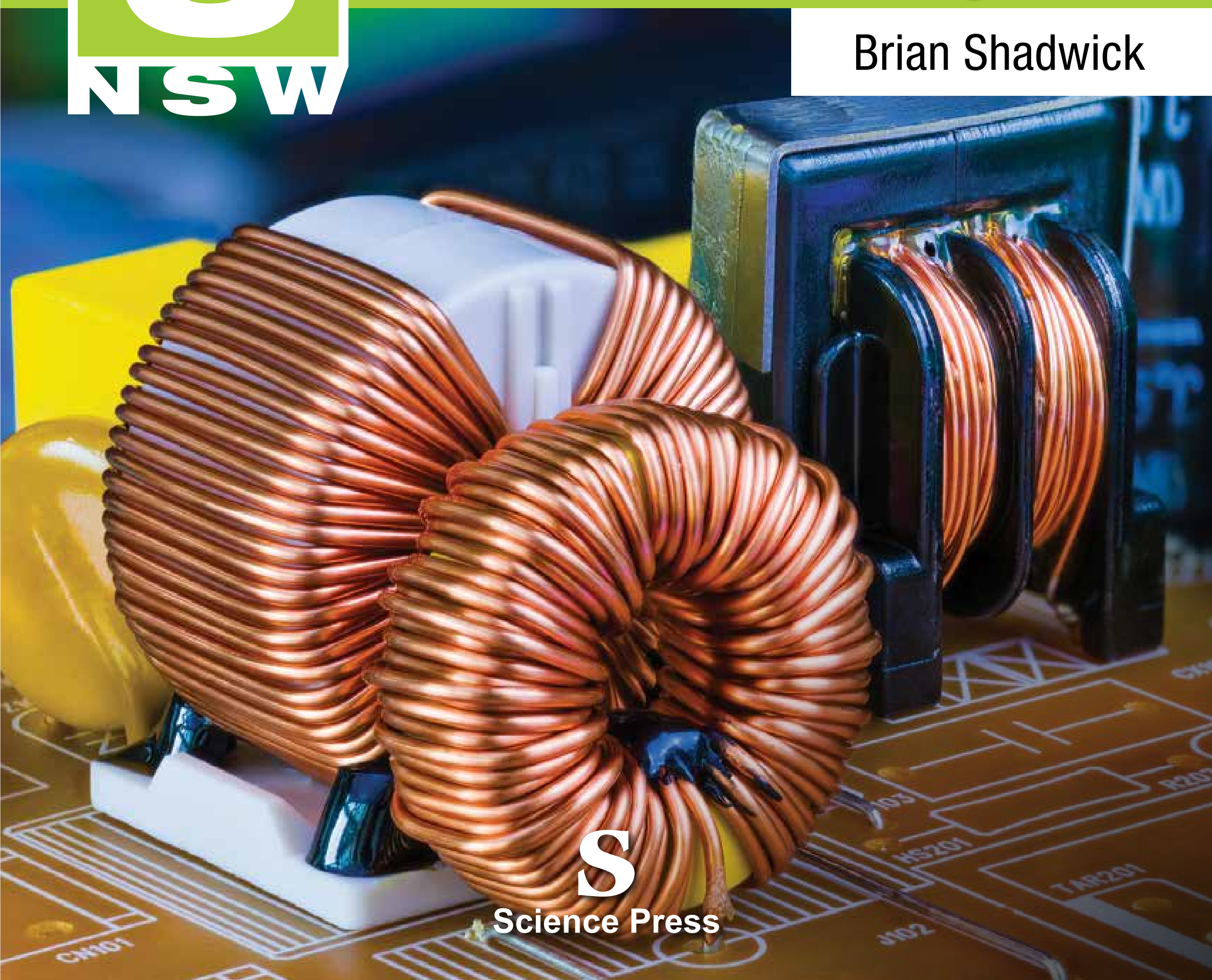
Mastering Physics

MODULE 6

NSW

Electromagnetism

Brian Shadwick



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Contents

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Words to Watch

account, account for State reasons for, report on, give an account of, narrate a series of events or transactions.

analyse Interpret data to reach conclusions.

annotate Add brief notes to a diagram or graph.

apply Put to use in a particular situation.

assess Make a judgement about the value of something.

calculate Find a numerical answer.

clarify Make clear or plain.

classify Arrange into classes, groups or categories.

comment Give a judgement based on a given statement or result of a calculation.

compare Estimate, measure or note how things are similar or different.

construct Represent or develop in graphical form.

contrast Show how things are different or opposite.

create Originate or bring into existence.

deduce Reach a conclusion from given information.

define Give the precise meaning of a word, phrase or physical quantity.

demonstrate Show by example.

derive Manipulate a mathematical relationship(s) to give a new equation or relationship.

describe Give a detailed account.

design Produce a plan, simulation or model.

determine Find the only possible answer.

discuss Talk or write about a topic, taking into account different issues or ideas.

distinguish Give differences between two or more different items.

draw Represent by means of pencil lines.

estimate Find an approximate value for an unknown quantity.

evaluate Assess the implications and limitations.

examine Inquire into.

explain Make something clear or easy to understand.

extract Choose relevant and/or appropriate details.

extrapolate Infer from what is known.

hypothesise Suggest an explanation for a group of facts or phenomena.

identify Recognise and name.

interpret Draw meaning from.

investigate Plan, inquire into and draw conclusions about.

justify Support an argument or conclusion.

label Add labels to a diagram.

list Give a sequence of names or other brief answers.

measure Find a value for a quantity.

outline Give a brief account or summary.

plan Use strategies to develop a series of steps or processes.

predict Give an expected result.

propose Put forward a plan or suggestion for consideration or action.

recall Present remembered ideas, facts or experiences.

relate Tell or report about happenings, events or circumstances.

represent Use words, images or symbols to convey meaning.

select Choose in preference to another or others.

sequence Arrange in order.

show Give the steps in a calculation or derivation.

sketch Make a quick, rough drawing of something.

solve Work out the answer to a problem.

state Give a specific name, value or other brief answer.

suggest Put forward an idea for consideration.

summarise Give a brief statement of the main points.

synthesise Combine various elements to make a whole.

