Physics 30 Unit B diploma pack: Forces and fields

This pack gets you ready for the Unit B questions on the Physics 30 diploma exam. You can work through it on your own, at your own speed.

1. Do the start check.
2. Tick the checklist.
3. Do each card you need: read the steps, follow the worked example, then answer the questions.
4. Hand in each card check.
5. When your Part 1 cards are done, ask for Quiz 1. When your Part 2 cards are done, ask for Quiz 2.
6. Do the practice unit check and the exam-style question sets at the end. Then ask for the unit final.

1. Start check

Do these questions first, one for each card. If you get a question right, you may skip that card. If you get it wrong, or you guessed, do that card.

Start check 1 (card 1)

Two identical metal spheres on insulating stands carry +6.0 μC and −2.0 μC. They touch and are then separated. The charge on each sphere is

A. +4.0 μC
B. +2.0 μC
C. −2.0 μC
D. +8.0 μC

Start check 2 (card 2)

Two point charges exert a force F on each other. The distance between them is doubled. The new force is

A. 2 F
B. ½ F
C. 4 F
D. ¼ F

Start check 3 (card 3)

A charge feels two electric forces: 6.0 N [east] and 8.0 N [north]. The size of the net force is

A. 10 N
B. 14 N
C. 2.0 N
D. 7.0 N

Start check 4 (card 4)

An electron is in an electric field that points north. The electric force on the electron points

A. north
B. east
C. south
D. west

Start check 5 (card 5)

The force F between two fixed charges q_1 and q_2 is plotted against $1/r^2$. The line of best fit is straight. The slope of the line equals

A. k
B. kq_1q_2
C. $k \div r^2$
D. q_1q_2

Start check 6 (card 6)

A charge of 4.0 C gains 20 J of energy when it moves between two points. The potential difference between the points is

A. 80 V
B. 0.20 V
C. 24 V
D. 5.0 V

Start check 7 (card 7)

Two parallel plates are 0.050 m apart. The potential difference across them is 100 V. The electric field strength between the plates is

A. 2.0×10^3 V/m
B. 5.0 V/m
C. 5.0×10^{-4} V/m
D. 2.0×10^2 V/m

Start check 8 (card 8)

A charged oil drop is held at rest between two horizontal charged plates. Which equation describes the forces on the drop?

A. qE = ma
B. qE + mg = ma
C. qE = mg
D. mg = ma

Start check 9 (card 9)

A long straight wire lies in the plane of the page. It carries conventional current toward the top of the page. The magnetic field at a point to the left of the wire is directed

A. into the page
B. out of the page
C. to the left
D. toward the top of the page

Start check 10 (card 10)

An electron moves to the right through a magnetic field that points into the page. The magnetic force on the electron is directed

A. toward the top of the page
B. to the left
C. into the page
D. toward the bottom of the page

Start check 11 (card 11)

A charged particle moves in a circle in a magnetic field. The speed of the particle is doubled. The radius of the circle

A. is half as large
B. stays the same
C. is twice as large
D. is 4 times as large

Start check 12 (card 12)

A particle passes straight through a velocity selector that has an electric field E and a magnetic field B. The speed of the particle is

A. $E \div B$
B. $B \div E$
C. $E \times B$
D. $qE \div B$

Start check 13 (card 13)

A wire carries a current of 2.0 A. A 0.50 m length of the wire lies at right angles to a magnetic field of 0.10 T. The size of the magnetic force on the wire is

A. 0.010 N
B. 0.40 N
C. 10 N
D. 0.10 N

Start check 14 (card 14)

The north pole of a magnet is pushed into a coil that is part of a closed circuit. Lenz's law says the induced current in the coil makes a force on the magnet that

A. pulls the magnet into the coil
B. pushes the magnet back out, against its motion
C. turns the magnet around
D. is zero until the magnet stops

Answers for the start check

Start check 1 (card 1): B. (+6.0) + (−2.0) = +4.0 μC in total. Divide by 2 spheres: +2.0 μC each. Wrong or unsure? Do card 1.

Start check 2 (card 2): D. The force depends on $1/r^2$. Double the distance gives $1 \div 2^2 = ¼$ of the force. Wrong or unsure? Do card 2.

Start check 3 (card 3): A. The forces are at right angles: $\sqrt{(6.0^2 + 8.0^2)} = 10$ N. Wrong or unsure? Do card 3.

Start check 4 (card 4): C. The field shows the force on a positive charge. An electron is negative, so the force on it is opposite to the field: south. Wrong or unsure? Do card 4.

Start check 5 (card 5): B. $F = (kq_1q_2) \times (1/r^2)$. Compare it with $y = mx$. The number that multiplies $1/r^2$ is the slope: kq_1q_2. Wrong or unsure? Do card 5.

Start check 6 (card 6): D. $\Delta V = \Delta E \div q = 20$ J ÷ 4.0 C = 5.0 V. Wrong or unsure? Do card 6.

Start check 7 (card 7): A. $E = \Delta V \div \Delta d = 100$ V ÷ 0.050 m = 2.0×10^3 V/m. Wrong or unsure? Do card 7.

Start check 8 (card 8): C. At rest, the forces balance. The electric force up equals the weight down: $qE = mg$. Wrong or unsure? Do card 8.

Start check 9 (card 9): B. Grip the wire with your right hand, thumb toward the top of the page. On the left of the wire your fingers come out of the page. Wrong or unsure? Do card 9.

Start check 10 (card 10): D. Right hand flat: fingers into the page, thumb to the right, palm toward the top of the page. That is for a positive charge. An electron is negative, so reverse it: toward the bottom of the page. Wrong or unsure? Do card 10.

Start check 11 (card 11): C. $qvB = mv^2 \div r$ gives $r = mv \div (qB)$. The speed is on top, so twice the speed gives twice the radius. Wrong or unsure? Do card 11.

Start check 12 (card 12): A. Straight through means the forces balance: $qE = qvB$. The charge cancels, so $v = E \div B$. Wrong or unsure? Do card 12.

Start check 13 (card 13): D. $F = IlB_\perp = (2.0\text{ A})(0.50\text{ m})(0.10\text{ T}) = 0.10$ N. Wrong or unsure? Do card 13.

Start check 14 (card 14): B. The induced current always opposes the motion that causes it. The magnet moves in, so the coil pushes it back. Wrong or unsure? Do card 14.

2. Checklist

Tick one box for each line. Come back and change it as you finish cards.

Card	I can …	Can do	Not yet
1	explain how an object was charged, and find the charge after spheres touch	☐	☐
2	find the force between two charges, and say what happens to the force when a charge or the distance changes	☐	☐
3	find the net force on one charge from two or more charges	☐	☐
4	find an electric field, add fields, and read a field-line picture	☐	☐
5	read a graph: find the slope, find a constant, and straighten a curve; name the variables in an experiment	☐	☐
6	use potential difference: energy per charge, the speed after a voltage, and the electron volt	☐	☐
7	solve a parallel-plate question: the field, the force, the acceleration, and the curved path	☐	☐
8	explain the oil-drop experiment, and solve a drop that is still or moving	☐	☐
9	find the direction of a magnetic field around a magnet, a wire or a coil, compare the three kinds of field, and find a current	☐	☐
10	find the size and direction of the magnetic force on a moving charge, or the sign of the charge	☐	☐
11	solve a circular-path question: the radius, the speed, the mass or the charge	☐	☐
12	solve a question with an electric field and a magnetic field together	☐	☐
13	find the force on a wire that carries a current in a magnetic field, and explain a motor	☐	☐
14	find an induced voltage and its direction, and use Lenz’s law	☐	☐

3. Terms

These are the words the diploma exam uses for this part of the unit. Each one has a plain meaning.

Part 1

electron
A tiny negative particle in an atom. Electrons are the only charges that move from one object to another.

proton
A positive particle in the nucleus of an atom. Protons stay where they are.

neutral
Having equal numbers of protons and electrons, so the total charge is zero.

net charge
The total charge on an object, with its sign. Add every charge, with its sign.

elementary charge (e)
The size of the charge on one electron or one proton: 1.60×10^{-19} C. It is on the data sheet.

coulomb (C)
The unit of charge. 1 µC is 10^{-6} C. 1 nC is 10^{-9} C.

conservation of charge
Charge is conserved: the total charge stays the same. Charge only moves from one object to another.

conductor
A material that lets electrons move through the whole object. Metals are conductors.

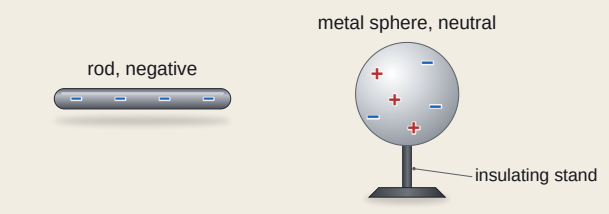
insulator
A material where electrons stay with their own atoms. Plastic, glass and rubber are insulators.

charging by rubbing
Rubbing two materials together moves electrons from one to the other. The exam may call this charging by friction.

charging by contact
A charged object touches another object and shares its charge. The exam may call this conduction. Both objects end with the same sign.

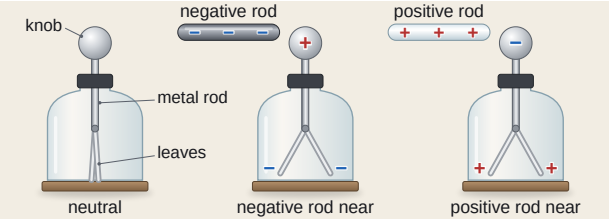
charging by induction
Charging an object without touching it: hold a charged rod near, connect a ground, remove the ground, then remove the rod. The object ends with the opposite sign to the rod.

charge separation
Electrons in an object shift to one side because a charged object is near. The object is still neutral.



ground
A wire to the Earth. The Earth can give or take any number of electrons.

electroscope
A metal knob, a metal rod and two thin metal leaves. The leaves push apart when they carry the same kind of charge.



point charge
A charge so small that it can be treated as a dot.

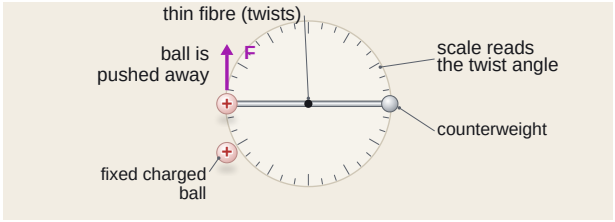
electric force
The push or pull between two charges. Alike charges repel. Unlike charges attract. The exam may call it the electrostatic force.

Coulomb's law
The rule for the size of the electric force between two point charges: $F = kq_1q_2 \div r^2$.

Coulomb's constant (k)
The constant in Coulomb's law: 8.99×10^9 $N \cdot m^2/C^2$. It is on the data sheet.

inverse square
Depending on $1/r^2$. Double the distance gives one quarter of the force or the field.

torsion balance
A balance that twists. Coulomb used one to measure the tiny force between charged balls. Cavendish used one to measure the tiny gravitational force between lead balls.



gravitational force
The pull between two masses. It has the same $1/r^2$ shape as the electric force, but it only attracts and it is far weaker.

magnitude
The size of a quantity, without its direction or sign.

vector
A quantity with a size and a direction, such as a force or a field.

net force
The sum of all the forces on one object, added as vectors. The exam may call it the resultant force.

free-body diagram
A drawing of one object as a dot, with one labelled arrow for each force on it. It never shows the parts of a force.

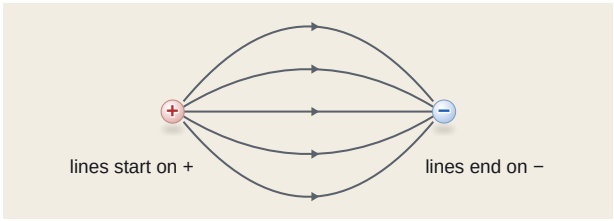
source charge
The charge that makes an electric field.

test charge
A small positive charge used to find the field at a point. The field shows the force on it.

electric field (E)
The electric force on each coulomb of charge at a point: $E = F \div q$, in N/C. It points the way a positive test charge is pushed.

vector field
A quantity that has a size and a direction at every point in a region. Electric, gravitational and magnetic fields are vector fields.

field lines
A picture of a field. Lines leave positive charges and end on negative charges. Closer lines mean a stronger field. Lines never cross.



radial field
The field of a point charge. The arrows point straight away from a positive charge or straight toward a negative charge, like bicycle spokes.

uniform field
A field with the same strength and the same direction everywhere. The field between parallel plates is uniform.

parallel plates
Two flat metal plates facing each other, one positive and one negative. The field between them is uniform.

work
Energy moved by a force that acts through a distance.

electric potential energy (Ep)
Energy a charge has because of where it is in an electric field. It is like the energy of a ball at the top of a hill.

electric potential difference (ΔV)
The change in electric potential energy for each coulomb of charge: $\Delta V = \Delta E \div q$. "Voltage" means the same thing.

volt (V)
The unit of potential difference. One volt is one joule per coulomb.

electron volt (eV)
A unit of energy, not of voltage. It is the energy one electron gains through one volt: 1.60×10^{-19} J.

kinetic energy (Ek)
The energy of motion: $E_k = \frac{1}{2}mv^2$.

conservation of energy
Energy is not made or lost. It changes form. For a charge in a field, lost potential energy becomes kinetic energy.

system
The objects you choose to study together, such as a charge and the plates. Name the system before you use conservation of energy.

parabola
The curved path of a particle with a constant speed one way and a constant acceleration at right angles to it.

oil-drop experiment
Millikan's experiment. He held tiny charged oil drops between plates and found the charge on each one.

quantized
Coming only in whole-number multiples of a smallest amount. Charge is quantized: every charge is a whole number times e.

manipulated variable
The one thing you change in an experiment. It goes on the horizontal axis.

responding variable
The thing you measure in an experiment. It goes on the vertical axis.

controlled variable
Anything you keep the same so the test is fair. The lessons call this "held fixed".

line of best fit
One straight line that follows the trend of the points, with about as many points above it as below it.

slope
Rise ÷ run for two points on the line. Its unit is the vertical unit ÷ the horizontal unit.

intercept
Where the line crosses the vertical axis. It is b in $y = mx + b$.

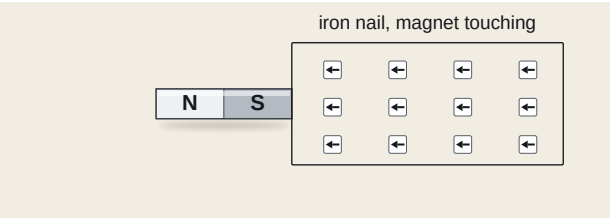
straightening a curve
Plotting against a new quantity, such as $1/r^2$, so that a curve becomes a straight line with a slope you can use. The exam may call this curve straightening.

Part 2

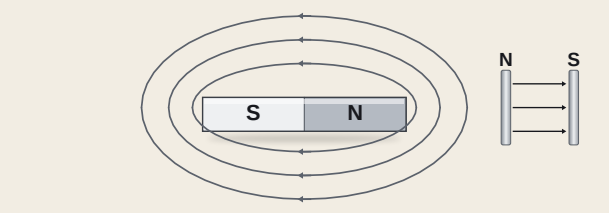
magnetic poles
The two ends of a magnet: north and south. Opposite poles attract. Like poles repel. Poles always come in pairs.

magnetic material
A material a magnet attracts, such as iron, nickel or cobalt. It is attracted to either pole and is never repelled. The exam may call it ferromagnetic.

domains
Tiny regions inside a magnetic material. Each one is a tiny magnet. In a magnet they line up the same way.



magnetic field (B)
The region around a magnet or a current where a compass feels a force. It is a vector. Its direction is the way the north pole of a compass points.



tesla (T)
The unit of magnetic field strength.

test compass
A tiny magnet on a pivot. It is the test object for a magnetic field, the way a positive test charge is for an electric field.

current (I)
The charge that passes a point each second: I = q ÷ t. The exam says “current” when the kind of moving charge does not matter.

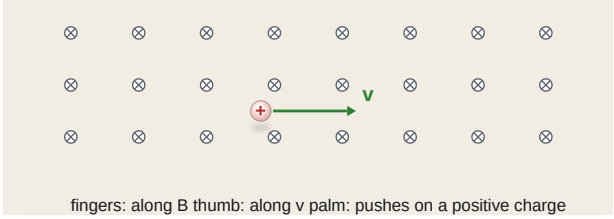
ampere (A)
The unit of current. One ampere is one coulomb each second.

conventional current
The way positive charge would move: out of the positive terminal. Every hand rule uses it.

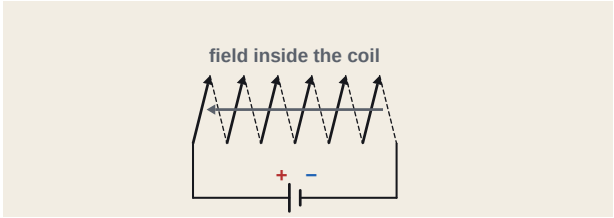
electron flow
The way the electrons really move in a wire. It is opposite to the conventional current.

into the page and out of the page
A circle with a cross means into the page, away from you. A circle with a dot means out of the page, toward you.

right-hand rule
A way to find a direction with your right hand. This unit has two: the grip, for the field around a current, and the flat hand, for the force on a moving charge or a current.



solenoid
A coil of wire. When it carries a current it has a north pole and a south pole, like a bar magnet.



electromagnet
A solenoid with an iron core. The iron makes the field much stronger. It is a magnet only while the current flows.

Oersted
The scientist who found that a current makes a magnetic field. A compass needle turned near his wire.

magnetic force
The push on a charge that moves across a magnetic field: F = qv⊥B. It is at right angles to the velocity and to the field.

perpendicular (⊥)
At right angles. v⊥ is the part of the velocity across the field. l⊥ is the length of wire across the field.

deflected
Pushed off a straight path. “Undeflected” means the path stays straight.

uniform circular motion
Motion in a circle at a constant speed. The net force always points to the centre.

centripetal force
The net force toward the centre of a circle: $mv^2 \div r$. For a charge in a magnetic field, it is the magnetic force.

mass spectrometer
A device that sends ions into a magnetic field and uses the radius of each circle to find the mass or the charge.

ion
An atom or molecule with a charge.

alpha particle
A helium nucleus. Its charge is 2 elementary charges, 3.20×10^{-19} C. Its mass is on the data sheet.

velocity selector
An electric field and a magnetic field at right angles. Only particles with the speed $E \div B$ pass straight through.

balanced and unbalanced forces
Balanced forces add to zero: the object stays at rest or moves in a straight line at a constant speed. Unbalanced forces give a net force and an acceleration.

current-carrying conductor
A wire or rod with a current in it.

motor effect
A wire that carries a current in a magnetic field is pushed. Current in, force out.

motor
A coil in a magnetic field that turns when a current flows. It changes electrical energy into motion.

split ring
The part of a motor that reverses the current in the coil every half turn, so the coil keeps turning one way. The exam may call it a commutator.

generator effect
A conductor moved through a magnetic field gets a potential difference between its ends. Motion in, electricity out.

generator
A coil turned in a magnetic field. It changes motion into electrical energy.

electromagnetic induction
Making a potential difference or a current by moving a conductor and a magnetic field past each other. Faraday discovered it.

induced current
A current made by motion in a magnetic field, with no battery.

