dfrac{4.8 \quad 10^{-19}}{e} = \dfrac{4.8 \quad 10^{-19}}{1.6 \quad 10^{-19}}$ [1]; number = 3 [1]

2 **a**



Radial field shown. [1]

Correct field direction. [1]

b **i** $E = \dfrac{Q}{4 \quad \Sigma_0 r^2}$ [1]

$E = \dfrac{1.3 \quad 10^{-17}}{4 \quad 8.85 \quad 10^{-12} \quad (6.8 \quad 10^{-15})^2}$ [1]

$E = 2.53 \quad 10^{21}$ V m^{-1} $\quad 2.5 \quad 10^{21}$ V m^{-1} [1]

ii $F = \dfrac{Q_1 Q_2}{4 \quad \Sigma_0 r^2}$ [1]

$F = \dfrac{1.3 \quad 10^{-17} \; 3.2 \quad 10^{-19}}{4 \quad 8.85 \quad 10^{-12} \quad (1.4 \quad 10^{-14})^2}$ [1]

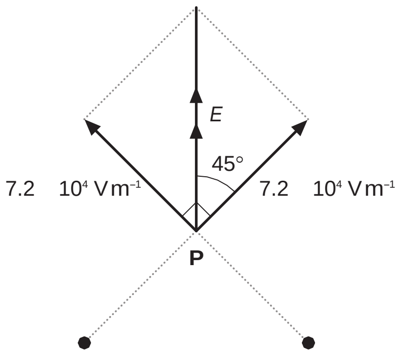
$F = 191$ N $\quad 190$ N [1]

3 **a** $E = \dfrac{Q}{4 \quad \Sigma_0 r^2}$ [1]

$E = \dfrac{20 \quad 10^{-9}}{4 \quad 8.85 \quad 10^{-12} \quad (0.05)^2}$ [1]

$E = 7.19 \quad 10^4$ V m^{-1} $\quad 7.2 \quad 10^4$ V m^{-1} [1]

b



Correct direction shown (judged by eye). [1]

c Net electric field strength $E = \sqrt{2 \quad (7.2 \quad 10^4)^2}$ [1]

$E = (\sqrt{2}) \quad 7.2 \quad 10^4$ V m^{-1} [1]