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Charged Particles, Conductors, Electric and Magnetic Fields

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6.1 Electric Fields and Parallel Plates

Investigate and quantitatively derive and analyse the interaction between charged particles and uniform electric fields, including the electric field between parallel charged plates: $E = \frac{V}{d}$.

Electric fields

A **field** is a region in which something will experience a force.

An **electric field** is a region in which charged particles experience forces.

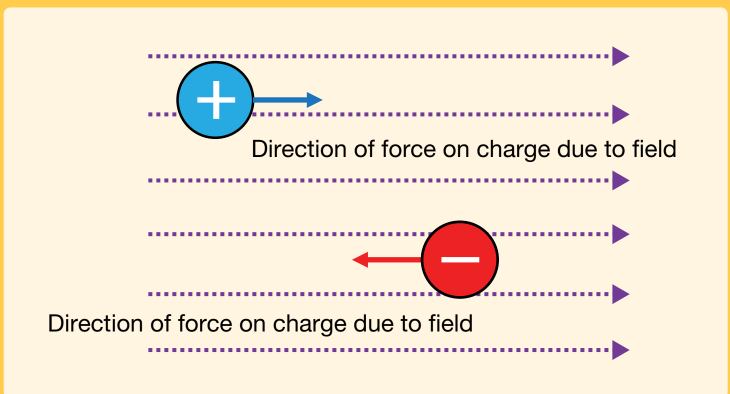
An electric field exists at a point if a charge placed at that point experiences a force.

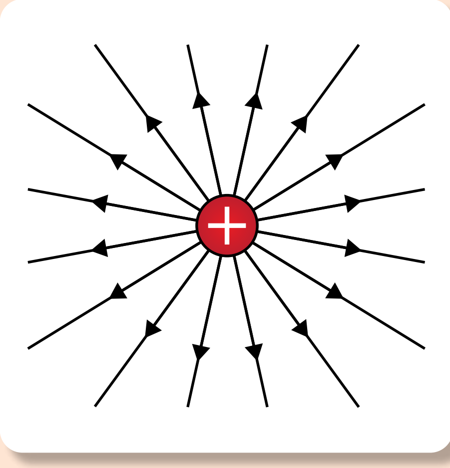
Electric field is directed **away from positive towards negative**, or

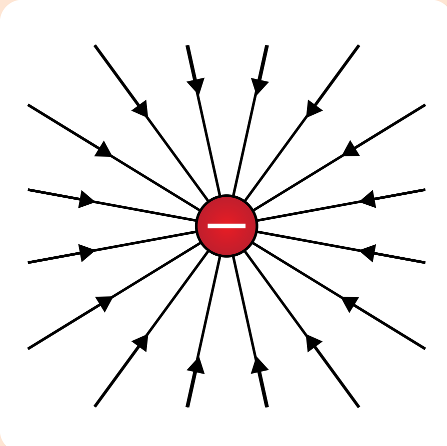
Electric field is directed **from high potential to low potential**.

As a result of these forces, if the charges are free to move they will accelerate in the direction of the force on them (Newton's second law of motion).

The direction of the electric field at a point can also be defined as the direction of the force experienced by a positive charge placed in the field at that point.







A positive charge will experience a force in the direction of the field.

A negative charge will experience a force in the opposite direction to the field.

Electric field is a **vector** quantity and can be represented by vector arrows.

The **direction of the arrow represents the direction of the field** (from positive to negative, or, from high to low potential), and

The **closeness of the arrows indicates** the magnitude of the field at each point in the field.

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Sample Questions

1. (a) Define an electric field.

(b) What are the units of electric field?

(c) In what direction relative to a field will a positive charge move when placed in it?

(d) In what direction relative to a field will a negative charge move when placed in it?

(e) Why do we use arrows to represent an electric field?

(f) How do we compare the relative strengths of electric fields by looking at diagrams representing them?

(g) What is the direction of electric field relative to a positive charge?

(h) What is the direction of electric field relative to a negative charge?

(i) What is the direction of electric field relative to a high potential position?

(j) What is the direction of electric field relative to a low potential position?

2. A uniform electric field acts to the left. In which direction will each of these particles accelerate?

(a) An electron.

(b) A positron (an antielectron).

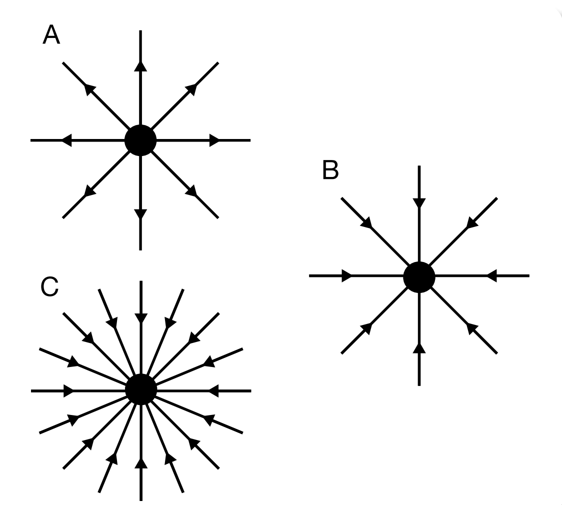
(c) A neutron.