Lenz’s law
The induced current always makes a force that opposes the motion that causes it.

aurora
Light in the sky near the Earth’s poles. Charged particles from the Sun are guided by the Earth’s magnetic field and hit the air.

4. Concept pages

Each page is one idea the diploma exam tests.

Concept 1: How diploma questions are answered

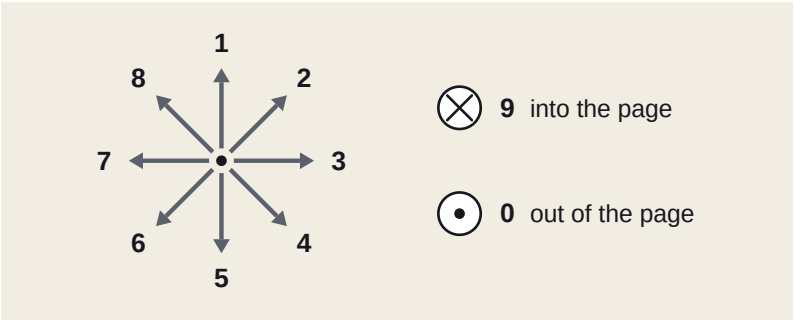
The diploma exam has 50 questions on a computer. Every question is marked by the computer. Fewer than half need a calculation.

Some questions are multiple choice. Some ask you to pick more than one answer, to finish a statement, to match items, or to put items in order.

Some questions ask you to type a number. This pack calls these numerical response. Read how the question tells you to record the answer. The table shows each way.

Some questions ask for a direction. The exam often shows a picture of numbered directions. Pick the one closest to your direction. This pack uses the picture below.

Use the constants from the data sheet, with three digits. Do not use a constant stored in your calculator.



The question says	Your answer	What you record	Why
Record your three-digit answer.	2.88 N	2 . 8 8	Type the number as it is, with its decimal point.
Write your answer as a.bc × 10^{w} N/C. Record the four digits a, b, c and w.	2.16 × 10^{5} N/C	2 1 6 5	a = 2, b = 1, c = 6 and w = 5. Do not type the “× 10”.
Write your answer as a.b × 10^{-cd} C. Record the four digits a, b, c and d.	9.6 × 10^{-19} C	9 6 1 9	a = 9, b = 6, c = 1 and d = 9. The minus sign is already in the question.
Record your three-digit answer.	0.601 N	0 . 6 0	For an answer below 1, the zero in front counts as one of the three digits. So 0.60 is a three-digit answer.
Record the number of the direction.	down and to the right	4	Use the direction picture on this page. Pick the direction closest to yours.
Record the four numbers in order.	step 2, then 4, then 1, then 3	2 4 1 3	Type the step numbers in the order the steps happen.
Record the numbers of the two principles.	principles 0 and 1	0 1	Either order is marked right.

Concept 2: Naming the physics principles

The data sheet lists ten physics principles, numbered 0 to 9. Some questions ask which two principles you need to solve a problem.

Ask two things. Is the object moving at a constant velocity, speeding up in a line, or moving in a circle? Is something conserved?

Unit B uses the six principles in the table.

Number	Principle	When you use it in this unit
0	Uniform motion (the net force is zero)	A charge hanging at rest. An oil drop that is still or moving at a constant velocity. The motion along the plates when a charge enters sideways. A particle that passes straight through a velocity selector. A wire that hangs still in a magnetic field.
1	Accelerated motion (the net force is not zero)	A charge speeding up in an electric field. An oil drop that speeds up. The motion across the plates. A particle that bends in a velocity selector.
2	Uniform circular motion (the net force points to the centre)	A charge moving in a circle in a magnetic field. A charge circling an unlike charge.
3	Work-energy theorem	Work done on a charge changes its energy.
5	Conservation of energy	A charge accelerated through a potential difference: $q\Delta V$ becomes kinetic energy. Lenz’s law: the work done against the induced force becomes electrical energy.
7	Conservation of charge	Spheres that touch and share their charge.

Concept 3: Charge, and three ways to charge an object

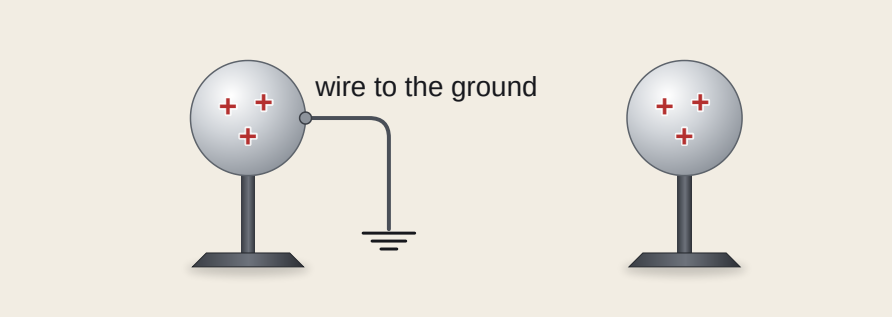
Only electrons move. An object that gains electrons is negative. An object that loses electrons is positive.

Rubbing moves electrons from one material to the other. Contact shares charge between two conductors. Induction charges a conductor without touching it, using a ground.

In every case the total charge stays the same. Charge is conserved.

On a conductor, extra charge spreads out over the surface. On an insulator, it stays where it was put.

The picture shows induction. The ground lets electrons enter or leave the sphere while the rod is near.



Concept 4: Force and field

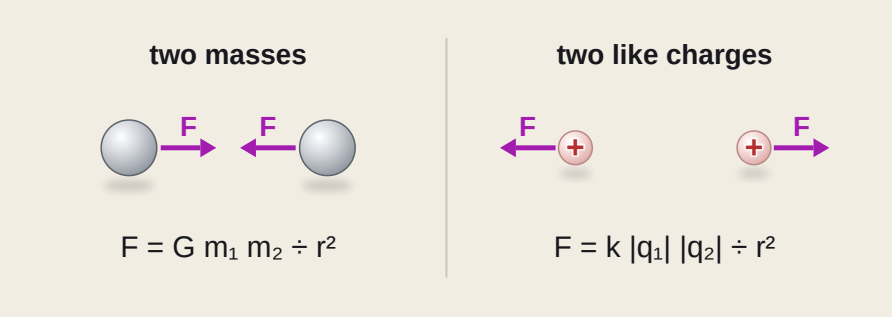
A force is a push or pull on one object. A field is what a source sets up in the space around it. Put a charge in the field, and the field gives it a force.

There are two ways to think about a field. The older view: a field is a way to explain how one object can push another without touching it. The view today: the field is real. We describe the field with mathematics, and we work out the force from how the motion of a charge changes.

Both views are models. Physics tests a model against the real world. When a model fails a test, it is changed, or a new test is made.

The electric force and the gravitational force follow laws of the same shape. Both get weaker with $1/r^2$.

The table compares the two. The exam may ask you to compare them in words or with numbers.



	Gravity	Electric
Source	mass	charge
Law for the force	$F = Gm_1m_2 \div r^2$	$F = kq_1q_2 \div r^2$
Attracts or repels	attracts only	attracts or repels
Direction of the field	toward the mass	away from a positive charge, toward a negative charge
Field	force on each kilogram	force on each coulomb
Strength	very weak	about 10^{39} times stronger, for an electron and a proton

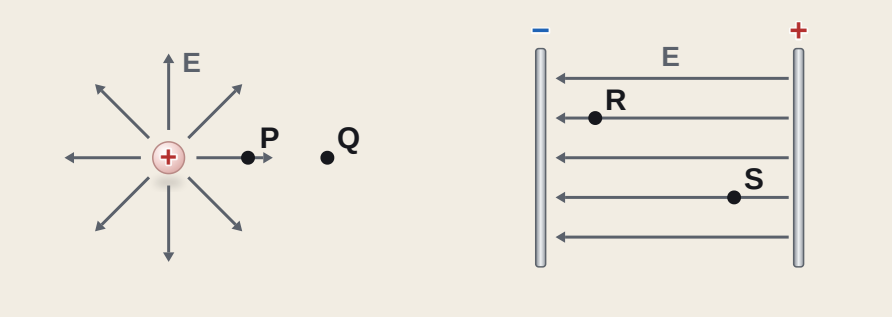
Concept 5: Radial fields and uniform fields

A point charge makes a radial field. It is stronger close to the charge, so the force on a charge changes as it moves.

Parallel plates make a uniform field. It has the same strength and direction everywhere between the plates, so the force on a charge stays the same.

Closer field lines mean a stronger field. The field points from positive to negative.

To map a field in a lab, move a small test charge or a field probe from point to point. At each point, record the size and the direction of the field. Then draw the field lines.



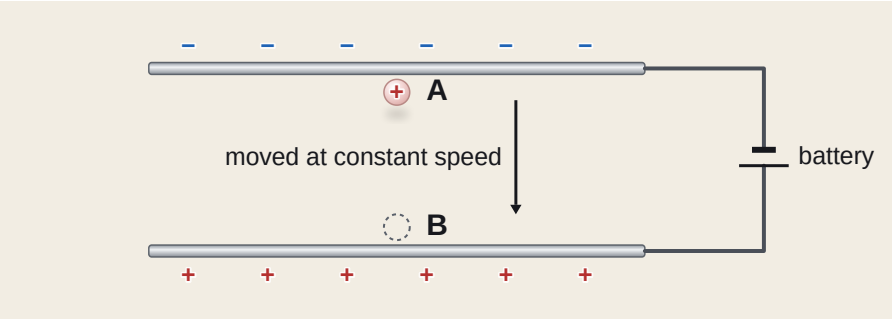
Concept 6: The energy of a charge

Pushing a charge against the electric force takes work. The work is stored as electric potential energy, like lifting a ball up a hill.

Potential difference is the energy for each coulomb: $\Delta V = \Delta E \div q$. So a charge q that moves through ΔV gains or loses the energy $q\Delta V$.

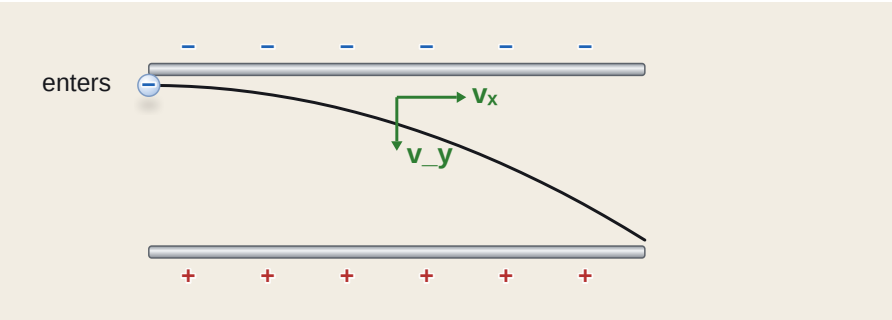
Let the charge go, and the stored energy becomes kinetic energy. Energy is conserved.

Small energies are often given in electron volts. $1\ eV = 1.60 \times 10^{-19}\ J$.



Concept 7: The shape of the path tells you the physics

The exam often names a path. The shape tells you which force acts and which steps to use.



Path	What it means	Where you see it
Straight line, constant speed	The net force is zero.	An oil drop moving at a constant velocity.
Straight line, speeding up or slowing down	A constant net force along the line of motion.	A charge released from rest between plates.
Parabola	A constant net force at right angles to the starting velocity.	A charge that enters a uniform electric field sideways.
Circle	A net force that always points to the centre. The speed stays the same.	A charge that circles an unlike charge in its radial electric field: the electric force is the force to the centre, so $kq_1q_2 \div r^2 = mv^2 \div r$. Part 2 of this pack: a charge in a magnetic field.

Concept 8: Where these ideas are used

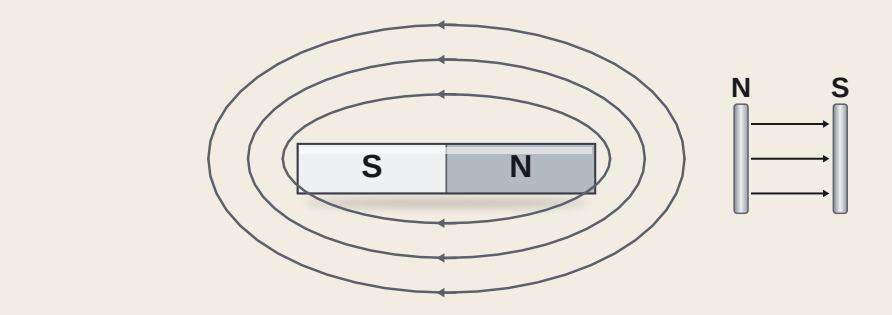
The exam sets questions in real situations. The physics is the same as on the cards.

Situation	The idea from this unit
Lightning rod	A conductor joined to the ground gives charge a path to the Earth.
Electrostatic air cleaner	Dust is given a charge. A plate with the opposite charge attracts it.
Photocopier	Charged areas on a drum attract the toner, which has the opposite charge.
A metal case around computer parts	Charge sits on the outside of a conductor, so the parts inside are shielded from outside electric fields.
Electron gun	A potential difference gives electrons kinetic energy: $q\Delta V = \frac{1}{2}mv^2$.

Concept 9: Three kinds of field

Gravity, electricity and magnetism each have a field. The exam asks you to compare them: where each comes from, and which way it points.

For all three, the field is stronger where the field lines are closer together. The picture shows the field lines of a bar magnet.

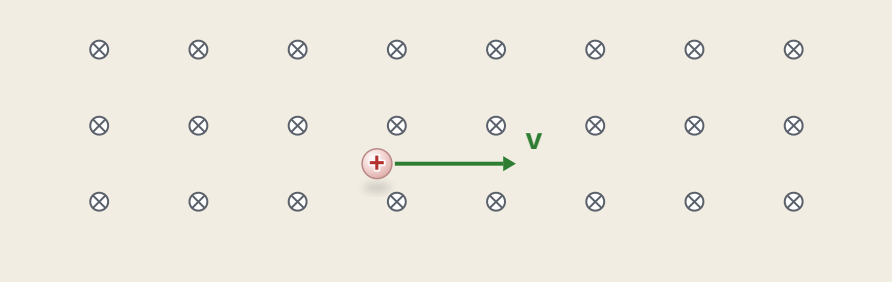


	Gravitational	Electric	Magnetic
Source	mass	charge	moving charge: a current or a magnet
Test object	a small mass	a small positive charge	a small compass
Direction of the field	toward the mass	away from positive, toward negative	the way the north pole of a compass points: out of a north pole, into a south pole
Acts on	any mass	any charge, at rest or moving	only a charge that moves across the field
Direction of the force	along the field	along the field for a positive charge, against it for a negative charge	at right angles to the field and to the velocity
Field lines	end on masses	start on positive charges, end on negative charges	closed loops: they have no start and no end

Concept 10: The hand rules

Every hand rule in this unit uses the right hand and the conventional current. If the question gives electron flow or a negative charge, find the answer for positive, then reverse it.

The picture shows the flat hand: fingers along the field, thumb along the velocity, and the palm faces the force.



fingers: along B thumb: along v palm: pushes on a positive charge

You want	Hand	What each part shows
The field around a straight wire or a moving charge	Grip	Thumb: the conventional current. Curled fingers: the field.
The north pole of a coil	Grip a front wire	Thumb: the conventional current in that wire. Fingers inside the coil: the field. The field leaves the north end.
The force on a moving charge	Flat hand	Fingers: the field. Thumb: the velocity. Palm: the force on a positive charge.
The force on a wire	Flat hand	Fingers: the field. Thumb: the conventional current. Palm: the force.
The positive end of a rod pulled through a field	Flat hand	Fingers: the field. Thumb: the velocity of the rod. Palm: the way positive charge is pushed. That end is positive.

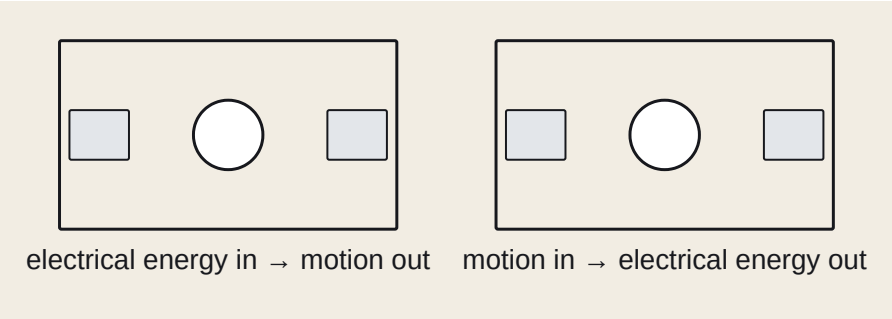
Concept 11: The motor effect and the generator effect

These are one idea run in two directions.

Motor effect: a current in a magnetic field feels a force. Electrical energy goes in. Motion comes out.

Generator effect: a conductor moved through a magnetic field gets a potential difference. Motion goes in. Electrical energy comes out.

Lenz's law joins them. When a generator makes a current, that current is in the field, so it feels a motor-effect force. The force opposes the motion. So you must do work to keep the generator turning. That work becomes the electrical energy. Energy is conserved.



Concept 12: Where the magnetism ideas are used

The exam sets questions in real situations. The physics is the same as on the cards.

Situation	The idea from this unit
Aurora	Charged particles from the Sun cross the Earth's magnetic field, so they feel a magnetic force. The field guides them toward the poles, where they hit the air and make it glow.
Motor	The motor effect: a coil that carries a current in a magnetic field is pushed, and it turns.
Generator	The generator effect: a coil turned in a magnetic field gets an induced current.
Speaker	The motor effect: a changing current in a coil near a magnet pushes the coil back and forth.
Mass spectrometer	A magnetic field bends ions into circles. The radius gives the mass or the charge.
MRI scanner	A very strong magnetic field from a large coil. The coil is a superconductor: a material that carries a current with no resistance when it is very cold.
Braking with magnets	Lenz's law: a magnet moving past metal makes induced currents, and the force on them opposes the motion.

5. Data sheet card

You get the Physics 30 data sheet in the exam. This card says where to look for what this unit needs. Use the constants as they are printed, with three digits.

What you need	Where it is on the data sheet	How to use it
Coulomb's constant, k	Constants	8.99×10^{9} N·m²/C². Use it in $F = kq_1q_2 \div r^2$ and $E = kq \div r^2$.
Elementary charge, e	Constants	1.60×10^{-19} C. The size of the charge on one electron or one proton.
Electron volt	Constants	1 eV = 1.60×10^{-19} J. Use it to change eV to J, or J to eV.
Acceleration due to gravity, g	Constants	9.81 m/s². You need it for a hanging charge and for an oil drop.
Gravitational constant, G	Constants	6.67×10^{-11} N·m²/kg². You need it to compare gravity with the electric force.
Mass and charge of an electron, a proton and an alpha particle	Particles table	The question may not give these. Look them up.
Prefixes, from n and μ up to G and T	Prefixes table	μ is 10^{-6} and n is 10^{-9}. M is 10^{6}, G is 10^{9} and T is 10^{12}. Change μC to C, or MeV to eV, before you calculate.
Force between two charges	Equations, Electricity and Magnetism	$F = kq_1q_2 \div r^2$. Use sizes. Get the direction from the signs.
Field of a point charge	Equations, Electricity and Magnetism	$E = kq \div r^2$. Here q is the source charge.
Field from a force	Equations, Electricity and Magnetism	$E = F \div q$. Rearranged: $F = qE$.
Field between parallel plates	Equations, Electricity and Magnetism	$E = \Delta V \div \Delta d$. Rearranged: $\Delta V = E\Delta d$.
Potential difference	Equations, Electricity and Magnetism	$\Delta V = \Delta E \div q$. Rearranged: $\Delta E = q\Delta V$.
Kinetic energy, and the equations of motion from Physics 20	Equations, Kinematics, Dynamics, and Momentum and Energy	$E_k = \frac{1}{2}mv^2$, $F = ma$, $d = v_it + \frac{1}{2}at^2$.
The ten physics principles	Physics Principles list	Numbered 0 to 9. See the concept page on naming the principles.
Current	Equations, Electricity and Magnetism	$I = q \div t$. Rearranged: $q = It$. Time in seconds.
Magnetic force on a moving charge	Equations, Electricity and Magnetism	$F = qv_\perp B$. Use the size of q. $v_\perp$ is the part of the velocity across the field.

Magnetic force on a wire	Equations, Electricity and Magnetism	$F = IlB_{\perp}$. Use only the length of wire inside the field.
Force toward the centre of a circle	Equations, Dynamics	$F = mv^2 \div r$. Set it equal to the force that points to the centre.
Not on the data sheet: the speed after a voltage	Build it from two equations that are	$\Delta E = q\Delta V$ and $Ek = \frac{1}{2}mv^2$ give $q\Delta V = \frac{1}{2}mv^2$, for a charge that starts from rest.
Not on the data sheet: the charge after identical spheres touch	Use conservation of charge	Add the signed charges. Divide by the number of spheres.
Not on the data sheet: the balance for an oil drop	Build it from two equations that are	$F = qE$ and the weight mg give $qE = mg$, for a drop at rest.
Not on the data sheet: the radius of a circular path	Build it from two equations that are	$qvB = mv^2 \div r$ gives $r = mv \div (qB)$.
Not on the data sheet: the speed for a velocity selector	Build it from two equations that are	$qE = qvB$ gives $v = E \div B$.
Not on the data sheet: the potential difference across a moving rod	Build it from equations that are	$qvB = qE$ and $E = \Delta V \div l$ give $\Delta V = Blv$.

Card 1: I can explain how an object was charged, and find the charge after spheres touch

Part 1 · from lessons B1

What the question looks like

The question shows rods, cloths, metal spheres on stands, a ground wire or an electroscope. It asks for the sign of a charge, the size of a charge, or which statement explains what happened. Words to look for: “touch”, “brought near”, “grounded”, “identical spheres”.

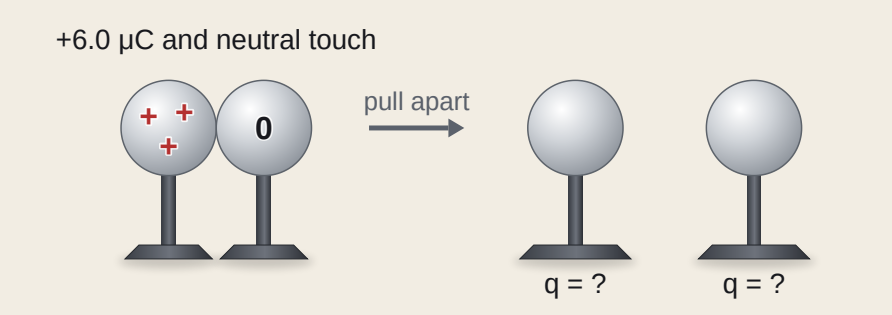
Steps: how to find the charge after spheres touch



1. **Write** each charge with its sign, such as +7.0 µC and −3.0 µC.
2. **Add** the signed charges to get the total.
3. **Divide** the total by the number of identical spheres.
4. **Give** every sphere that same charge, with its sign.
5. **Check** that the charges after add up to the total before.

Check: the total after the touch equals the total before, so no charge was created or lost.

Worked example



Givens: two identical metal spheres carry +7.0 µC and −3.0 µC. They touch and are then separated.

Question: What is the charge on each sphere after the separation?

Step 1 Write: (+7.0 µC) and (−3.0 µC).

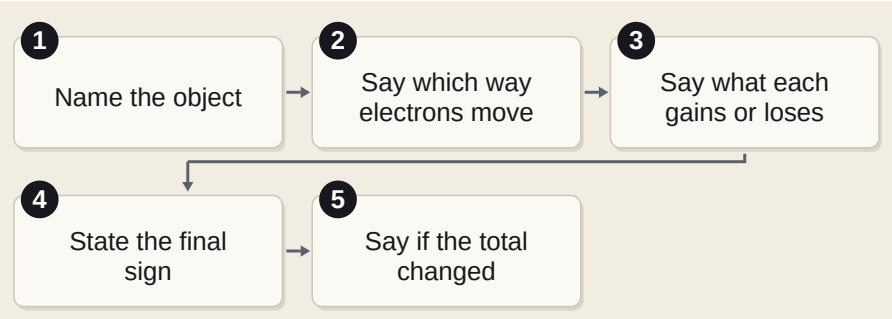
Step 2 Add: (+7.0) + (−3.0) = +4.00 µC.

Step 3 Divide by 2 spheres: (+4.00) ÷ 2 = +2.00 µC.

Step 4 Each sphere has +2.00 µC.

Step 5 Check: (+2.00) + (+2.00) = +4.00 µC, the same total as before.

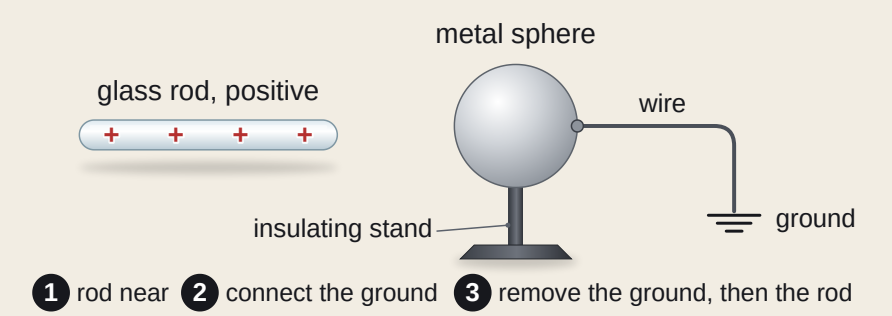
Steps: how to explain a charging result in words



1. **Name** the object and say whether it is a conductor, so electrons can move through it.
2. **Say** which way the electrons move.
3. **Say** what each object gains or loses: electrons gained or electrons lost.
4. **State** the final sign: gaining electrons gives negative, losing electrons gives positive.
5. **Say** whether the total charge changed. It never does.

Check: every sentence is about electrons moving, never protons.

Worked example



Givens: a positive rod is brought near a neutral metal sphere on an insulating stand. The sphere is grounded, the ground is removed, and then the rod is removed.

Question: Explain the final charge on the sphere.

Step 1 The sphere is metal, so electrons can move through it.

Step 2 The positive rod attracts electrons up from the ground into the sphere.

Step 3 The sphere gains electrons.

Step 4 The ground is removed first, so the electrons stay, and the sphere is negative.

Step 5 The total charge of sphere and ground did not change. Electrons only moved.

The common mistake

> Saying that protons moved. **Only electrons move.** A second mistake: dropping the minus sign when you add the charges. Write (+7.0) + (−3.0), never 7.0 + 3.0.

Your turn

The questions go from easy to exam level. Use your data sheet. Do each one on paper, then check your answer.

Question 1.1

A neutral glass rod is rubbed with silk. The rod loses 3.0×10^{13} electrons. The charge on the rod is

A. -4.80×10^{-6} C
B. $+4.80 \times 10^{-6}$ C
C. $+1.9 \times 10^{32}$ C
D. -5.3×10^{-33} C

Question 1.2

Two identical metal spheres on insulating stands carry −9.0 μC and +3.0 μC. They touch and are then separated. The charge on each sphere is

A. −6.0 μC
B. +3.0 μC
C. −3.0 μC
D. −12 μC

Question 1.3

Three identical metal spheres on insulating stands carry these charges: X has +12.0 μC, Y has 0 μC and Z has −4.0 μC. X touches Y and they are separated. Then Y touches Z and they are separated. The final charge on sphere Z, in μC, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Question 1.4

A negative rod is brought near a neutral metal sphere on an insulating stand. The rod does not touch the sphere. The sphere is grounded. The ground wire is removed first, and then the rod is taken away. Which row gives the final charge on the sphere and the reason?

A. Negative, because electrons moved from the rod to the sphere
B. Positive, because electrons moved from the sphere to the ground
C. Positive, because protons moved from the ground to the sphere
D. Neutral, because the rod never touched the sphere

Question 1.5

An electroscope has been charged positive, so its leaves stand apart. A charged object is held near the knob and does not touch it. The leaves move closer together. The charge on the object is

A. positive, because it pushes electrons down into the leaves
B. positive, because it pulls electrons up to the knob
C. negative, because it pulls electrons up to the knob
D. negative, because it pushes electrons down into the leaves

Question 1.6

A student uses a negative rod to give a neutral metal sphere on an insulating stand a positive charge by induction. The four steps are listed out of order: **1** remove the ground wire; **2** bring the rod near the sphere; **3** take the rod away; **4** connect the ground wire to the sphere. Put the steps in the order the student must do them.

Put in order. Record the four numbers in order. ☐☐☐☐

Challenge question

Two identical metal spheres on insulating stands carry these charges: A has −2.0 nC and B has +9.0 nC. They touch and are then separated. Electrons moved from one sphere to the other during the touch. The number of electrons that moved is

Numerical response. Write your answer as $a.b \times 10^{cd}$ electrons. Record the four digits a, b, c and d.

□□□□

Hint: Find the charge on each sphere after the touch. Then ask how much the charge on A changed. That change is the charge of the electrons that moved. 1 nC = 10^{-9} C.

Card 1 check: hand this in

Three questions. No answers are given here. Your teacher uses them to see what to go over with you.

Check 1.1

When an object is charged by rubbing, by contact or by induction, the particles that move are

A. protons only
B. electrons only
C. protons and electrons
D. neutrons and electrons

Check 1.2

Two identical metal spheres on insulating stands carry +5.0 µC and −1.0 µC. They touch and are then separated. The charge on each sphere, in µC, is

Numerical response. Record your three-digit answer. □□□□

Check 1.3

A negative rod touches a neutral metal sphere on an insulating stand. The rod is taken away. The sphere is now

A. negative, because electrons moved from the rod to the sphere
B. positive, because electrons moved from the sphere to the rod
C. positive, because protons moved from the rod to the sphere
D. neutral, because the stand is an insulator

Need more? Go back to the lesson: Lesson B1. Then find this idea on the Videos by concept page.

Answers for card 1

Question 1.1: B. Size: $q = ne = (3.0 \times 10^{13})(1.60 \times 10^{-19}\ \text{C}) = 4.80 \times 10^{-6}$ C. The rod lost electrons, so it is positive.

Question 1.2: C. Add the signed charges: (−9.0) + (+3.0) = −6.0 μC. Divide by 2 spheres: −3.0 μC each. Check: (−3.0) + (−3.0) = −6.0 μC.

Question 1.3: Record 1.00. First touch: (+12.0 + 0) ÷ 2 = +6.00 μC on X and on Y. Second touch: (+6.00) + (−4.0) = +2.00 μC, and ÷ 2 gives +1.00 μC on Y and on Z.

Question 1.4: B. The negative rod repels electrons. With the ground connected, electrons leave the sphere and go to the ground. The ground is removed first, so they cannot come back. The sphere lost electrons, so it is positive. This is charging by induction.

Question 1.5: D. A negative object repels electrons in the knob. They move down to the leaves. The leaves were positive, so the extra electrons make them less positive. They push apart less.

Question 1.6: Record 2413. Bring the rod near (2). Connect the ground (4): electrons leave the sphere. Remove the ground first (1), so the electrons cannot come back. Then take the rod away (3). The order is 2, 4, 1, 3.

Challenge: Record 3410. Each sphere ends with ((−2.0) + (+9.0)) ÷ 2 = +3.5 nC. Sphere A went from −2.0 nC to +3.5 nC. It became more positive by 5.5 nC, so it lost electrons to B. $n = q \div e = (5.5 \times 10^{-9}\ \text{C}) \div (1.60 \times 10^{-19}\ \text{C}) = 3.44 \times 10^{10}$ electrons, from A to B. Written as $a.b \times 10^{cd}$, that is 3.4×10^{10} electrons.

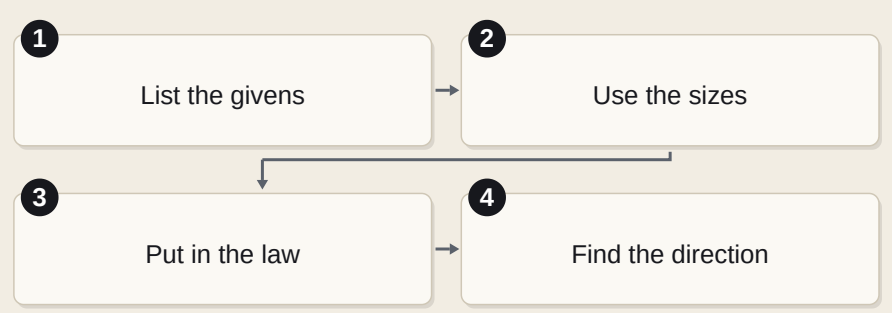
Card 2: I can find the force between two charges, and say what happens to the force when a charge or the distance changes

Part 1 · from lessons B2

What the question looks like

The question gives two point charges or two small charged spheres and the distance between them. It asks for the electric force. Or it says a charge or the distance is doubled, halved or tripled, and asks for the new force. Words to look for: “point charges”, “a distance r apart”, “is doubled”.

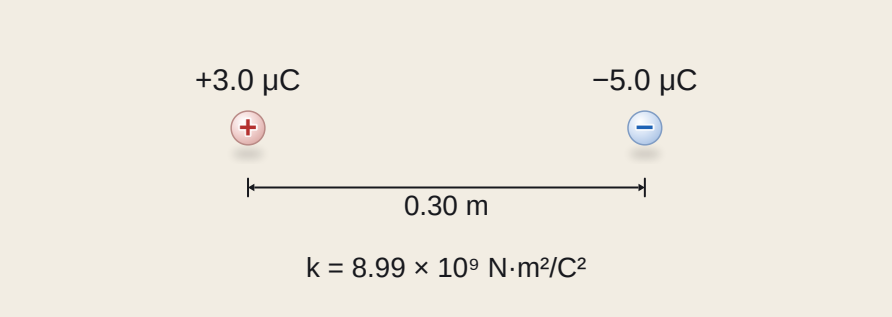
Steps: how to find the force between two charges



1. **List the givens in coulombs and metres.** Convert µC by multiplying by 10^{-6}, and use the distance in metres.
2. **Use the sizes of the charges.** Drop any minus sign from q_1 and q_2. The size of a force is never negative.
3. **Put the numbers into the law.** $F = k|q_1||q_2|/r^2$, with $k = 8.99 \times 10^9$ N·m²/C². Square the distance.
4. **Find the direction from the signs.** Like charges repel and unlike charges attract. Each charge feels the same size of force.

Check: The unit is newtons, and the power of ten fits the picture: microcoulombs a short distance apart give a force near 1 N, not 10^{12} N.

Worked example



Givens: a +3.0 µC sphere and a −5.0 µC sphere are 0.30 m apart.

Question: What is the size of the force on each sphere, and does the force attract or repel?

Step 1 $q_1 = 3.0 \times 10^{-6}$ C, $q_2 = 5.0 \times 10^{-6}$ C, r = 0.30 m.

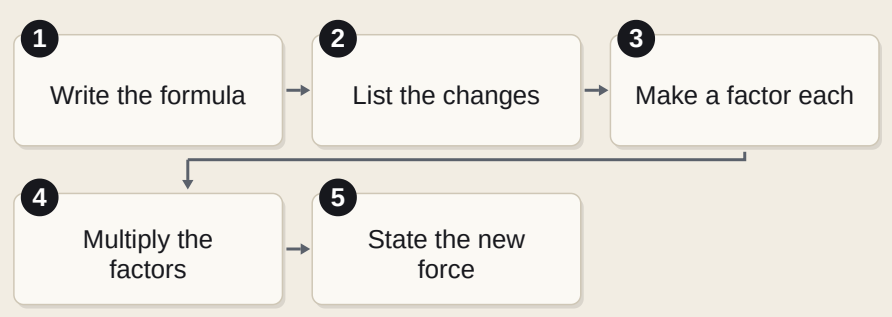
Step 2 Use 3.0×10^{-6} C and 5.0×10^{-6} C, without the minus sign.

Step 3 $F = (8.99 \times 10^{9})(3.0 \times 10^{-6})(5.0 \times 10^{-6}) \div (0.30)^2 = 1.498...$ N, which is 1.50 N.

Step 4 The signs are opposite, so the force is attraction, 1.50 N on each sphere.

Step ✓ Newtons, and a size near 1 N for microcoulombs 0.30 m apart.

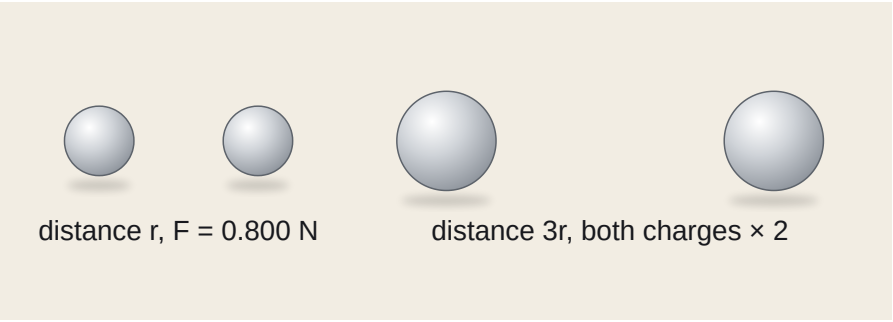
Steps: how to solve a "what happens to the force" problem



1. **Write the formula.** $F = k|q_1||q_2|/r^2$. The constant k never changes, so it drops out.
2. **List the changes.** Say each one in words, such as "q_1 doubles" or "r triples".
3. **Make one factor for each change.** A charge that changes by n gives a factor of n. A distance that changes by n gives $1/n^2$: flip it, then square it.
4. **Multiply the factors.** Keep the total as a fraction, such as $2 \times 2 \times 1/9 = 4/9$.
5. **State the new force.** New force = old force × the total factor. Say if it grew or shrank.

Check: A bigger charge or a smaller distance must make the force bigger. Does your total factor agree?

Worked example



Givens: the force is 0.800 N, both charges are doubled and the distance is tripled.

Question: What is the new force?

Step 1 $F = k|q_1||q_2|/r^2$. The starting force is 0.800 N, and k stays the same.