(d) An antiproton.

(e) A helium nucleus (He^{2+}).

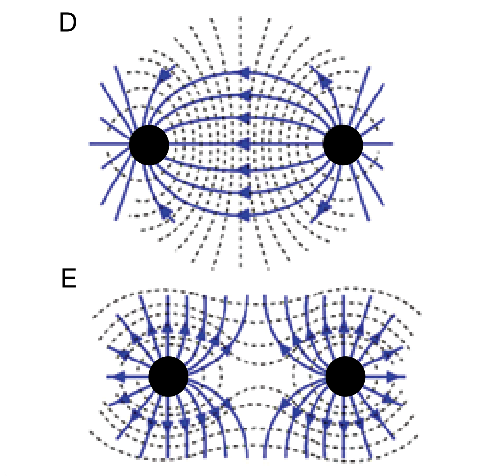
(f) A neutrino.

3. Consider the field lines around the charges shown.

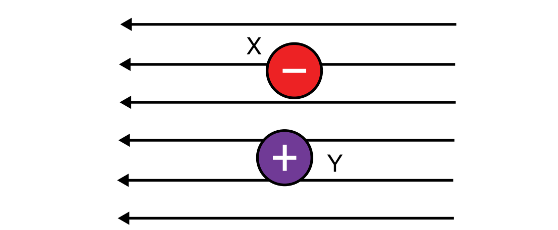


(a) Compare the fields A, B and C and the charges causing them. Justify your answer.

(b) Compare fields D and E and the charges causing them. Justify your answer.



4. Two charged particles X and Y are placed in an electric field as shown. The field is directed towards the left.

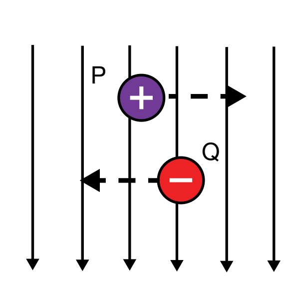


(a) Describe what happens to each particle.

(b) Describe what happens to the kinetic energy of each particle.

(c) Describe what happens to the electrical potential energy of each particle.

5. Consider charged particles P and Q in an electric field directed towards the bottom of the page as shown. P is moved at constant velocity to the right through the field and Q is moved to the left.



(a) How does the electrical potential energy of each charge change? Justify your answer.

(b) Describe the nature and source of the force causing the movement of each charge. Justify your answer.

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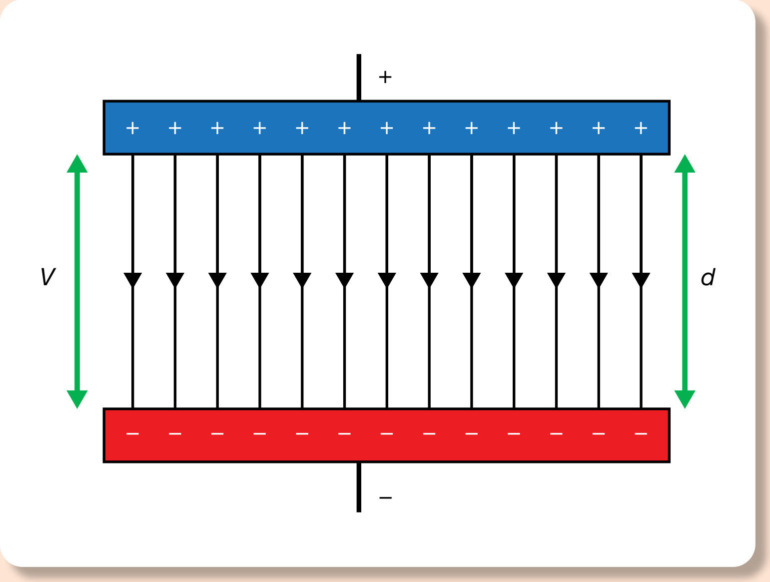
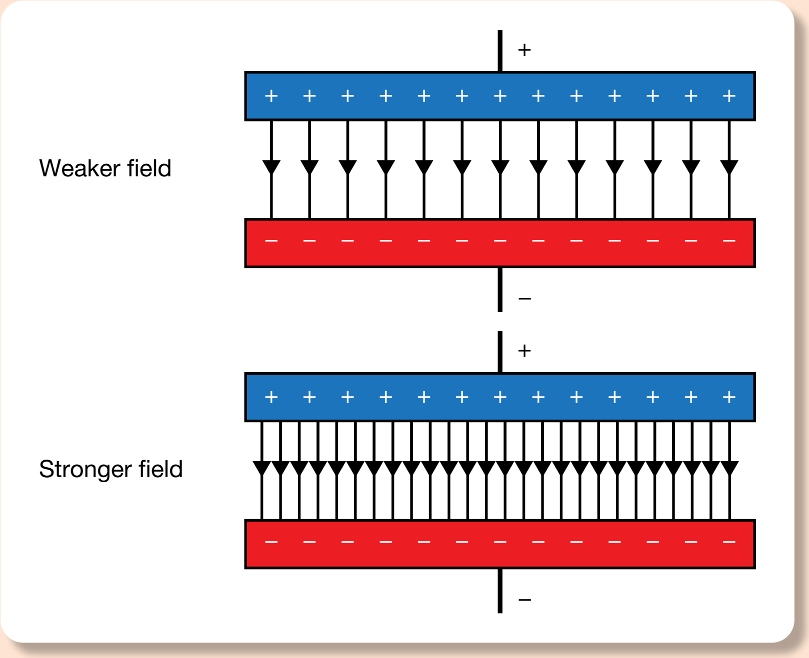
Parallel plates

- The electric field between parallel plates is directed from the high potential (positive) plate to the low potential (negative) plate.
- The field between the plates is **uniform** in intensity.
- This is shown by the field lines being equidistant from each other.



- The **closeness of the arrows indicates** the magnitude of the field at each point in the field.



- The intensity of the field is given by the following.

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

Where V = electrical potential difference between plates (V)

d = distance between plates (m)

E = electric field in volts per metre (V m^{-1})

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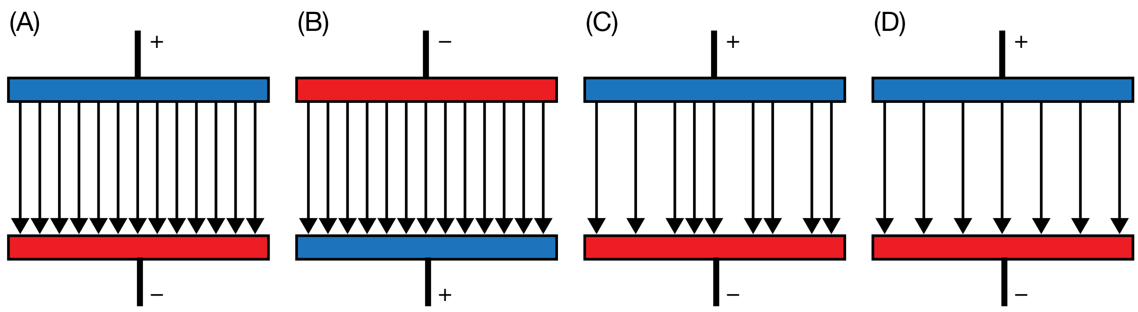
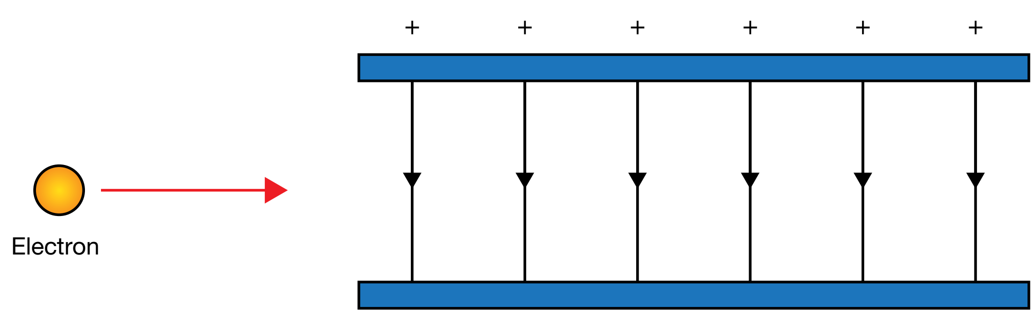
Sample Questions

1. (a) Which of the following fields between the parallel plates is correct and the strongest?

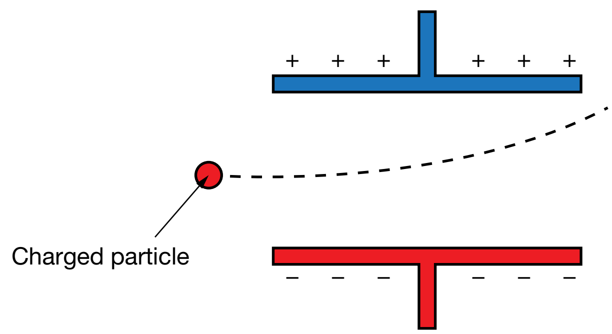


(b) Which of the fields above are represented correctly?

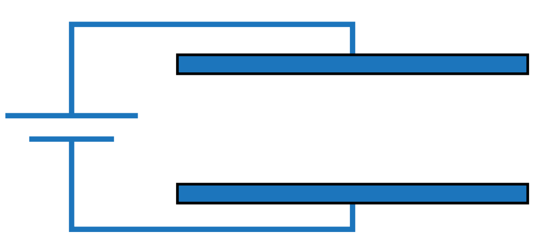
2. An electron is about to enter and pass through the electric field between the parallel plates shown below. Draw in its path through the field and after it leaves the field.



3. What is the charge on the particle in this diagram? Justify your answer.



4. (a) Draw in the field lines between the parallel plates shown. Justify your answer.
(b) What would these field lines look like if the voltage between the plates was doubled?
(c) What would these field lines look like if the distance between the plates was doubled?
(d) Why should you have drawn your field lines equidistant apart?



6.2 Interaction Between Charges and Electric Fields

Investigate and quantitatively derive and analyse the interaction between charged particles and uniform electric fields, including acceleration of charged particles by the electric field: $F = ma$, $F = qE$:

Interaction between charges and electric fields

- The force on a charge in an electric field can be found using: $$\boxed{F = qE}$$

And we already have: $$\boxed{E = \frac{V}{d}}$$

- Where F = force on charge Q_1 due to field produced by charge Q_2 (N)
  E = strength of electric field V m^{-1} or, from the equation above, N C^{-1}
  q = charge (C)
  k = constant = 9×10^9 (N m^2 C^{-2})
- Combining these two equations, we get: $$\boxed{F = \frac{qV}{d}}$$
- Note that the equation above for electric field will give us another definition for the strength of the field:

The strength of an electric field can be defined as the force per unit charge at that point.