Step 2 q_1 doubles, q_2 doubles, and r triples.

Step 3 Each charge gives a factor of 2. The distance: flip 3 to 1/3, then square it to get 1/9.

Step 4 2 × 2 × 1/9 = 4/9. This is less than 1, so the force gets weaker.

Step 5 New force = 0.800 N × 4/9 = 0.3556... N, which is 0.356 N. The tripled distance wins over the doubled charges.

The common mistake

> Forgetting to square the distance, or forgetting to change µC to C and cm to m. A second mistake: putting the minus sign of a charge into the formula. Use sizes only. Then get the direction from the signs: alike charges repel, unlike charges attract.

Your turn

The questions go from easy to exam level. Use your data sheet. Do each one on paper, then check your answer.

Question 2.1

A +2.0 µC point charge and a −6.0 µC point charge are 0.40 m apart. The electric force on each charge is

A. 0.674 N, attraction
B. 0.674 N, repulsion
C. 0.27 N, attraction
D. 6.7×10^{11} N, attraction

Question 2.2

Two point charges exert a force F on each other. One charge is made three times as large, and the distance between the charges is doubled. The new force is

A. ⅔ F
B. ¾ F
C. ½ F
D. 6 F

Question 2.3

Two small charged spheres exert a force of 0.360 N on each other. The charge on one sphere is doubled, and the distance between the spheres is cut in half. The new force, in newtons, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Question 2.4

A +4.0 μC point charge and a +5.0 μC point charge repel each other with a force of 2.00 N. The distance between the charges, in centimetres, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Question 2.5

Which statement compares the electric force between two charges with the gravitational force between two masses?

A. Both forces get 4 times weaker when the distance doubles, but only the electric force can repel.
B. Both forces get 2 times weaker when the distance doubles, and both can repel.
C. Only the gravitational force depends on $1/r^2$, and only the electric force can repel.
D. Both forces depend on $1/r^2$, and gravity is the stronger force between a proton and an electron.

Question 2.6

Coulomb could not measure the charge on a sphere. To study how the force depends on charge, he changed the charge in a known way. He did this by

A. measuring the twist of the fibre
B. moving the spheres twice as far apart
C. touching a charged sphere to an identical uncharged sphere
D. using lead spheres in place of charged spheres

Challenge question

Two identical metal spheres carry +9.0 μC and −3.0 μC. Their centres are 0.30 m apart. The spheres touch and are then put back, with their centres 0.30 m apart. The size of the electric force on each sphere after the touch is

Numerical response. Write your answer as a.bc × 10^{-w} N. Record the four digits a, b, c and w.

□□□□

Hint: Two things happen, so use two steps. First share the charge. Then use Coulomb's law with the new charges.

Card 2 check: hand this in

Three questions. No answers are given here. Your teacher uses them to see what to go over with you.

Check 2.1

Two point charges exert a force F on each other. The distance between them is tripled. The new force is

A. 3 F
B. ⅓ F
C. ⅑ F
D. 9 F

Check 2.2

A 1.5 μC point charge and a 2.5 μC point charge are 0.15 m apart. The size of the electric force on each charge, in newtons, is

Numerical response. Record your three-digit answer. □□□□

Check 2.3

Sphere X is negative. Sphere Y is negative. The electric force that X exerts on Y is directed

A. toward X, because alike charges attract
B. away from X, because alike charges repel
C. toward X, because unlike charges attract
D. away from X, because unlike charges repel

Need more? Go back to the lesson: Lesson B2. Then find this idea on the Videos by concept page.

Answers for card 2

Question 2.1: A. $F = k|q_1||q_2| \div r^2 = (8.99 \times 10^9)(2.0 \times 10^{-6})(6.0 \times 10^{-6}) \div (0.40)^2 = 0.674$ N. The signs are unlike, so the force is attraction.

Question 2.2: B. The charge gives a factor of 3. The distance gives $1 \div 2^2 = \frac{1}{4}$. Multiply: $3 \times \frac{1}{4} = \frac{3}{4}$. The new force is $\frac{3}{4}$ F.

Question 2.3: Record 2.88. The charge gives a factor of 2. Half the distance gives $1 \div (\frac{1}{2})^2 = 4$. Multiply: $2 \times 4 = 8$. New force = 0.360 N × 8 = 2.88 N.

Question 2.4: Record 30.0. Rearrange Coulomb's law: $r = \sqrt{(k|q_1||q_2| \div F)} = \sqrt{((8.99 \times 10^9)(4.0 \times 10^{-6})(5.0 \times 10^{-6}) \div 2.00)} = 0.300$ m. That is 30.0 cm.

Question 2.5: A. Both laws have r^2 on the bottom, so double the distance gives ¼ of the force. There is one kind of mass, so gravity only attracts. There are two kinds of charge, so the electric force attracts or repels.

Question 2.6: C. Identical spheres share charge equally. One touch leaves half the charge on each sphere. Half the charge gave half the force. Cavendish later used the same kind of twisting balance with lead spheres to measure the gravitational force.

Challenge: Record 8991. After the touch, each sphere has $((+9.0) + (-3.0)) \div 2 = +3.0$ μC. $F = (8.99 \times 10^9)(3.0 \times 10^{-6})(3.0 \times 10^{-6}) \div (0.30)^2 = 8.99 \times 10^{-1}$ N. Both are positive, so the spheres now repel. Before the touch the force was 2.70 N of attraction, 3 times as large.

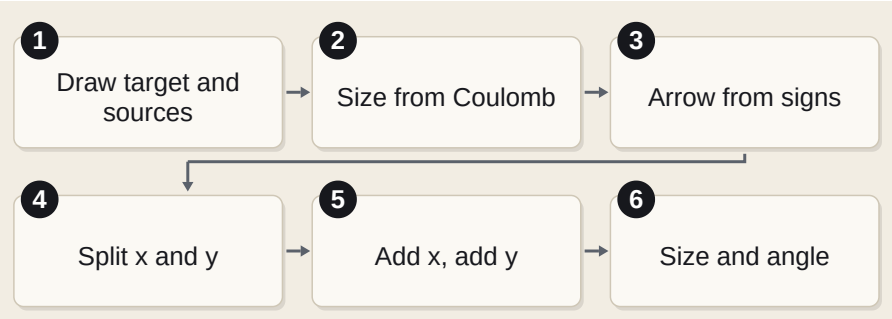
Card 3: I can find the net force on one charge from two or more charges

Part 1 · from lessons B3

What the question looks like

The question gives three or more charges, on a line or at the corners of a right angle. It asks for the net electric force on one of them. Or a small charged sphere hangs at rest on a thread. Words to look for: “net force”, “resultant”, “the force on charge B due to A and C”, “hangs at rest”.

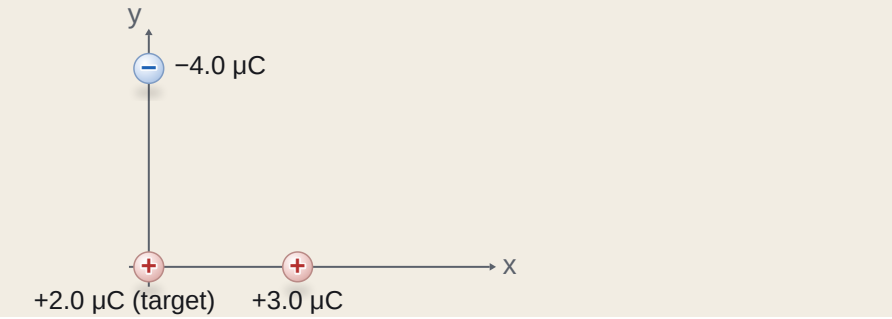
Steps: net force on one charge



1. **Draw.** Sketch the target and every source. Label each charge and each distance.
2. **Size.** For each source, $F = k|q_1||q_2| \div r^2$, using sizes of charges only.
3. **Arrow.** Alike charges push the target away. Unlike charges pull it toward the source. Draw each arrow from the target.
4. **Split.** Write each force as an x part and a y part. East and north are +. West and south are −.
5. **Add.** Add all the x parts. Add all the y parts. Keep extra digits.
6. **Finish.** Size = $\sqrt{(x^2 + y^2)}$. Angle = $\tan^{-1}(y \div x)$, using sizes only. Name the direction from a reference, such as “north of west”.

Check: when the forces are at right angles, the answer is bigger than either force and smaller than their sum.

Worked example



Givens: target +2.0 µC at (0, 0), a +3.0 µC source at (0.30 m, 0) and a −4.0 µC source at (0, 0.40 m).

Question: What is the net force on the target, with its direction?

Step 1 Target at the origin. Sources east (0.30 m) and north (0.40 m).

Step 2 $F = (8.99 \times 10^{9})(3.0 \times 10^{-6})(2.0 \times 10^{-6}) \div (0.30)^{2} = 0.599$ N. $F = (8.99 \times 10^{9})(4.0 \times 10^{-6})(2.0 \times 10^{-6}) \div (0.40)^{2} = 0.450$ N.

Step 3 +3.0 µC is alike, so the push is west. −4.0 µC is unlike, so the pull is north.

Step 4 x part = −0.599 N (west). y part = +0.450 N (north).

Step 5 Only one force on each axis, so the sums are x = −0.599 N and y = +0.450 N.

Step 6 $F = \sqrt{(0.599^{2} + 0.450^{2})} = 0.749$ N. $\tan\theta = 0.450 \div 0.599$, so $\theta = 36.9°$ north of west.

The common mistake

> Adding the two forces as plain numbers when they point in different directions. Forces are vectors. On one line, give each force a + or − sign. At right angles, use $\sqrt{(x^{2} + y^{2})}$. A second mistake: drawing the arrow on the source charge. Every arrow starts on the target.

Your turn

The questions go from easy to exam level. Use your data sheet. Do each one on paper, then check your answer.

Question 3.1

Three point charges are on a line. A is +3.0 µC at x = 0. B is −2.0 µC at x = 0.20 m. C is +5.0 µC at x = 0.50 m. East is the +x direction. The net electric force on B is

A. 0.350 N [east]
B. 2.35 N [west]
C. 0.350 N [west]
D. 2.35 N [east]

Question 3.2

A charge feels two electric forces: 1.2 N [west] and 0.50 N [south]. The net force on the charge is

A. 1.7 N [23° south of west]
B. 1.3 N [67° south of west]
C. 0.70 N [23° south of west]
D. 1.3 N [23° south of west]

Question 3.3

A +1.0 µC target charge is at the origin. A +2.0 µC charge is at (0.20 m, 0). A +4.0 µC charge is at (0, 0.30 m). The size of the net electric force on the target, in newtons, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Question 3.4

A small charged sphere of mass 0.0150 kg hangs on a thread. A second charged sphere pushes it sideways. The sphere hangs at rest, and the thread makes an angle of 25.0° with the vertical. The size of the electric force on the hanging sphere is

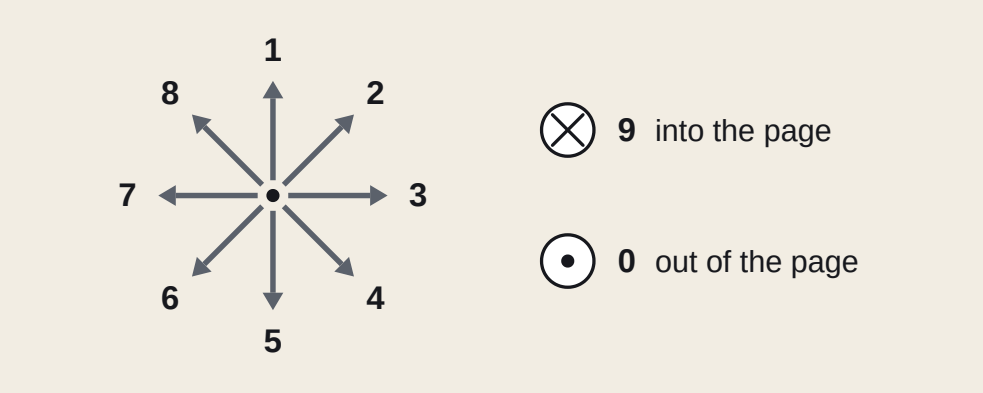
Numerical response. Write your answer as $a.bc \times 10^{-w}$ N. Record the four digits a, b, c and w.
☐☐☐☐

Question 3.5

A charged sphere hangs at rest on a thread, pushed sideways by another charge. A free-body diagram of the hanging sphere shows

A. two arrows: the weight and the electric force
B. three arrows: the weight, the tension along the thread and the electric force
C. four arrows: the weight, the electric force and the two parts of the tension
D. one arrow: the net force along the thread

Question 3.6



A positive target charge is at the centre dot of the direction picture. A positive charge is to the left of the target. A negative charge is below the target. The two charges exert forces of the same size on the target. The direction of the net electric force on the target is direction

Direction. Record the number of the direction. ☐

Challenge question

A +4.0 μC point charge is at x = 0. A +1.0 μC point charge is at x = 0.60 m. A small positive charge is placed on the line between them, at the point where the net electric force on it is zero. The distance of this point from the +4.0 μC charge, in centimetres, is

Numerical response. Record your three-digit answer. ☐☐☐

Hint: The two pushes must be the same size. Call the distance from the +4.0 μC charge x. Then the distance from the other charge is 0.60 − x. Set the two forces equal and cancel what is the same on both sides.

Card 3 check: hand this in

Three questions. No answers are given here. Your teacher uses them to see what to go over with you.

Check 3.1

A charge feels two electric forces: 0.90 N [east] and 0.40 N [west]. The net force on the charge is

A. 1.3 N [east]
B. 0.50 N [west]
C. 0.98 N [east]
D. 0.50 N [east]

Check 3.2

Charge B is between charge A and charge C on a line. A is positive, B is positive and C is negative. The force of A on B and the force of C on B are

A. in the same direction, toward C
B. in the same direction, toward A
C. in opposite directions
D. both zero

Check 3.3

A charge feels two electric forces: 3.00 N [north] and 4.00 N [east]. The size of the net force, in newtons, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Need more? Go back to the lesson: Lesson B3. Then find this idea on the Videos by concept page.

Answers for card 3

Question 3.1: C. A is unlike B, so A pulls B west: $F = (8.99 \times 10^{9})(3.0 \times 10^{-6})(2.0 \times 10^{-6}) \div (0.20)^{2} = 1.3485$ N. C is unlike B, so C pulls B east. Its distance is 0.50 − 0.20 = 0.30 m: $F = (8.99 \times 10^{9})(5.0 \times 10^{-6})(2.0 \times 10^{-6}) \div (0.30)^{2} = 0.99889$ N. The forces are opposite, so subtract: 1.3485 − 0.99889 = 0.350 N, toward the larger force, west.

Question 3.2: D. The forces are at right angles. Size: $\sqrt{(1.2^{2} + 0.50^{2})} = 1.3$ N. Angle: $\tan^{-1}(0.50 \div 1.2) = 23°$ from west, toward south.

Question 3.3: Record 0.60. Force from the charge on the x axis: $(8.99 \times 10^{9})(2.0 \times 10^{-6})(1.0 \times 10^{-6}) \div (0.20)^{2} = 0.4495$ N, a push west. Force from the charge on the y axis: $(8.99 \times 10^{9})(4.0 \times 10^{-6})(1.0 \times 10^{-6}) \div (0.30)^{2} = 0.3996$ N, a push south. They are at right angles: $\sqrt{(0.4495^{2} + 0.3996^{2})} = 0.601$ N. For an answer below 1, the zero in front counts as a digit, so record 0.60.

Question 3.4: Record 6862. The sphere is at rest, so the three forces close into a right triangle. The weight mg is beside the angle and the electric force is across from it. $\tan\theta = F_e \div mg$, so $F_e = mg \tan\theta = (0.0150\ \text{kg})(9.81\ \text{m/s}^{2})(\tan 25.0°) = 6.86 \times 10^{-2}$ N.

Question 3.5: B. A free-body diagram shows each real force as one arrow from the object. There are three forces. A free-body diagram never shows the parts of a force in place of the force.

Question 3.6: Record 4. The positive charge is alike, so it pushes the target away from it: to the right (direction 3). The negative charge is unlike, so it pulls the target toward it: down (direction 5). The two forces have the same size, so the net force points halfway between them: down and to the right, direction 4.

Challenge: Record 40.0. Both charges push the small charge, in opposite directions. The net force is zero where the two sizes are equal: $k(4.0\ \mu C)q \div x^{2} = k(1.0\ \mu C)q \div (0.60 - x)^{2}$. k and q cancel. Take the square root of both sides: $2 \div x = 1 \div (0.60 - x)$. So $2(0.60 - x) = x$, and $x = 1.20 \div 3 = 0.400$ m. That is 40.0 cm. The point is closer to the smaller charge.

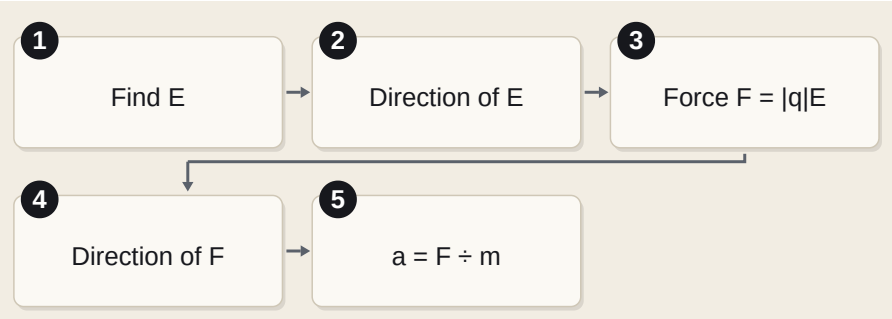
Card 4: I can find an electric field, add fields, and read a field-line picture

Part 1 · from lessons B4, B7

What the question looks like

The question asks for the “electric field” or “electric field strength” at a point, or for the force or acceleration of a charge placed in a field. Or it shows field lines and asks what they tell you. The unit N/C is a clue. So are the words “test charge”, “at point P” and “source charge”.

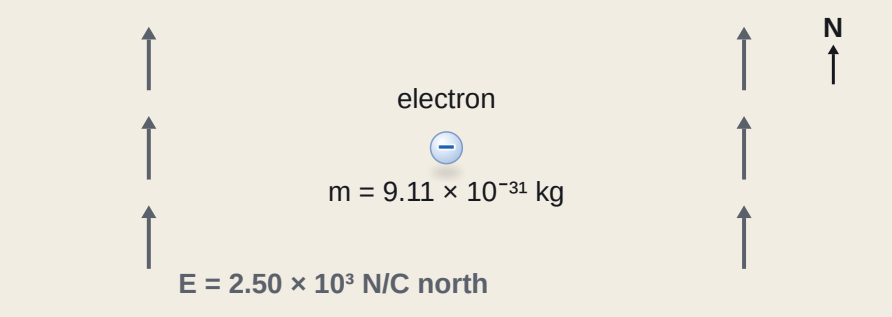
Steps: how to go from field to force to acceleration



1. **Find the field E.** Use the given field, or $E = k|Q|/r^2$ for a point source. Use the size of Q.
2. **Name the direction of E.** Away from a positive source, toward a negative source.
3. **Find the force.** $F = |q|E$. Use the size of q, the charge in the field, not the test charge.
4. **Name the direction of F.** Same as E if q is positive. Opposite to E if q is negative.
5. **Find the acceleration.** $a = F \div m$. It points the same way as F.