- Note also that the force on a charge in an electric field may also be a net force in which case Newton's second law of motion applies to it. It will therefore **accelerate** within the field according to: $$\boxed{F = qE = \frac{qV}{d} = ma}$$
- From which we can find the acceleration of the charge in the field: $$\boxed{a = \frac{F}{m} = \frac{qE}{m} = \frac{qV}{md}}$$

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Sample Questions

1. A charge of +9.0 μC experiences a force of 2.5×10^{-8} N north at point P. Calculate the electric field at P.

2. A charge of –4.0 mC experiences a force of 8.4×10^{-6} N west at point P. Calculate the electric field at P.

3. A charge of +1.5 nC is in an electric field of strength 7.5×10^{3} N C^{-1} south at point P. Calculate the force on the charge.

4. A charge of –2.7 μC is in an electric field of strength 5.4×10^{-8} N C^{-1} east at point P. What force acts on the charge?

5. 3.3×10^{-14} N north acts on point charge P in an electric field of strength 4.0×10^{-6} N C^{-1} north. Find the magnitude and sign of P.

6. 1.6×10^{-6} N west acts on point charge P in an electric field of strength 8.0×10^{-5} N C^{-1} east. Find the magnitude and sign of P.

7. A charge of -8.0×10^{-9} C is midway between two parallel plates which are 5.0 cm apart. The potential between the plates is 6000 V. Find the force on the charge.

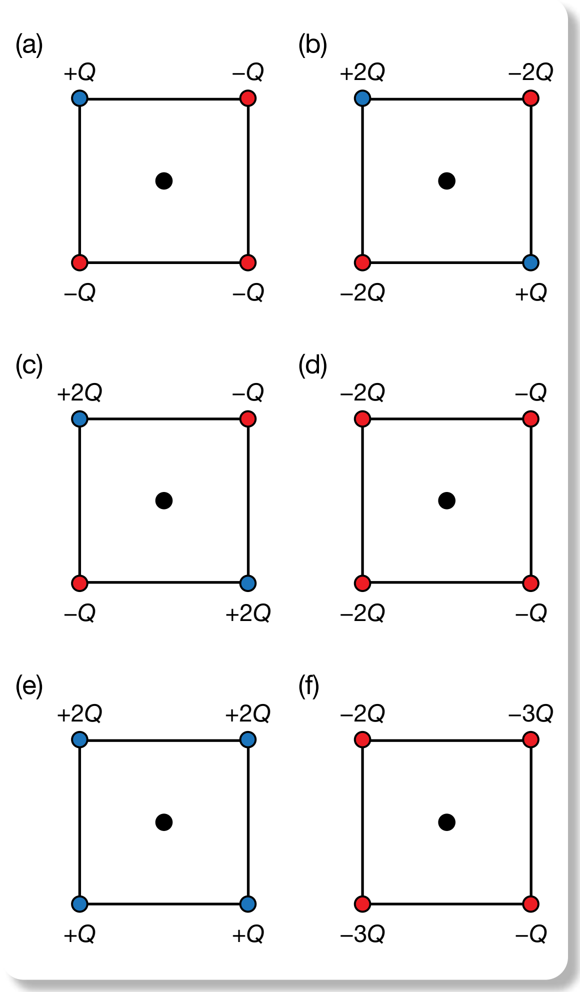
8. An electron, charge -1.6×10^{-19} C, in a cathode ray tube experiences a force of 1.6×10^{-15} N towards the north. Calculate the magnitude and direction of the electric field at that point.

9. (a) Two parallel plates P and Q have potentials of +800 V and +350 V respectively. They are separated by 9.0 cm in air. Determine the electric field at point R, midway between P and Q.
   (b) What would be the force on a helium nucleus placed at R?

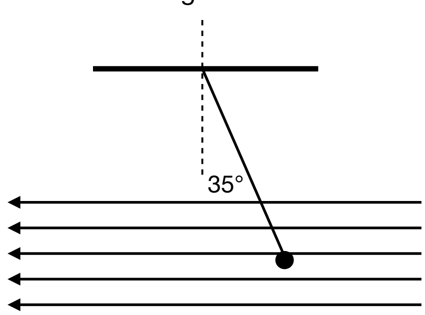
10. Calculate the acceleration of a proton on an electric field of strength 1.5×10^{-5} N C^{-1}. The charge on a proton is $+1.6 \times 10^{-19}$ C and its mass is 1.7×10^{-27} kg.

11. A force of 7.5×10^{-10} N east acts on a charge at point X in an electric field of strength 6.0×10^{-5} N C^{-1} east.
   (a) Calculate the magnitude of the charge.
   (b) Identify the sign of the charge. Justify your answer.

12. Four charges are arranged on the corners of six different rectangles in the situations shown below. Draw in vectors to represent the direction of the net field at the centre of each of the figures.



13. A uniform electric field points to the left. A small metal ball charged to –5.0 μC hangs at a 35° angle from a string of negligible mass attached to the ceiling as shown.



The tension in the string is measured to be 0.4 N. What is the magnitude of the electric field?

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6.3 Interactions Between Charges and Work Done

Investigate and quantitatively derive and analyse the interaction between charged particles and uniform electric fields, including the work done on the charge: $W = qV$, $W = qEd$, $K = \frac{1}{2}mv^2$.

Interactions between charges and work done

- Charges in electric fields experience a force, which if unbalanced, will cause them to accelerate.
- In other words, the field does work on the charge.
- If the charge is positive, it will accelerate in the direction of the field, and if negative, it will accelerate in the opposite direction to the field.
- In both cases the work is done by the field and electrical potential energy of the charge is changed into kinetic energy as described in the equations below.

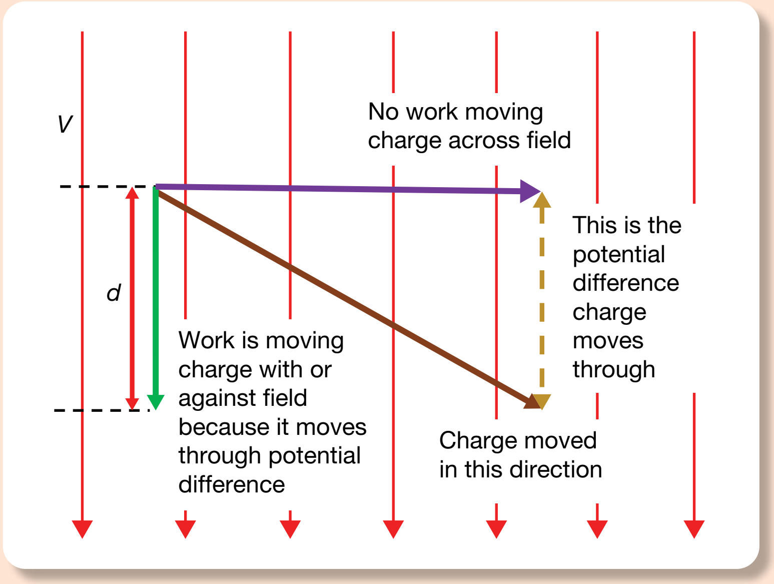
$$\boldsymbol{W = qV = qEd = \Delta KE = \frac{1}{2}mv^2} \text{ (Assuming particle starts from rest)}$$

Where W = work done (joules)
q = charge (coulombs)
V = potential difference moved through (volts)
E = electric field (V m^{-1} or N C^{-1})
d = distance moved parallel to field (m)
m = mass of charged particle (kg)
v = velocity given to particle (m s^{-1})
u = initial velocity (m s^{-1})

If the particle does not start from rest, then:

$$\boldsymbol{\Delta KE = \frac{1}{2}m(v^2 - u^2)}$$

- Note that no work is done by the field in moving the charge perpendicular to the field because it has not moved through any change in potential.



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Sample Questions

1. A positive test charge moves from point A to higher potential point B in an electric field. The work done by the field during this process is proportional to:

(A) The potential difference between A and B and is done by the field.

(B) The difference in the potential energy between A and at point B and is done by an external source.

(C) The difference between the values of the electric field at points A and B and is done by the field.

(D) Zero if the field is uniform.

2. A uniform electric field is directed from left to right. In which case would the field do work to move a positive test charge in this field?

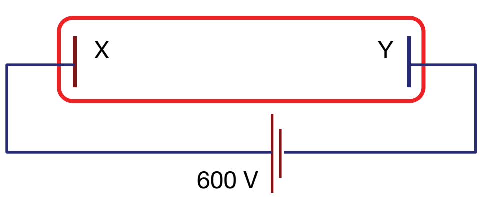
(A) If it is moved from left to right.

(B) If it is moved from right to left.

(C) If it is moved sideways at 90°.

(D) If it is moved vertically upwards through the field.

3. The diagram shows a cathode ray tube where 9.6×10^{15} electrons, each with mass 9.11×10^{-31} kg move from X to Y per second.



(a) What is the direction of the electric field inside the cathode ray tube? Justify your answer.

(b) What current flows in the circuit?

(c) What work is done on each electron as it moves between X and Y?

(d) What will be the speed of the electrons as they hit electrode Y?

4. A negative charge, *Q* at point X midway between two oppositely charged parallel plates moves at constant speed to point Y also midway between the plates. Which statement is correct?

(A) Work is done on *Q* by an external force

(B) Work done to move it = *QV*.

(C) The field does work on *Q* to move it.

(D) The work done in moving *Q* is zero.

5. Two parallel plates are 6.0 mm apart and have a potential of 240 V across them.

(a) What is the strength of the electric field between the plates?

(b) Describe the motion of an electron released from the negative plate and travelling to the positive plate.

(c) Find the force on this electron

(d) What will be its acceleration?

(e) Find the work done on the electron.

(f) With what speed will the electron reach the positive plate?

6. A lightning strike transfers 3500 C of charge 1.4 km to the ground through a potential difference of 1.75×10^6 V. How much energy was carried by the lightning?

(A) 4900 J

(B) 4.375×10^9 J

(C) 6.125×10^9 J

(D) 8.575×10^9 J

7. The potential across a 30 cm long cathode ray tube is 45 000 V. What is the *KE* of an electron, just before it hits the anode?

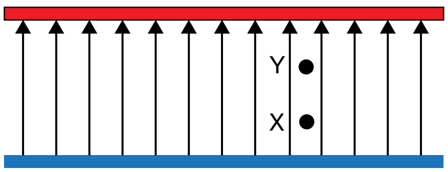
(A) 13 500 J

(B) 2.16×10^{-16} J

(C) 7.20×10^{-15} J

(D) 2.4×10^{-14} J

8. The diagram shows two parallel plates 6 cm apart, and points X and Y. A $+8.0 \times 10^{-18}$ C charge, mass 8×10^{-25} kg is placed at X.



(a) The charge is moved from X to Y. Identify any changes to the force on it. Justify your answer.

(b) Moving from X to Y, the charge moves through 900 V. What work is done on the charge and by what?

(c) Find the speed of the charge at Y?