Check: Does the answer have units of m/s^2, and does the direction match the sign of q?

Worked example



Givens: an electron (data sheet: $q = -1.60 \times 10^{-19}$ C, $m = 9.11 \times 10^{-31}$ kg) is in a uniform field of 2.50×10^{3} N/C north. Only the electric force acts.

Question: What are the size and direction of the electron's acceleration?

Step 1 The field is given: $E = 2.50 \times 10^{3}$ N/C.

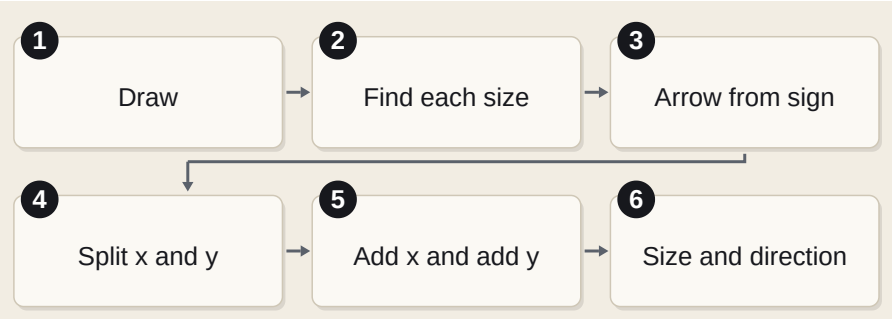
Step 2 The field points north.

Step 3 $F = |q|E = (1.60 \times 10^{-19}\ \text{C})(2.50 \times 10^{3}\ \text{N/C}) = 4.00 \times 10^{-16}$ N.

Step 4 The electron is negative, so the force is opposite to the field: south.

Step 5 $a = F \div m = (4.00 \times 10^{-16}\ \text{N}) \div (9.11 \times 10^{-31}\ \text{kg}) = 4.39 \times 10^{14}$ m/s², south.

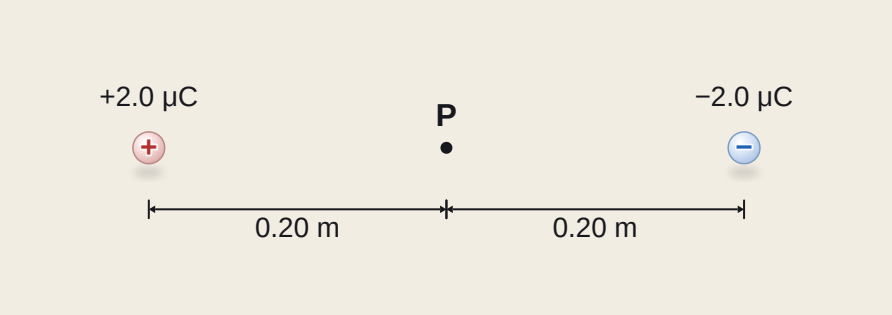
Steps: how to add fields from several sources



1. **Draw.** Mark the point and every source, with each source's sign and distance.
2. **Find each field size.** $E = k|Q|/r^2$ for each source on its own.
3. **Draw each arrow from its sign.** Away from +, toward −. Start every arrow at the point.
4. **Split into x and y.** Choose a positive direction for each axis. Give each part a + or − sign.
5. **Add all x and add all y.** Ex = sum of the x parts. Ey = sum of the y parts.
6. **Find size and direction.** $E = \sqrt{(Ex^2 + Ey^2)}$. Name the direction from a reference, such as east.

Check: Is the net arrow on the drawing the same way as your answer?

Worked example



Givens: +2.0 µC at x = 0 and −2.0 µC at x = 0.40 m, with point P midway between them, 0.20 m from each.

Question: What is the net field at P?

Step 1 Draw P with +2.0 µC on the left and −2.0 µC on the right, each 0.20 m from P.

Step 2 Each field: $E = (8.99 \times 10^{9})(2.0 \times 10^{-6}) \div (0.20)^{2} = 4.50 \times 10^{5}$ N/C.

Step 3 The + source: away from it, east. The − source: toward it, east.

Step 4 Both arrows lie on the x axis, so both x parts are positive and each y part is zero.

Step 5 $E_x = 4.50 \times 10^{5} + 4.50 \times 10^{5} = 9.00 \times 10^{5}$ N/C. $E_y = 0$.

Step 6 $E = 9.00 \times 10^{5}$ N/C east.

The common mistake

> Giving a negative charge a force in the direction of the field. The field arrow shows the force on a **positive** test charge. A negative charge, such as an electron, is pushed the opposite way. A second mistake: using the test charge in $E = k|Q| \div r^{2}$. Q is the source charge.

Your turn

The questions go from easy to exam level. Use your data sheet. Do each one on paper, then check your answer.

Question 4.1

A −2.00 µC test charge at point P feels an electric force of 0.0300 N [east]. The electric field at P is

A. 1.50×10^{4} N/C [east]
B. 6.00×10^{-8} N/C [west]
C. 1.50×10^{4} N/C [west]
D. 6.00×10^{-8} N/C [east]

Question 4.2

A +6.0 μC point charge is the source of an electric field. The size of the electric field 0.50 m from the charge is

Numerical response. Write your answer as a.bc × 10^{w} N/C. Record the four digits a, b, c and w.

□□□□

Question 4.3

A proton is placed in a uniform electric field of 3.00 × 10^{3} N/C [east]. Only the electric force acts. The acceleration of the proton is

A. 2.87 × 10^{11} m/s² [east]
B. 2.87 × 10^{11} m/s² [west]
C. 5.27 × 10^{14} m/s² [east]
D. 4.80 × 10^{-16} m/s² [east]

Question 4.4

A +4.0 μC point charge is at x = 0. A −1.0 μC point charge is at x = 0.60 m. Point P is midway between them. East is the +x direction. The net electric field at P is

A. 3.00 × 10^{5} N/C [east]
B. 4.99 × 10^{5} N/C [west]
C. 3.00 × 10^{5} N/C [west]
D. 4.99 × 10^{5} N/C [east]

Question 4.5

A drawing shows the electric field lines around two charges. Which statement about the drawing must be true?

A. The lines show the path a charge will follow.
B. The field is stronger where the lines are closer together.
C. The lines start on the negative charge.
D. Two lines cross where the field is strongest.

Question 4.6

An electron moves at a constant speed in a circle around a fixed positive charge. The only force on the electron is the electric force. Which row gives the direction of the electric force on the electron and the physics principle that describes its motion?

A. Along the path of the electron; accelerated motion
B. Away from the positive charge; uniform circular motion
C. Toward the positive charge; uniform circular motion
D. Toward the positive charge; uniform motion

Challenge question

A +2.0 µC point charge is at (0.30 m, 0). A −2.0 µC point charge is at (0, 0.30 m). The size of the net electric field at the origin is

Numerical response. Write your answer as a.bc × 10^{w} N/C. Record the four digits a, b, c and w.

□□□□

Hint: Find each field on its own first. Draw each arrow at the origin: away from the positive charge, toward the negative charge. The two arrows are at right angles.

Card 4 check: hand this in

Three questions. No answers are given here. Your teacher uses them to see what to go over with you.

Check 4.1

The electric field at a point near a negative point charge is directed

A. away from the charge
B. in a circle around the charge
C. toward the charge
D. toward the nearest positive charge only

Check 4.2

An electron is in a uniform electric field of 250 N/C. The size of the electric force on the electron is

Numerical response. Write your answer as a.b × 10^{-cd} N. Record the four digits a, b, c and d.

□□□□

Check 4.3

Point P is a distance r from a point charge. The electric field at P is E. At a distance of 2r from the same charge, the electric field is

A. 2 E
B. ½ E
C. 4 E
D. ¼ E

Need more? Go back to the lesson: Lesson B4 · Lesson B7. Then find this idea on the Videos by concept page.

Answers for card 4

Question 4.1: C. Size: E = F ÷ q = (0.0300 N) ÷ (2.00 × 10^{-6} C) = 1.50 × 10^{4} N/C. The test charge is negative, so the field points opposite to the force: west.

Question 4.2: Record 2165. $E = k|Q| \div r^2 = (8.99 \times 10^9)(6.0 \times 10^{-6}) \div (0.50)^2 = 2.16 \times 10^5$ N/C. The source is positive, so the field points away from it.

Question 4.3: A. $F = |q|E = (1.60 \times 10^{-19}\ \text{C})(3.00 \times 10^3\ \text{N/C}) = 4.80 \times 10^{-16}$ N. $a = F \div m = (4.80 \times 10^{-16}\ \text{N}) \div (1.67 \times 10^{-27}\ \text{kg}) = 2.87 \times 10^{11}\ \text{m/s}^2$. A proton is positive, so it accelerates along the field: east.

Question 4.4: D. P is 0.30 m from each charge. From the + charge: $(8.99 \times 10^9)(4.0 \times 10^{-6}) \div (0.30)^2 = 3.996 \times 10^5$ N/C, away from it: east. From the − charge: $(8.99 \times 10^9)(1.0 \times 10^{-6}) \div (0.30)^2 = 9.989 \times 10^4$ N/C, toward it: east. Both point east, so add: 4.99×10^5 N/C [east].

Question 4.5: B. Closer lines mean a stronger field. Lines start on a positive charge and end on a negative charge. They never cross. A field line is a picture of the field. It is not the path of a particle.

Question 4.6: C. The positive charge makes a radial field. It attracts the electron, so the force always points toward the positive charge at the centre of the circle. A force that always points to the centre gives uniform circular motion (principle 2). The force equation is $kq_1q_2 \div r^2 = mv^2 \div r$.

Challenge: Record 2835. Each field has the size $(8.99 \times 10^9)(2.0 \times 10^{-6}) \div (0.30)^2 = 1.998 \times 10^5$ N/C. The field of the + charge points away from it: west. The field of the − charge points toward it: north. They are at right angles: $\sqrt{((1.998 \times 10^5)^2 + (1.998 \times 10^5)^2)} = 2.83 \times 10^5$ N/C, at 45° north of west.

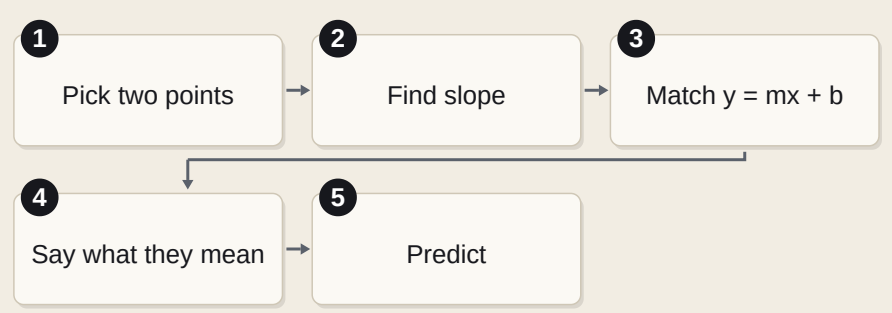
Card 5: I can read a graph: find the slope, find a constant, and straighten a curve; name the variables in an experiment

Part 1 · from lessons B5

What the question looks like

The question describes an experiment, or shows a graph with a line of best fit. It asks which variable is manipulated, responding or held fixed. Or it asks for the slope, for what the slope means, or for a constant such as k. Words to look for: “line of best fit”, “slope”, “plotted against”, “to give a straight line”.

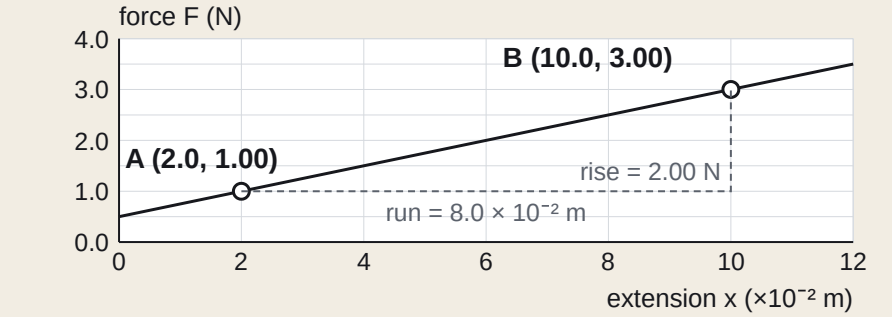
Steps: how to get slope and constants from a graph



1. **Pick two points on the line.** Choose points where grid lines cross and far apart. Use line points, never data points.
2. **Find the slope.** Slope = rise ÷ run. Keep the power of ten in the run, and give the unit: vertical unit ÷ horizontal unit.
3. **Match y = mx + b.** Ask which symbol plays y, which plays x, what multiplies x, and what stands alone.
4. **Say what they mean.** Say what the slope and the intercept are in physics, with units. Does the physics equation have a b term?
5. **Predict with the whole line.** Put the value into y = mx + b and keep the intercept.

Check: The slope unit is the vertical unit ÷ the horizontal unit, and the answer has a size that fits the picture.

Worked example



Givens: A and B lie on the line F = 25.0x + 0.50.

Question: Find the spring constant, then the extension for a force of 1.20 N.

Step 1 A (2.0 × 10^{-2} m, 1.00 N) and B (10.0 × 10^{-2} m, 3.00 N), both on the line at grid crossings.

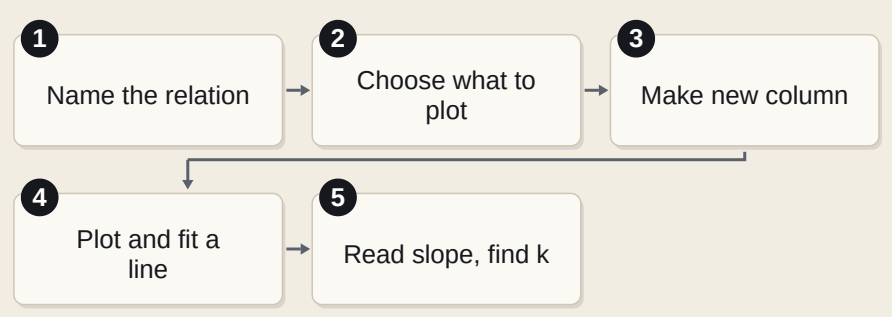
Step 2 Rise = 3.00 − 1.00 = 2.00 N. Run = (10.0 − 2.0) × 10^{-2} m = 0.080 m. Slope = 2.00 ÷ 0.080 = 25.0 N/m.

Step 3 Compare F = 25.0x + b with y = mx + b. F plays y, x plays x, and 25.0 N/m multiplies x.

Step 4 The slope is the spring constant, k = 25.0 N/m. The intercept, 0.50 N, is an offset. Hooke's law has no b.

Step 5 Use the whole line: 1.20 = 25.0x + 0.50, so 0.70 = 25.0x and x = 0.0280 m.

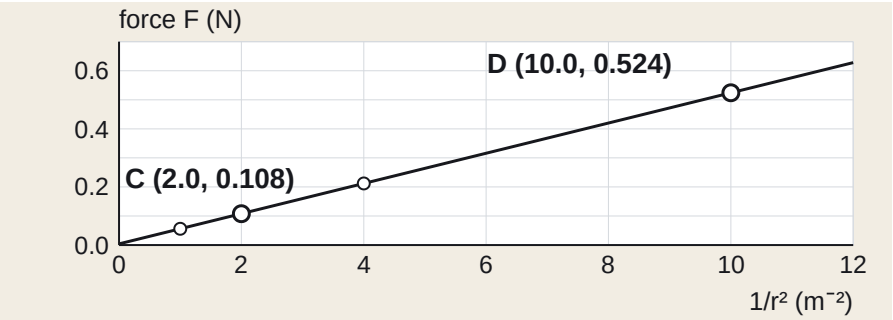
Steps: how to straighten a curve



1. **Name the relationship.** Say what the law says: the force is proportional to $1/r^2$, not to r.
2. **Choose what to plot.** Plot against the quantity the law is proportional to. Here that is $1/r^2$.
3. **Make the new column.** Square each r, then flip it. Keep an extra digit until the column is finished.
4. **Plot and draw the line.** Plot the new column on the horizontal axis. Draw one line of best fit through the points.
5. **Read the slope and find the constant.** Use two points on the line. The slope holds every constant, so divide by the ones you know.

Check: The points fall on a straight line near the origin, and the slope unit is the vertical unit ÷ m^{-2}.

Worked example



Givens: $Q_1 = 3.00\ \mu C$, $Q_2 = 2.00\ \mu C$, and r = 1.00, 0.707, 0.500 and 0.316 m.

Question: Find the experimental value of Coulomb's constant.

Step 1 $F = kQ_1Q_2 \times (1/r^2)$, so F is proportional to $1/r^2$.

Step 2 Plot F against $1/r^2$.

Step 3 $0.500^2 = 0.250$ and $1 \div 0.250 = 4.00$. The column is 1.00, 2.00, 4.00 and 10.0 m^{-2}.

Step 4 The points fall on a line. Two points on it are C (2.0 m^{-2}, 0.108 N) and D (10.0 m^{-2}, 0.524 N).

Step 5 Slope = $(0.524 - 0.108) \div (10.0 - 2.0) = 0.0520\ N{\cdot}m^2$. The charge product is $Q_1Q_2 = (3.00 \times 10^{-6})(2.00 \times 10^{-6}) = 6.00 \times 10^{-12}\ C^2$. Then $k = 0.0520 \div (6.00 \times 10^{-12}) = 8.67 \times 10^9\ N{\cdot}m^2/C^2$.

The common mistake

> Stopping at the slope. The slope is a number with a unit. The question usually wants what the slope **means**. Match the physics equation to y = mx + b to see what the slope equals. A second mistake: reading the scale wrong when an axis does not start at zero, or when it is marked "× 10^5". Read the axis labels first.

Your turn

The questions go from easy to exam level. Use your data sheet. Do each one on paper, then check your answer.

Question 5.1

A student measures the electric force between two charged spheres. She changes the distance between the spheres and measures the force each time. The charges stay the same. Which row names the variables?

A. Manipulated: force. Responding: distance. Held fixed: the charges.
B. Manipulated: distance. Responding: force. Held fixed: the charges.
C. Manipulated: the charges. Responding: force. Held fixed: distance.
D. Manipulated: distance. Responding: the charges. Held fixed: force.

Question 5.2

The electric field strength E is measured at a fixed distance r from a source charge Q. The charge Q is changed, and E is plotted against Q. The line of best fit is straight. The slope of the line equals

A. k
B. $k\ r^2$
C. $k \div r^2$
D. $kQ \div r^2$

Question 5.3

A probe measures the electric field strength E at 0.400 m from a source charge Q. A graph of E against Q has a line of best fit that passes through (2.0×10^{-6} C, 1.5×10^5 N/C) and (8.0×10^{-6} C, 5.1×10^5 N/C). The experimental value of Coulomb's constant is

Numerical response. Write your answer as $a.bc \times 10^w$ $N{\cdot}m^2/C^2$. Record the four digits a, b, c and w.