(d) What is the electric field between the plates if the distance XY represents one third the distance between the plates?

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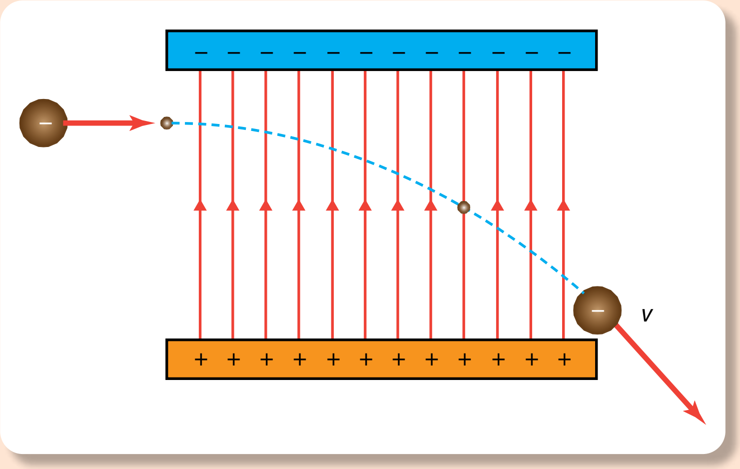
6.4 Trajectories Of Particles

Model qualitatively and quantitatively the trajectories of charged particles in electric fields and compare them with the trajectories of projectiles in a gravitational field.

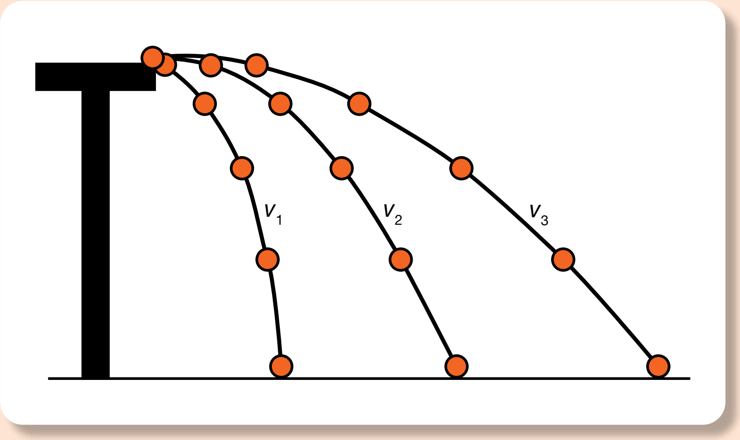
Trajectories of particles

Path of charged particle in an electric field



- A charged particle, such as an electron, fired into a uniform electric field will follow a **parabolic path** because only one force acts on it in a constant direction.
- In this case, the horizontal velocity will be constant, and the vertical velocity is accelerated.
- The electron in this example accelerates towards the positive plate.
- Note that from $F = Eq = ma$:
- If charge is increased, force increases so acceleration increases, so curve is increased.
- If horizontal velocity is increased, curvature decreases.
- If mass of charge is increased, acceleration decreases, so curvature decreases.

Path of projectile in a gravitational field



- A projectile, launched horizontally or at an elevation, will follow a parabolic path because only a vertical force acts on it.
- The direction of the force is constant (in this case gravity downwards).
- In all cases, the horizontal velocity is constant, and vertical velocity is accelerated.
- The projectile will accelerate towards the ground, its range depending on its horizontal velocity.
- Note that:
  - If mass of projectile is increased, there will be no change to the path followed.
  - If horizontal velocity is increased, range will increase.

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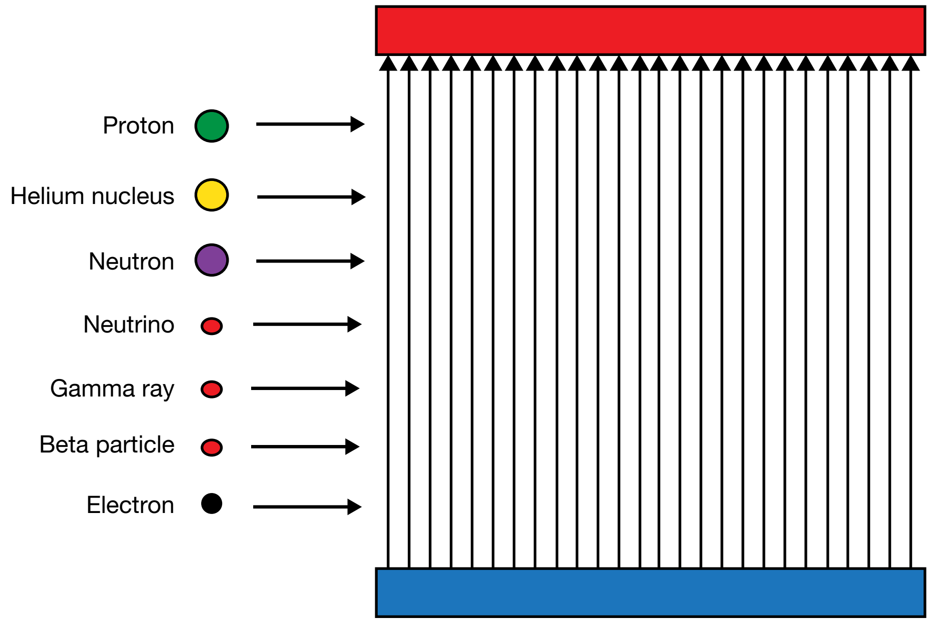
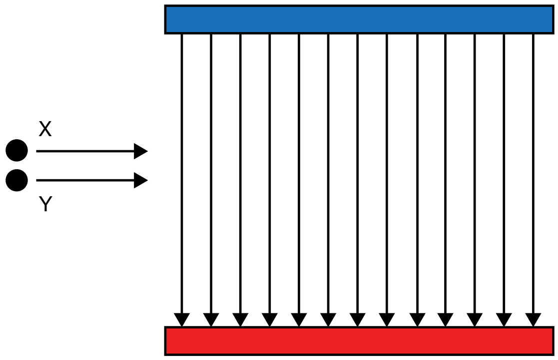
Sample Questions

1. Complete the diagram to compare the relative paths of the particles indicated through (and out of if it is relevant) the electric field shown. All particles enter the field with the same speed.