☐☐☐☐

Question 5.4

A student measures the electric force F between two fixed charges at several distances r. A graph of F against r is a curve. To get a straight line, the student should plot

A. F against r^2
B. F^2 against r
C. F against 1/r
D. F against $1/r^2$

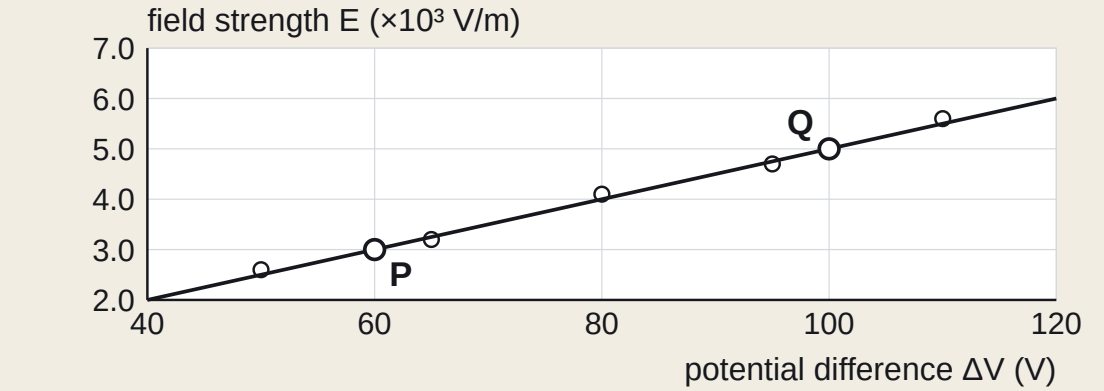
Question 5.5

Two charges are both 2.00 µC. The force F between them is measured at several distances r. A graph of F against $1/r^2$ has a line of best fit that passes through ($1.0\ m^{-2}$, 0.040 N) and ($9.0\ m^{-2}$, 0.328 N). The experimental value of Coulomb's constant is

Numerical response. Write your answer as $a.bc \times 10^w$ $N{\cdot}m^2/C^2$. Record the four digits a, b, c and w.

☐☐☐☐

Question 5.6



A student changes the potential difference ΔV across two parallel plates and measures the electric field strength E between them. The distance between the plates stays the same. The graph shows the results and the line of best fit. Neither axis starts at zero. Points P and Q are on the line. The distance between the plates, in centimetres, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Challenge question

A probe measures the electric field strength E at 0.450 m from a source charge Q. The line of best fit for a graph of E against Q has the equation $E = (4.50 \times 10^{10}\ N/C^2)Q + 2.0 \times 10^4\ N/C$. The electric field strength that this experiment predicts for a source charge of 6.0 μC is

Numerical response. Write your answer as $a.bc \times 10^w$ N/C. Record the four digits a, b, c and w.

☐☐☐☐

Hint: The line does not pass through zero. Keep the intercept: put the charge into y = mx + b. Change μC to C first.

Card 5 check: hand this in

Three questions. No answers are given here. Your teacher uses them to see what to go over with you.

Check 5.1

On a graph of experimental results, the manipulated variable is plotted on the

A. vertical axis
B. horizontal axis
C. line of best fit
D. axis with the larger numbers

Check 5.2

A line of best fit on a graph of force against extension passes through (0.020 m, 0.80 N) and (0.100 m, 2.80 N). The slope of the line, in N/m, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Check 5.3

For a point source with a fixed charge, a graph of electric field strength E against distance r is a curve. A straight line is given by a graph of

A. E against r^2
B. E against 1/r
C. E against $1/r^2$
D. E^2 against r

Need more? Go back to the lesson: Lesson B5. Then find this idea on the Videos by concept page.

Answers for card 5

Question 5.1: B. The manipulated variable is the one you change: the distance. The responding variable is the one you measure: the force. Everything else is held fixed: the charges.

Question 5.2: C. The equation is $E = kQ \div r^2$, which is $E = (k \div r^2) \times Q$. Compare it with $y = mx + b$. E plays y and Q plays x. The number that multiplies Q is the slope: $k \div r^2$.

Question 5.3: Record 9609. Rise = $(5.1 - 1.5) \times 10^5 = 3.6 \times 10^5$ N/C. Run = $(8.0 - 2.0) \times 10^{-6} = 6.0 \times 10^{-6}$ C. Slope = $3.6 \times 10^5 \div (6.0 \times 10^{-6}) = 6.0 \times 10^{10}$ N/C². The slope equals $k \div r^2$, so k = slope × r^2 = $(6.0 \times 10^{10})(0.400)^2 = 9.60 \times 10^9$ N·m²/C².

Question 5.4: D. Coulomb's law says F is proportional to $1/r^2$. Plot against the quantity the law is proportional to. Then $F = (kq_1q_2) \times (1/r^2)$ matches $y = mx$, and the slope is kq_1q_2.

Question 5.5: Record 9009. Slope = $(0.328 - 0.040) \div (9.0 - 1.0) = 0.0360$ N·m². The slope equals kq_1q_2. $q_1q_2 = (2.00 \times 10^{-6})(2.00 \times 10^{-6}) = 4.00 \times 10^{-12}$ C². $k = 0.0360 \div (4.00 \times 10^{-12}) = 9.00 \times 10^9$ N·m²/C².

Question 5.6: Record 2.00. Read P and Q from the line, not from the data points: P is (60 V, 3.0×10^3 V/m) and Q is (100 V, 5.0×10^3 V/m). Check the numbers on each axis first: neither starts at zero. Slope = $(5.0 \times 10^3 - 3.0 \times 10^3) \div (100 - 60) = 50.0$ m⁻¹. The equation is $E = \Delta V \div \Delta d = (1 \div \Delta d) \times \Delta V$, so the slope equals $1 \div \Delta d$. $\Delta d = 1 \div 50.0 = 0.0200$ m. That is 2.00 cm.

Challenge: Record 2905. Use the whole line, with the intercept. $E = (4.50 \times 10^{10})(6.0 \times 10^{-6}) + 2.0 \times 10^4 = 2.70 \times 10^5 + 0.20 \times 10^5 = 2.90 \times 10^5$ N/C. The slope also gives the constant: k = slope × r^2 = $(4.50 \times 10^{10})(0.450)^2 = 9.11 \times 10^9$ N·m²/C².

Card 6: I can use potential difference: energy per charge, the speed after a voltage, and the electron volt

Part 1 · from lessons B6

What the question looks like

The question gives a potential difference in volts, or says a particle is “accelerated through” a voltage. It asks for an energy, a speed or a potential difference. Before you start, name the system: the charge and the plates. Energy is conserved inside that system. Words to look for: “potential difference”, “voltage”, “accelerated from rest”, “electron volts”, “kinetic energy”.

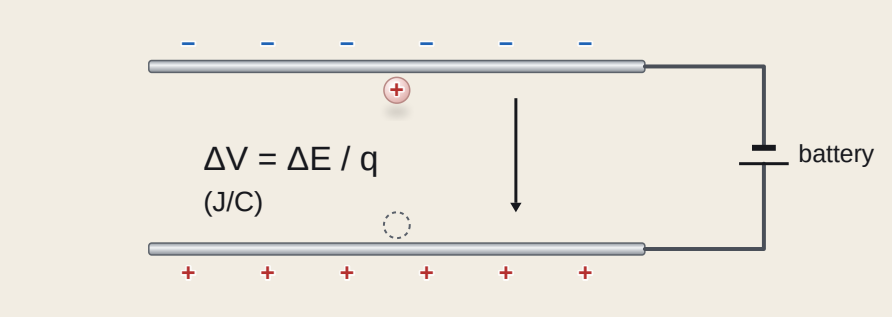
Steps: how to solve an energy-per-charge problem



1. **Name the unknown.** Is it ΔE, q or ΔV? Write it first.
2. **Write the equation for it.** ΔV = ΔE/q, ΔE = qΔV or q = ΔE/ΔV.
3. **Put in the sizes.** Charge in coulombs, energy in joules. Toward the plate that attracts it, it gains kinetic energy.
4. **Calculate with units.** J/C is the volt. Keep the full value until the end.

Check: Does the unit work out? Does a bigger charge store more energy?

Worked example



Givens: a charge of 6.0 × 10^{-18} C stores 1.8 × 10^{-16} J when it is moved from A to B. A charge of 1.5 × 10^{-17} C is then moved between the same two points.

Question: Find the potential difference between A and B. Then find the energy stored when the second charge is moved between the same two points.

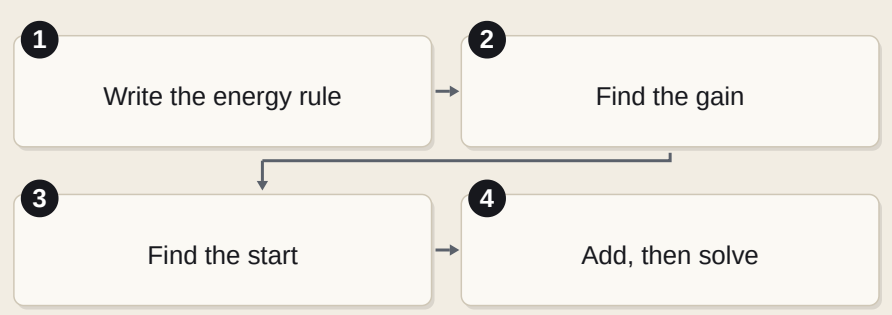
Step 1 Part one: ΔV is the unknown. Part two: ΔE is the unknown.

Step 2 ΔV = ΔE ÷ q. For part two, rearrange to ΔE = qΔV.

Step 3 ΔV = (1.8 × 10^{-16} J) ÷ (6.0 × 10^{-18} C). Then ΔE = (1.5 × 10^{-17} C) × ΔV, using the sizes of the charges.

Step 4 ΔV = 30 J/C, so ΔE = (1.5 × 10^{-17})(30) = 4.5 × 10^{-16} J. The unit J/C is the volt, so ΔV = 30 V.

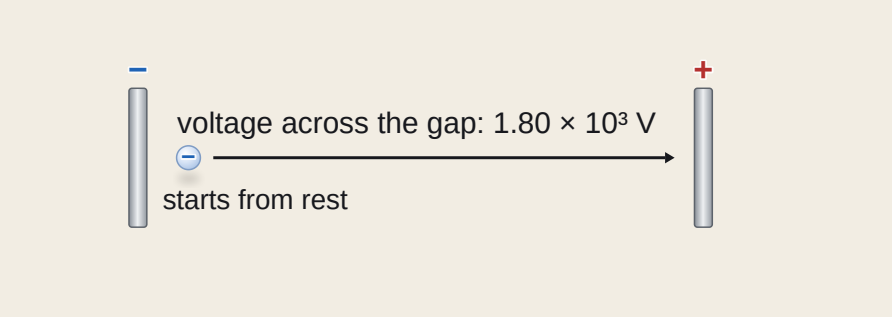
Steps: how to find the speed of a charge accelerated through a voltage



1. **Write the energy rule.** qΔV = ½mvf^2 − ½mvi^2. The energy from the voltage becomes kinetic energy.
2. **Find the energy gained.** qΔV: charge in coulombs, voltage in volts. The answer is in joules.
3. **Find the starting energy.** "From rest" means ½mvi^2 = 0. Already moving? Work out ½mvi^2 with its own mass.
4. **Add, then solve for v.** Final Ek = start + gain. v = √(2 × Ek ÷ m). Keep the full value.

Check: The unit must be m/s. A sped-up particle must end faster than it began.

Worked example



Givens: an electron starts from rest and crosses a gap with a voltage of 1.80×10^{3} V. Its charge is 1.60×10^{-19} C and its mass is 9.11×10^{-31} kg.

Question: What is the final speed of the electron?

Step 1 $q\Delta V = \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2$. For the electron, $q = 1.60 \times 10^{-19}$ C and $m = 9.11 \times 10^{-31}$ kg.

Step 2 $q\Delta V = (1.60 \times 10^{-19}\ \text{C})(1.80 \times 10^{3}\ \text{V}) = 2.88 \times 10^{-16}$ J.

Step 3 The electron starts from rest, so the starting energy is 0.

Step 4 Final $E_k = 2.88 \times 10^{-16}$ J. $v = \sqrt{(2 \times 2.88 \times 10^{-16} \div (9.11 \times 10^{-31}))} = 2.5145... \times 10^{7}$ m/s, so $v = 2.51 \times 10^{7}$ m/s.

The common mistake

> Leaving out the energy a particle already has. “From rest” means the starting kinetic energy is zero. If the particle is already moving, find $\frac{1}{2}mv_i^2$ first and add the energy gained. If the voltage slows the particle, subtract. A second mistake: treating eV as a voltage. The electron volt is a unit of energy.

Your turn

The questions go from easy to exam level. Use your data sheet. Do each one on paper, then check your answer.

Question 6.1

A charge of 8.0×10^{-17} C gains 3.6×10^{-15} J of electric potential energy when it is moved from point A to point B. The potential difference between A and B is

A. 45 V
B. 2.9×10^{-31} V
C. 0.022 V
D. 4.5×10^{3} V

Question 6.2

A 12.0 V battery is connected to a lamp. The energy delivered when 3.50 C of charge passes through the lamp, in joules, is

Numerical response. Record your three-digit answer. ☐☐☐

Question 6.3

A proton starts from rest and is accelerated through a potential difference of 2.50×10^{3} V. The final speed of the proton is

Numerical response. Write your answer as a.bc × 10^{w} m/s. Record the four digits a, b, c and w.

□□□□

Question 6.4

An alpha particle has a charge of 3.20×10^{-19} C, which is twice the size of an electron's charge. It is accelerated from rest through a potential difference of 250 V. The kinetic energy it gains is

A. 125 eV
B. 250 eV
C. 8.00×10^{-17} eV
D. 500 eV

Question 6.5

An electron is moving at 2.00×10^{6} m/s. It is then accelerated through a potential difference of 30.0 V, which speeds it up. The final speed of the electron is

Numerical response. Write your answer as a.bc × 10^{w} m/s. Record the four digits a, b, c and w.

□□□□

Question 6.6

A positive charge is moved at constant speed from a negative plate to a positive plate. This is most like

A. a ball rolling down a hill, because the charge loses potential energy
B. a ball carried up a hill, because work is done on it and it gains potential energy
C. a ball at rest on level ground, because its energy does not change
D. a ball falling freely, because it gains kinetic energy

Challenge question

An alpha particle (charge 3.20×10^{-19} C, mass 6.65×10^{-27} kg) has 800 eV of kinetic energy. It then moves through a potential difference of 150 V that slows it down. The speed of the alpha particle afterwards is

Numerical response. Write your answer as a.bc × 10^{w} m/s. Record the four digits a, b, c and w.

□□□□

Hint: Work in electron volts first. The voltage slows the particle, so subtract the energy it loses. Change the energy that is left to joules before you find the speed.

Card 6 check: hand this in

Three questions. No answers are given here. Your teacher uses them to see what to go over with you.

Check 6.1

A potential difference of one volt is the same as one

A. joule per coulomb
B. coulomb per joule
C. newton per coulomb
D. joule per second

Check 6.2

A charge of 2.0×10^{-6} C is moved through a potential difference of 9.0 V. The change in its electric potential energy is

Numerical response. Write your answer as $a.bc \times 10^{-w}$ J. Record the four digits a, b, c and w.

☐☐☐☐

Check 6.3

An electron is accelerated from rest through a potential difference of 12 V. The kinetic energy it gains is

A. 1.6×10^{-19} eV
B. 12 J
C. 12 eV
D. 1.9×10^{-18} eV

Need more? Go back to the lesson: Lesson B6. Then find this idea on the Videos by concept page.

Answers for card 6

Question 6.1: A. $\Delta V = \Delta E \div q = (3.6 \times 10^{-15}\ \text{J}) \div (8.0 \times 10^{-17}\ \text{C}) = 45\ \text{J/C} = 45\ \text{V}$.

Question 6.2: Record 42.0. $\Delta E = q\Delta V = (3.50\ \text{C})(12.0\ \text{V}) = 42.0\ \text{J}$. One volt is one joule for each coulomb.

Question 6.3: Record 6925. The system is the proton and the plates. Energy is conserved in it: $q\Delta V = \frac{1}{2}mv^2$. $q\Delta V = (1.60 \times 10^{-19}\ \text{C})(2.50 \times 10^{3}\ \text{V}) = 4.00 \times 10^{-16}\ \text{J}$. $v = \sqrt{(2 \times 4.00 \times 10^{-16} \div (1.67 \times 10^{-27}))} = 6.92 \times 10^{5}$ m/s.

Question 6.4: D. One electron volt is the energy one elementary charge gains through 1 V. The alpha particle has 2 elementary charges, so it gains $2 \times 250 = 500$ eV. In joules that is 8.00×10^{-17} J.

Question 6.5: Record 3816. Start: $\frac{1}{2}mv_i^2 = \frac{1}{2}(9.11 \times 10^{-31})(2.00 \times 10^{6})^2 = 1.822 \times 10^{-18}$ J. Gain: $q\Delta V = (1.60 \times 10^{-19})(30.0) = 4.800 \times 10^{-18}$ J. Total: 6.622×10^{-18} J. $v = \sqrt{(2 \times 6.622 \times 10^{-18} \div (9.11 \times 10^{-31}))} = 3.81 \times 10^{6}$ m/s. It is faster than it began, as it must be.

Question 6.6: B. The positive plate repels the positive charge, so a push is needed. The work done by the push is stored as electric potential energy, the way lifting a ball stores gravitational potential energy.

Challenge: Record 1555. The alpha particle has 2 elementary charges, so it loses 2 × 150 = 300 eV. Kinetic energy left: 800 − 300 = 500 eV. In joules: (500)(1.60 × 10^{-19}) = 8.00 × 10^{-17} J. v = √(2 × 8.00 × 10^{-17} ÷ (6.65 × 10^{-27})) = 1.55 × 10^{5} m/s.

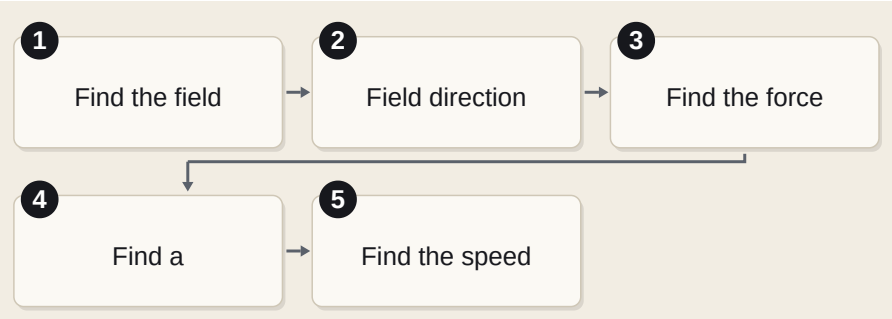
Card 7: I can solve a parallel-plate question: the field, the force, the acceleration, and the curved path

Part 1 · from lessons B7, B8

What the question looks like

The question shows two parallel plates connected to a battery, with a charged particle between them. It gives a voltage and a plate spacing. The particle starts from rest, or it enters sideways and follows a curved path. Words to look for: “parallel plates”, “uniform electric field”, “enters horizontally”, “potential difference across the plates”.