2. Account for the similarity between the paths of charged particles through electric fields to that of projectiles through gravitational fields.

3. Consider the two particles X and Y about to enter the electric field shown.
   (a) Draw in the paths of the particles in the field if they are same charge, same mass but X is moving slower than Y.
   (b) Draw in the paths of the particles in the field if they are the same charge and same speed but X has less mass than Y.
   (c) Draw in the paths of the particles in the field if they are the same mass and same speed but X has a larger charge than Y.



4. A student compared the trajectory of a charged particle fired between two parallel charged plates in a cathode ray tube with that of a ball rolled off the laboratory desk. Both trajectories were photographed with a strobe camera and compared.
   (a) One of these experiments is not as valid as the other. Which one and why?
   (b) How would this affect the observed results?
   (c) What could be done to make them equally valid?

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Answers

6.1 Electric Fields and Parallel Plates

Electric fields

1. (a) An electric field is a region in which a charged particle experiences a force.
(b) Depending on the situation, N C^{-1} or, for parallel plates, V m^{-1}.
(c) In the direction of the field.
(d) In the opposite direction to the field.
(e) Because fields are vector quantities.
(f) The closer together the field vectors, the stronger the field they represent.
(g) Field is directed away from the charge.
(h) Field is directed towards a negative charge.
(i) Field is directed from high potential.
(j) Field is directed towards low potential.

2. (a) To the right (in the opposite direction to the field).
(b) To the left (in the direction of the field).
(c) No force will act on a neutron in an electric field.
(d) To the right (opposite the direction of the field = antiprotons carry a negative charge).
(e) To the left (in the direction of the field).
(f) No force will act on a neutrino in an electric field.

3. (a) Field C is stronger than fields A and B because the field lines are closer together which means charge C has a larger magnitude than charges A or B. The magnitude of the charges on A and B are equal because the field lines are equal distance apart. B and C are negatively charged because the field lines are directed towards them while A is positively charged – field lines directed away from positive.
(b) Field D is stronger than field C because there are more field lines around the charges in D (17 compared to 16) which means charges in D have a slightly larger magnitude than charges in C.
Charges in D are opposite, because it shows an attractive field. The left hand charge is negative (field lines towards it), the right hand charge is positive (field lines away from it).
Charges in E are both positive because the field is repulsive and the lines are going away from the charges.

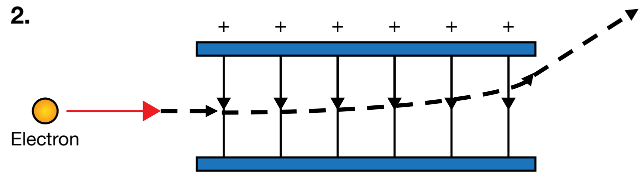
4. (a) X will accelerate against the field (to the right).
Y will accelerate in the direction of the field (left).
(b) The kinetic energy of both particles will increase as work will be done on them by the field.
(c) The electrical potential of each charge will decrease as they both accelerate to a lower potential energy position in the field (relative to their charge).

5. (a) Electrical potential of the charges does not change – there is no movement parallel to the field.
(b) In each case the movement is due to an externally applied force because they are moving across the field not in the direction of the force on them due to the field. This externally applied force must also be preventing them moving in the direction of the force on them due to the field.

Parallel plates

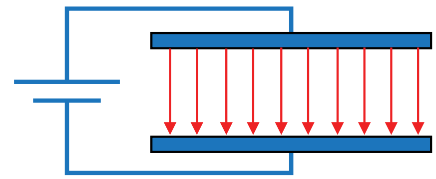
1. (a) A
(b) A and D

2.



3. Charge is negative because it is deflected towards the positively charged plate.

4. (a)



(b) There would be twice as many lines, twice as close together.
(c) There would be half as many lines, twice the distance apart because the field would be half strength.
(d) Because the equidistance property indicates that the field is uniform in intensity.

6.2 Interaction Between Charges and Electric Fields

1. From $E = \frac{F}{q} = \frac{2.5 \times 10^{-8}}{9 \times 10^{-6}} = 2.8 \times 10^{-3}$ N north

2. From $E = \frac{F}{q} = \frac{8.4 \times 10^{-6}}{4 \times 10^{-3}} = 2.1 \times 10^{-3}$ N east

3. From $F = Eq = 7.5 \times 10^{3} \times 1.5 \times 10^{-9}$
$= 1.125 \times 10^{-5}$ N south

4. From $F = Eq = 5.4 \times 10^{-8} \times 2.7 \times 10^{-6}$
$= 1.46 \times 10^{-13}$ N west

5. From $q = \frac{F}{E} = \frac{3.3 \times 10^{-14}}{4.0 \times 10^{-6}} = +8.25$ nC

6. From $q = \frac{F}{E} = \frac{1.6 \times 10^{-6}}{8.0 \times 10^{-5}} = -0.02$ C

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