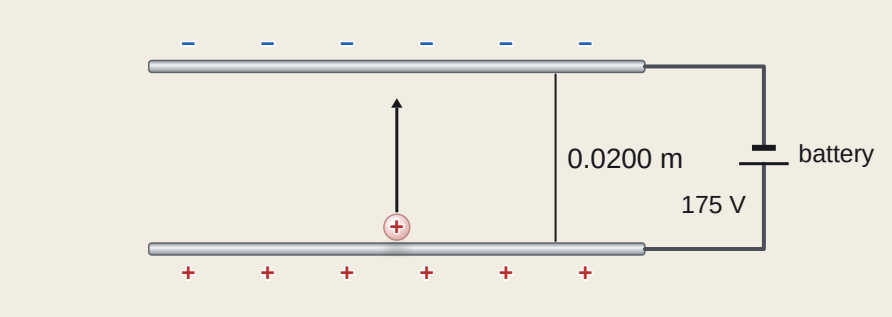
Steps: how to solve a parallel-plate problem



1. **Find the field.** $E = \Delta V/\Delta d$. Put the gap in metres.
2. **Find the field direction.** The field points from the positive plate to the negative plate.
3. **Find the force.** $F = qE$, using the size of q. A positive charge is pushed along the field. A negative charge is pushed against it.
4. **Find the acceleration.** $a = F \div m$, in the same direction as the force.
5. **Find the speed.** From rest, use $q\Delta V = \frac{1}{2}mv^2$. Or use $v = \sqrt{(2a\Delta d)}$ as a second route.

Check: Units: V/m, N, m/s^2, m/s. A speed stays well below the speed of light, 3.00×10^8 m/s.

Worked example



Givens: an alpha particle ($q = 3.20 \times 10^{-19}$ C, $m = 6.65 \times 10^{-27}$ kg) starts from rest against the positive plate. The gap is 0.0200 m and the battery is 175 V.

Question: Find the field, the force on the alpha particle, its acceleration and its final speed.

Step 1 $E = \Delta V/\Delta d = 175\ V \div 0.0200\ m = 8.75 \times 10^{3}$ V/m.

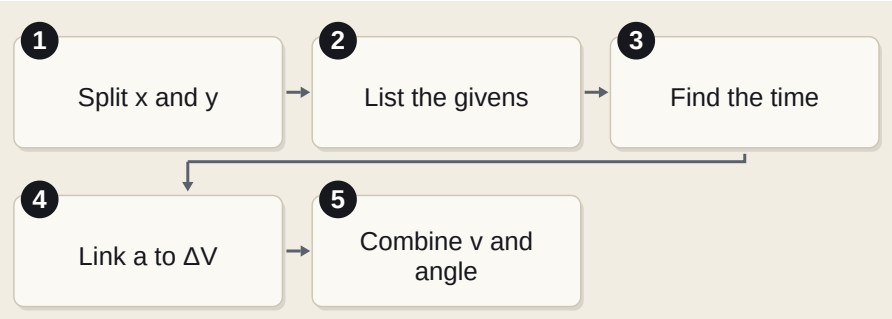
Step 2 The positive plate is the start, so the field points from it toward the negative plate.

Step 3 $F = qE = (3.20 \times 10^{-19}\ C)(8.75 \times 10^{3}\ V/m) = 2.800 \times 10^{-15}$ N. The charge is positive, so the force points along the field.

Step 4 $a = F \div m = 2.800 \times 10^{-15} \div (6.65 \times 10^{-27}) = 4.2105... \times 10^{11}\ m/s^2$, which is $4.21 \times 10^{11}\ m/s^2$. Keep the full value.

Step 5 $v = \sqrt{(2a\Delta d)} = \sqrt{(2 \times 4.2105... \times 10^{11} \times 0.0200)} = 1.30 \times 10^{5}$ m/s. The energy route $\sqrt{(2q\Delta V/m)}$ gives the same speed.

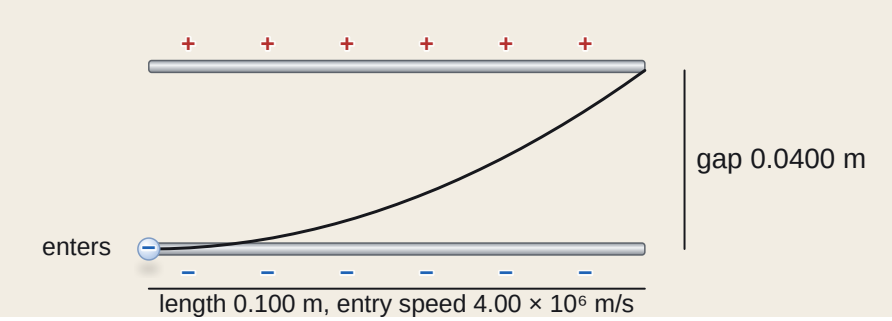
Steps: two-direction problem



1. **Split.** Two columns. Along the plates (x): constant speed. Across the plates (y): constant acceleration.
2. **List.** Write the givens in each column. Sideways entry: the starting across speed is 0.
3. **Time.** Time is the link. Get it from the column with enough numbers: $t = L \div v_x$.
4. **Link.** Across: $\Delta d = \frac{1}{2}at^2$, $F = ma$, $E = F \div q$, $\Delta V = E\Delta d$. Go forwards or backwards.
5. **Combine.** $v_y = at$. $v = \sqrt{(v_x^2 + v_y^2)}$. Angle $= \tan^{-1}(v_y \div v_x)$ from the horizontal.

Check: v_x never changes and v_y grows, so the final speed is bigger than v_x.

Worked example



Givens: an electron enters at 4.00×10^6 m/s beside one plate. The plates are 0.100 m long and 0.0400 m apart, and it just reaches the far end of the other plate.

Question: Find the potential difference between the plates. Then find the speed and the angle of the electron as it leaves the plates.

Step 1 x: along the plates, constant speed. y: across the plates, constant acceleration.

Step 2 x: L = 0.100 m, $v_x = 4.00 \times 10^6$ m/s. y: $\Delta d = 0.0400$ m, starting across speed 0. Find ΔV, then the speed and angle.

Step 3 Time from x: $t = L \div v_x = 0.100 \div (4.00 \times 10^6) = 2.50 \times 10^{-8}$ s.

Step 4 $a = 2\Delta d \div t^2 = 1.28 \times 10^{14}$ m/s². $F = ma = 1.166... \times 10^{-16}$ N. $E = F \div q = 728.8...$ N/C. $\Delta V = E\Delta d = 29.2$ V. Keep the full values.

Step 5 $v_y = at = (1.28 \times 10^{14})(2.50 \times 10^{-8}) = 3.20 \times 10^6$ m/s. $v = \sqrt{((4.00 \times 10^6)^2 + (3.20 \times 10^6)^2)} = 5.12 \times 10^6$ m/s. Angle $= \tan^{-1}(3.20 \div 4.00) = 38.7°$ from the horizontal.

The common mistake

> Mixing up the two directions when a particle enters sideways. Along the plates there is no force, so the speed stays the same. Across the plates the electric force gives a constant acceleration. Keep two columns and never put an “along” number into an “across” equation. Time is the only number the two columns share.

Your turn

The questions go from easy to exam level. Use your data sheet. Do each one on paper, then check your answer.

Question 7.1

Two parallel plates are 0.0300 m apart. The potential difference across them is 240 V. The electric field strength between the plates is

A. 7.20 V/m
B. 8.00×10^3 V/m
C. 1.25×10^{-4} V/m
D. 2.67×10^5 V/m

Question 7.2

An electron is released from rest midway between two horizontal parallel plates. The top plate is positive and the bottom plate is negative. Gravity is too small to matter. Which row gives the direction of the electric field and of the electron's acceleration?

A. Field: up. Acceleration: up.
B. Field: up. Acceleration: down.
C. Field: down. Acceleration: up.
D. Field: down. Acceleration: down.

Question 7.3

A proton is between two parallel plates that are 0.0250 m apart. The potential difference across the plates is 150 V. Only the electric force acts. The size of the proton's acceleration is

Numerical response. Write your answer as $a.b \times 10^{cd}$ m/s². Record the four digits a, b, c and d.

□□□□

Question 7.4

An electron enters the uniform electric field between two parallel plates. It is moving parallel to the plates when it enters. Gravity is too small to matter. Between the plates, the path of the electron is

A. a straight line, because the field is uniform
B. a circle, because the force is always at right angles to the velocity
C. a straight line toward the positive plate
D. a parabola that curves toward the positive plate

Question 7.5

An electron enters a uniform electric field of 2.00×10^{3} N/C. It enters at 5.00×10^{6} m/s, moving parallel to the plates. The plates are 0.0600 m long. Gravity is too small to matter. The distance the electron moves across the plates, toward the positive plate, while it is between them is

Numerical response. Write your answer as $a.bc \times 10^{-w}$ m. Record the four digits a, b, c and w.

□□□□

Question 7.6

An electron enters a uniform electric field, moving parallel to the plates. A student calculates how far the electron moves across the plates while it is between them. The physics principles on the data sheet are numbered 0 to 9. Pick the two principles the student must use.

Pick two. Record the numbers of the two principles. □□

Challenge question

An electron enters midway between two parallel plates, moving parallel to the plates at 6.00×10^{6} m/s. The plates are 0.0500 m long and 0.0200 m apart. Gravity is too small to matter. The electron just misses the end of the positive plate as it leaves. The potential difference across the plates, in volts, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Hint: Work backward: time from the “along” column, then acceleration, force, field and voltage. The electron starts midway, so it only moves half the gap. The voltage is across the whole gap.

Card 7 check: hand this in

Three questions. No answers are given here. Your teacher uses them to see what to go over with you.

Check 7.1

The potential difference across two parallel plates stays the same. The distance between the plates is doubled. The electric field strength between the plates

A. doubles
B. stays the same
C. is 4 times as large
D. is half as large

Check 7.2

An electron is in a uniform electric field of 5.00×10^{3} V/m between two parallel plates. The size of the electric force on the electron is

Numerical response. Write your answer as $a.b \times 10^{-cd}$ N. Record the four digits a, b, c and d.
☐☐☐☐

Check 7.3

A proton enters a uniform electric field, moving at right angles to the field. The shape of its path in the field is

A. a circle
B. a parabola
C. a straight line
D. a spiral

Need more? Go back to the lesson: Lesson B7 · Lesson B8. Then find this idea on the Videos by concept page.

Answers for card 7

Question 7.1: B. $E = \Delta V \div \Delta d = 240\ V \div 0.0300\ m = 8.00 \times 10^{3}$ V/m. V/m is the same unit as N/C.

Question 7.2: C. The field points from the positive plate to the negative plate: down. An electron is negative, so the force on it is opposite to the field: up, toward the positive plate.

Question 7.3: Record 5711. $E = \Delta V \div \Delta d = 150 \div 0.0250 = 6.00 \times 10^{3}$ V/m. $F = qE = (1.60 \times 10^{-19})(6.00 \times 10^{3}) = 9.60 \times 10^{-16}$ N. $a = F \div m = (9.60 \times 10^{-16}) \div (1.67 \times 10^{-27}) = 5.749 \times 10^{11}$ m/s². Written as $a.b \times 10^{cd}$, that is 5.7×10^{11} m/s².

Question 7.4: D. Along the plates there is no force, so that speed stays the same. Across the plates the force is constant, so the electron speeds up toward the positive plate. Constant speed one way and constant acceleration the other way gives a parabola, like a ball thrown sideways.

Question 7.5: Record 2532. Along: $t = L \div v_x = 0.0600 \div (5.00 \times 10^{6}) = 1.20 \times 10^{-8}$ s. Across: $a = qE \div m = (1.60 \times 10^{-19})(2.00 \times 10^{3}) \div (9.11 \times 10^{-31}) = 3.513 \times 10^{14}$ m/s². The starting across speed is 0, so $\Delta d = \frac{1}{2}at^2 = \frac{1}{2}(3.513 \times 10^{14})(1.20 \times 10^{-8})^2 = 2.53 \times 10^{-2}$ m.

Question 7.6: Record 01. Along the plates the net force is zero, so the time comes from uniform motion (principle 0). Across the plates the net force is the electric force, so the distance comes from accelerated motion (principle 1). Record 01. The order does not matter, so 10 is also right.

Challenge: Record 32.8. The electron starts midway, so it moves 0.0100 m across. Along: $t = 0.0500 \div (6.00 \times 10^{6}) = 8.333 \times 10^{-9}$ s. Across: $\Delta d = \frac{1}{2}at^2$, so $a = 2(0.0100) \div t^2 = 2.880 \times 10^{14}$ m/s². $F = ma = 2.624 \times 10^{-16}$ N. $E = F \div q = 1.640 \times 10^{3}$ N/C. $\Delta V = E\Delta d = (1.640 \times 10^{3})(0.0200\ m) = 32.8$ V. Use the full plate gap for ΔV.

Card 8: I can explain the oil-drop experiment, and solve a drop that is still or moving

Part 1 · from lessons B8

What the question looks like

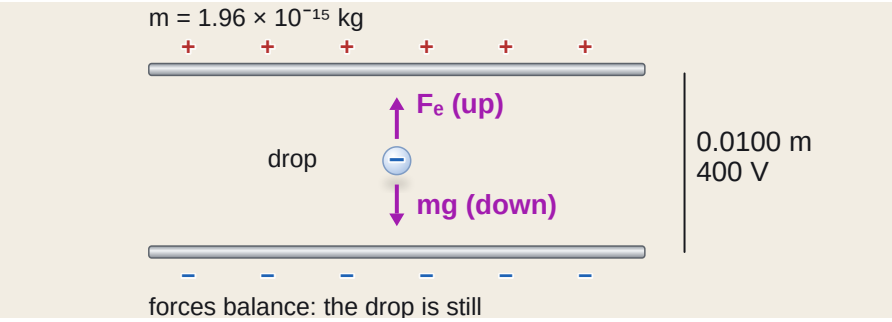
The question shows a tiny charged oil drop between two horizontal parallel plates. The drop is “suspended”, “held at rest”, moving at a constant speed, or speeding up. It asks for the charge on the drop, the number of extra electrons, the voltage or the acceleration. The name Millikan is a clue.

Steps: how to solve a still oil drop

1. **Draw the drop and its forces.** The weight mg points down. The electric force qE points up. Draw each force as one arrow from the drop.
2. **Find the field.** $E = \Delta V \div \Delta d$, with the gap in metres.
3. **Balance the forces.** The drop is still, so the net force is zero: $qE = mg$.
4. **Solve for the unknown.** For the charge, $q = mg \div E$.
5. **Count the electrons.** $n = q \div e$. Round to the nearest whole number.

Check: n must be very close to a whole number, because charge comes in whole units of e.

Worked example



Givens: an oil drop of mass 1.96×10^{-15} kg floats still between two horizontal plates. The plates are 0.0100 m apart and the voltage across them is 400 V. The top plate is positive. Data sheet: $g = 9.81\ m/s^2$, $e = 1.60 \times 10^{-19}$ C.

Question: What is the charge on the drop, and how many extra electrons does it carry?

Step 1 Weight down, electric force up. The drop is pulled toward the positive top plate, so it is negative.

Step 2 $E = \Delta V \div \Delta d = 400 \div 0.0100 = 4.00 \times 10^4$ N/C.

Step 3 The drop is still, so $qE = mg$.

Step 4 $mg = (1.96 \times 10^{-15})(9.81) = 1.923 \times 10^{-14}$ N. $q = mg \div E = 4.807 \times 10^{-19}$ C.

Step 5 $n = q \div e = (4.807 \times 10^{-19}) \div (1.60 \times 10^{-19}) = 3.00$, so the drop carries 3 extra electrons.

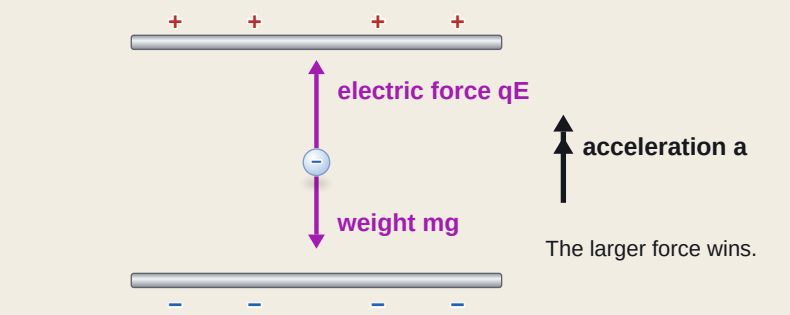
Steps: how to solve a moving oil drop

1. **Draw the drop and its forces.** The weight mg points down. The electric force qE points up or down. Draw each force as one arrow.

2. **Ask: is the velocity changing?** A constant velocity means the forces balance, the same as a still drop: qE = mg. A changing velocity means the forces do not balance.
3. **Choose a positive direction.** Use the direction of the acceleration as positive.
4. **Write the net force.** Net force = the larger force − the smaller force. For a drop that speeds up upward: Fnet = qE − mg.
5. **Use Fnet = ma.** Solve for the unknown. Keep the weight in the equation.

Check: The acceleration points the same way as the larger force.

Worked example



Givens: an oil drop of mass 2.40×10^{-15} kg carries a charge of size 4.80×10^{-19} C. It is in a uniform electric field of 6.00×10^{4} N/C. The electric force on the drop points up. Data sheet: g = 9.81 m/s².

Question: What are the size and direction of the acceleration of the drop?

Step 1 Electric force up: $qE = (4.80 \times 10^{-19})(6.00 \times 10^{4}) = 2.880 \times 10^{-14}$ N. Weight down: $mg = (2.40 \times 10^{-15})(9.81) = 2.354 \times 10^{-14}$ N.

Step 2 The two forces are not equal, so the velocity changes.

Step 3 The electric force is larger, so the acceleration is up. Up is positive.

Step 4 $F_{net} = qE - mg = 2.880 \times 10^{-14} - 2.354 \times 10^{-14} = 5.256 \times 10^{-15}$ N.

Step 5 $a = F_{net} \div m = (5.256 \times 10^{-15}) \div (2.40 \times 10^{-15}) = 2.19$ m/s², up.

The common mistake

> Leaving out the weight when the drop speeds up. A still drop has qE = mg. A drop that speeds up has two forces that are **not** equal, and the net force is their difference. A second mistake: giving a number of electrons that is not a whole number. If n comes out as 2.5, check your work.

Your turn

The questions go from easy to exam level. Use your data sheet. Do each one on paper, then check your answer.

Question 8.1

A student measures the charge on four oil drops. One of the values must be wrong. It is

A. 3.20×10^{-19} C
B. 6.40×10^{-19} C
C. 8.80×10^{-19} C
D. 9.60×10^{-19} C

Question 8.2

An oil drop of mass 3.91×10^{-15} kg is held at rest between two horizontal parallel plates. The plates are 0.0150 m apart, and the potential difference across them is 600 V. The size of the charge on the drop is

Numerical response. Write your answer as $a.b \times 10^{-cd}$ C. Record the four digits a, b, c and d.

☐☐☐☐

Question 8.3

A negative oil drop is held at rest between two horizontal parallel plates. Which row gives the direction of the electric force on the drop and the sign of the top plate?

A. Electric force: up. Top plate: positive.
B. Electric force: up. Top plate: negative.
C. Electric force: down. Top plate: positive.
D. Electric force: down. Top plate: negative.

Question 8.4

An oil drop of mass 1.80×10^{-15} kg carries a charge of size 4.80×10^{-19} C. It is in a uniform electric field of 5.00×10^{4} N/C, and the electric force on the drop points up. The size of the acceleration of the drop, in m/s^2, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Question 8.5

A charged oil drop moves upward at a constant speed between two horizontal parallel plates. Air resistance is too small to matter. The electric force on the drop is

A. larger than its weight, because the drop is moving up
B. smaller than its weight, because the drop is not speeding up
C. zero, because the speed is constant
D. equal in size to its weight, because the velocity is not changing

Question 8.6

Millikan's oil-drop experiment was important because it showed that

A. oil drops fall at a constant speed in air
B. electric charge comes only in whole-number multiples of a smallest charge
C. the electric field between parallel plates is uniform
D. an electron has a much smaller mass than a proton

Challenge question

An oil drop is held at rest between two horizontal parallel plates when the potential difference across the plates is 400 V. The potential difference is then raised to 550 V. The plate spacing does not change. The size of the acceleration of the drop, in m/s^2, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Hint: You are not given the mass or the charge. You do not need them. At 400 V the electric force equals the weight. How many times larger is the electric force at 550 V?

Card 8 check: hand this in

Three questions. No answers are given here. Your teacher uses them to see what to go over with you.

Check 8.1

An oil drop is held at rest between two charged plates. The net force on the drop is

A. equal to its weight
B. equal to the electric force
C. zero
D. directed toward the positive plate

Check 8.2

An oil drop of mass 1.63×10^{-15} kg is held at rest in a uniform electric field of 2.00×10^{4} N/C. The number of extra electrons on the drop is

A. 2
B. 5
C. 8
D. 50

Check 8.3

The smallest charge that an oil drop can carry is the elementary charge. Its size is

Numerical response. Write your answer as $a.b \times 10^{-cd}$ C. Record the four digits a, b, c and d.
☐☐☐☐

Need more? Go back to the lesson: Lesson B8. Then find this idea on the Videos by concept page.

Answers for card 8

Question 8.1: C. Divide each value by e = 1.60×10^{-19} C. The results are 2, 4, 5.5 and 6. A drop cannot carry half an electron, so 8.80×10^{-19} C is wrong.

Question 8.2: Record 9619. E = ΔV ÷ Δd = 600 ÷ 0.0150 = 4.00×10^{4} N/C. The drop is at rest, so qE = mg. q = mg ÷ E = $(3.91 \times 10^{-15})(9.81) \div (4.00 \times 10^{4}) = 9.589 \times 10^{-19}$ C. Written as a.b × 10^{-cd}, that is 9.6×10^{-19} C. Check: n = q ÷ e = 5.99, so 6 extra electrons.

Question 8.3: A. The weight pulls the drop down, so the electric force must push it up. A negative drop is pulled toward a positive plate, so the top plate is positive.

Question 8.4: Record 3.52. qE = $(4.80 \times 10^{-19})(5.00 \times 10^{4}) = 2.400 \times 10^{-14}$ N up. mg = $(1.80 \times 10^{-15})(9.81) = 1.766 \times 10^{-14}$ N down. Fnet = $2.400 \times 10^{-14} - 1.766 \times 10^{-14} = 6.342 \times 10^{-15}$ N up. a = Fnet ÷ m = 3.52 m/s², up.

Question 8.5: D. A constant velocity means the net force is zero, the same as for a drop at rest. The electric force up equals the weight down. The motion is uniform motion (principle 0).

Question 8.6: B. Every charge he measured was a whole number times 1.60×10^{-19} C. Charge is quantized: it comes in whole units of the elementary charge e.

Challenge: Record 3.68. At 400 V the drop is at rest, so qE_1 = mg. The field is ΔV ÷ Δd, so at 550 V the electric force is 550 ÷ 400 = 1.375 times the weight. Fnet = 1.375mg − mg = 0.375mg. a = Fnet ÷ m = 0.375g = (0.375)(9.81) = 3.68 m/s², up. The mass and the charge cancel, so they are not needed.

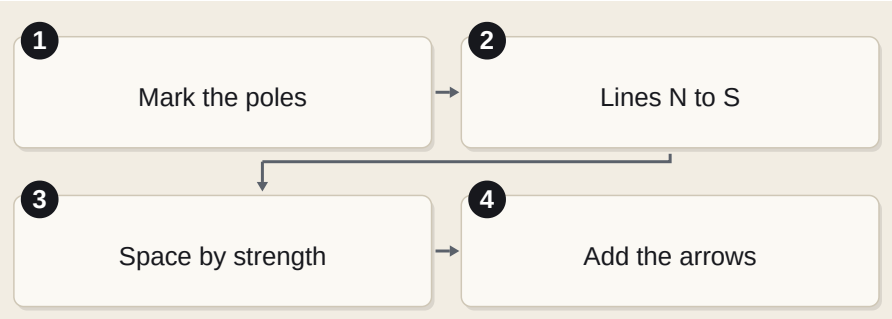
Card 9: I can find the direction of a magnetic field around a magnet, a wire or a coil, compare the three kinds of field, and find a current

Part 2 · from lessons B9, B10

What the question looks like

The question shows a bar magnet with compasses, a wire that carries a current, or a coil joined to a battery. It asks which way a compass points, which way the magnetic field points at a place, or which end of a coil is the north pole. Words to look for: “compass”, “conventional current”, “electron flow”, “into the page”, “solenoid”.

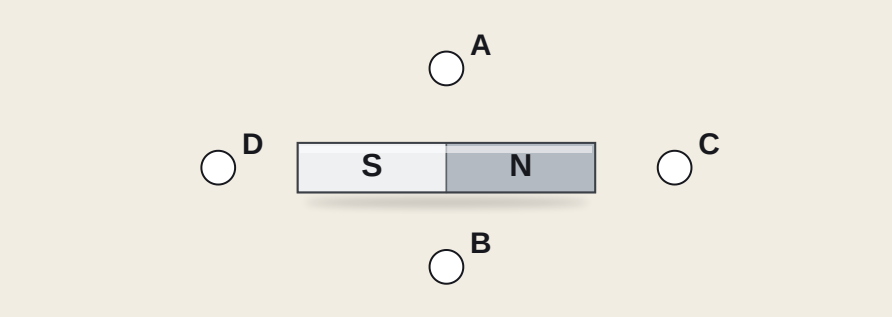
Steps: how to draw the field lines of a bar magnet



1. **Mark the poles.** Label the north end and the south end of the magnet.
2. **Draw the lines out of N and into S.** Each line leaves north, curves around and enters south. Lines never cross.
3. **Space the lines by strength.** Crowd them near the poles (strongest field). Spread them far away. Parallel, evenly spaced lines mean a uniform field.
4. **Add an arrow to every line.** Point it from N to S outside the magnet. At any point the field follows the arrow. A compass’s north pole lines up that way.

Check: Do any lines cross, or start in empty space? They must not.

Worked example



Givens: a bar magnet has its north pole on the right and its south pole on the left. Compasses A and B are above and below the middle of the magnet. C is just past the north end and D is just past the south end.

Question: Which way does the north pole of each compass point?

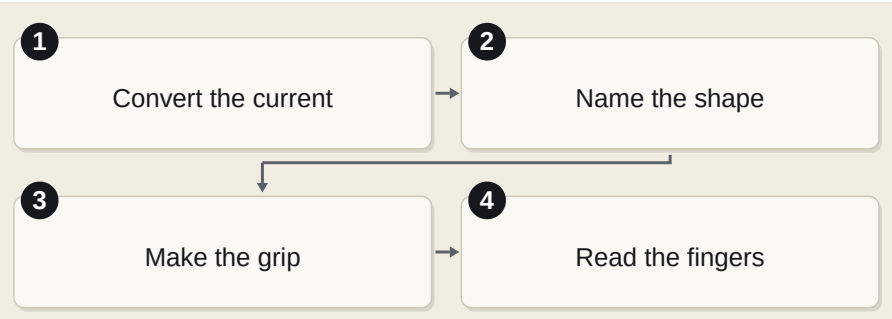
Step 1 The right end is north. The left end is south.

Step 2 Every line leaves the right end, curves around and enters the left end.

Step 3 Lines are close near the two ends and far apart away from the magnet.

Step 4 Arrows run from the right end around to the left end. A and B point left. C and D point right.

Steps: which right-hand rule do I use?



1. **Convert to conventional current.** Electron flow? Reverse it.
2. **Name the shape.** Straight wire, one moving charge, or a coil.
3. **Make the grip with your right hand.** Wire or charge: thumb along the current. Coil: grip a front wire.
4. **Read the fingers.** Wire or charge: fingers curl the way the field goes. Coil: fingers inside show the field; where it leaves is north.

Check: Right hand? Conventional current in the thumb?

Worked example



Givens: the electrons in a wire flow into the page. R is a point to the right of the wire and S is a point directly above it.

Question: What is the field direction at R and at S?

Step 1 Electrons flow into the page, so conventional current comes out of the page.

Step 2 This is a straight wire seen end-on.

Step 3 Make the right-hand grip with the thumb pointing out of the page, toward you.

Step 4 The fingers curl counterclockwise. R is at 3 o'clock, where a counterclockwise circle goes up, so the field at R points up the page. S is at 12 o'clock, where it goes left, so the field at S points left.

The common mistake

> Using the direction the electrons move in the hand rule. The right-hand rules use **conventional current**, the way positive charge would move. If the question gives electron flow, reverse it first. A second mistake: using the left hand. Every hand rule in this unit uses the right hand.

Your turn

The questions go from easy to exam level. Use your data sheet. Do each one on paper, then check your answer.

Question 9.1

A bar magnet lies on a table with its north pole on the left and its south pole on the right. A small compass is placed just past the north end, on the line through the magnet. The north pole of the compass points

A. toward the top of the page
B. to the right, toward the magnet
C. to the left, away from the magnet
D. toward the bottom of the page

Question 9.2

A long straight wire lies in the plane of the page. It carries conventional current toward the top of the page. Point P is to the right of the wire. The magnetic field at P is directed

A. into the page
B. out of the page
C. toward the top of the page
D. to the right

Question 9.3

A long straight wire lies in the plane of the page. Electrons flow through it from left to right. Point P is above the wire. The magnetic field at P is directed

A. out of the page
B. to the left
C. to the right
D. into the page

Question 9.4

A solenoid makes a magnetic field of strength B at its centre. The current in the solenoid is made three times as large, and half of its turns are removed. The new field strength at the centre is

A. ⅙ B
B. 1.5 B
C. ⅔ B
D. 6 B

Question 9.5

In 3.0 s, 4.80×10^{19} electrons pass a point in a wire. The current in the wire, in amperes, is

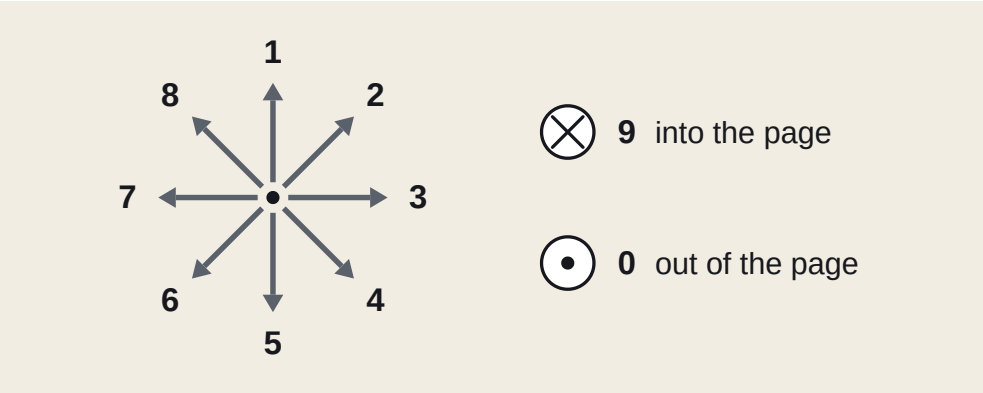
Numerical response. Record your three-digit answer. ☐☐☐☐

Question 9.6

Gravitational, electric and magnetic fields each have a source and a test object that shows the direction of the field. Which row is correct for a magnetic field?

A. Source: any mass. Test object: a small mass.
B. Source: a charge at rest. Test object: a positive test charge.
C. Source: a moving charge or a magnet. Test object: a small compass.
D. Source: a moving charge or a magnet. Test object: a positive test charge at rest.

Challenge question



A wire is seen end-on at the centre dot of the direction picture. Electrons in the wire flow out of the page, toward you. Point P is to the left of the wire. The direction of the magnetic field at P is direction

Direction. Record the number of the direction. ☐

Hint: Change the electron flow to conventional current first. Then point your right thumb along the current and look at which way your fingers curl around the wire.

Card 9 check: hand this in

Three questions. No answers are given here. Your teacher uses them to see what to go over with you.

Check 9.1

A compass needle's north pole points toward geographic north. So the magnetic pole of the Earth that is near geographic north is

A. a magnetic south pole, because it attracts the north pole of the compass
B. a magnetic north pole, because it is in the north
C. a magnetic north pole, because like poles attract
D. not a pole, because the Earth is not a magnet

Check 9.2

An iron nail that is not a magnet is brought near the north pole of a bar magnet, and then near its south pole. The nail is

A. attracted to the north pole and repelled by the south pole
B. repelled by both poles
C. attracted to both poles
D. not affected by either pole

Check 9.3

A wire carries a current of 1.5 A. The charge that passes a point in the wire in 8.0 s, in coulombs, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Need more? Go back to the lesson: Lesson B9 · Lesson B10. Then find this idea on the Videos by concept page.

Answers for card 9

Question 9.1: C. Outside a magnet, the field lines leave the north pole and enter the south pole. Just past the north end, the field points away from the magnet: to the left. A compass's north pole points along the field.

Question 9.2: A. Grip the wire with your right hand, thumb along the current, toward the top of the page. On the right of the wire your fingers go into the page.

Question 9.3: D. Electrons flow to the right, so conventional current flows to the left. Grip the wire with your right hand, thumb to the left. Above the wire your fingers go into the page.

Question 9.4: B. The field is directly proportional to the current and to the number of turns. Current gives a factor of 3. Turns give a factor of ½. Multiply: 3 × ½ = 1.5. The new field is 1.5 B.

Question 9.5: Record 2.56. Charge: $q = ne = (4.80 \times 10^{19})(1.60 \times 10^{-19}\ \text{C}) = 7.68\ \text{C}$. Current: $I = q \div t = 7.68\ \text{C} \div 3.0\ \text{s} = 2.56\ \text{A}$.

Question 9.6: C. A magnetic field comes from moving charge: a current, or a magnet. Its direction is the way the north pole of a small compass points. A mass is the source and the test object for gravity. A charge is the source of an electric field, and a positive test charge shows its direction.

Challenge: Record 1. Electrons flow out of the page, so conventional current flows into the page. Grip with your right hand, thumb pointing into the page. Your fingers curl clockwise. P is at 9 o'clock, where a clockwise circle goes up the page. That is direction 1.

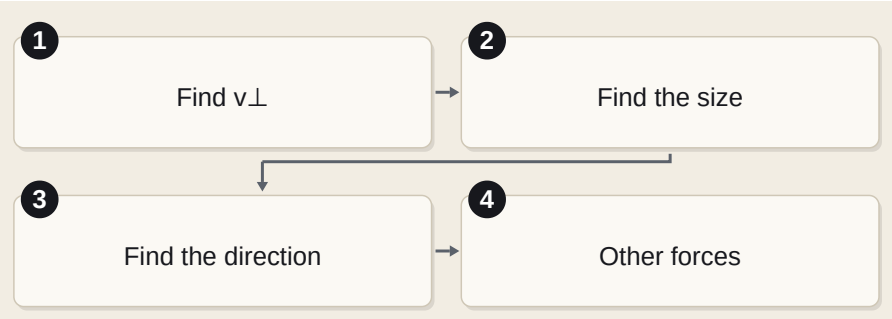
Card 10: I can find the size and direction of the magnetic force on a moving charge, or the sign of the charge

Part 2 · from lessons B11

What the question looks like

The question shows a charged particle moving through a magnetic field. The field is drawn as arrows, as crosses (into the page) or as dots (out of the page). It asks for the force on the particle, the direction it is pushed, or whether the particle is positive or negative. Words to look for: “moves at right angles to a magnetic field”, “is deflected”, “tesla”.

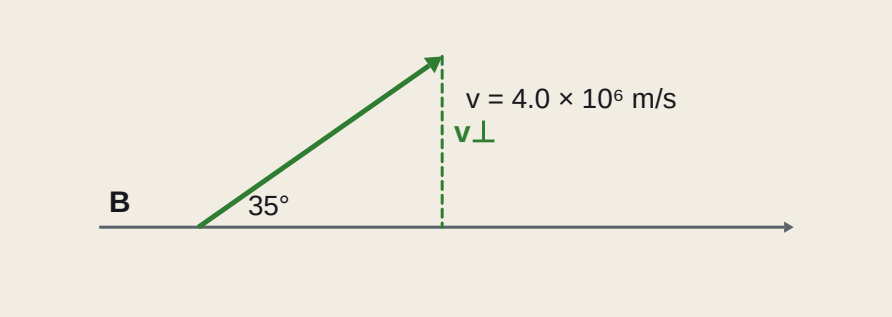
Steps: how to find the force on a moving charge



1. **Find v⊥.** Only the part across B counts. θ from the field: $v_\perp = v \sin\theta$. θ from across the field: $v_\perp = v \cos\theta$.
2. **Find the size.** $F = |q| v_\perp B$. Use the size of the charge, with no minus sign.
3. **Find the direction.** Fingers along B, thumb along v, palm gives the force on a positive charge. Reverse it for a negative charge.
4. **Look for other forces.** A mass is given? Add gravity mg. Not deflected: the forces cancel.

Check: $v_\perp \le v$, so $F \le |q| vB$. Is yours? F is zero along the field.

Worked example



Givens: a proton, charge $+1.60 \times 10^{-19}$ C, moves at 4.0×10^{6} m/s at 35° to a field of 0.620 T.

Question: What is the size of the magnetic force on the proton?

Step 1 The angle is measured from the field, so $v\perp = v \sin 35° = 2.2943... \times 10^{6}$ m/s. Keep the full value on your calculator.

Step 2 $F = |q|v\perp B = (1.60 \times 10^{-19})(2.2943... \times 10^{6})(0.620) = 2.276... \times 10^{-13}$ N, so $F = 2.28 \times 10^{-13}$ N.

Step 3 Only the size is asked. For direction: fingers along B, thumb along v, palm gives the force. Reverse it for an electron.

Step 4 No mass is given, so no gravity. The most F could be is $|q|vB = 3.97 \times 10^{-13}$ N. Ours is smaller, as it must be.

The common mistake

> Forgetting to reverse the direction for a negative charge. The flat right hand gives the force on a **positive** charge: fingers along the field, thumb along the velocity, palm shows the force. For an electron, turn the answer around. A second mistake: using electric ideas. A magnetic force is never along the field. It is at right angles to the field and to the velocity.

Your turn

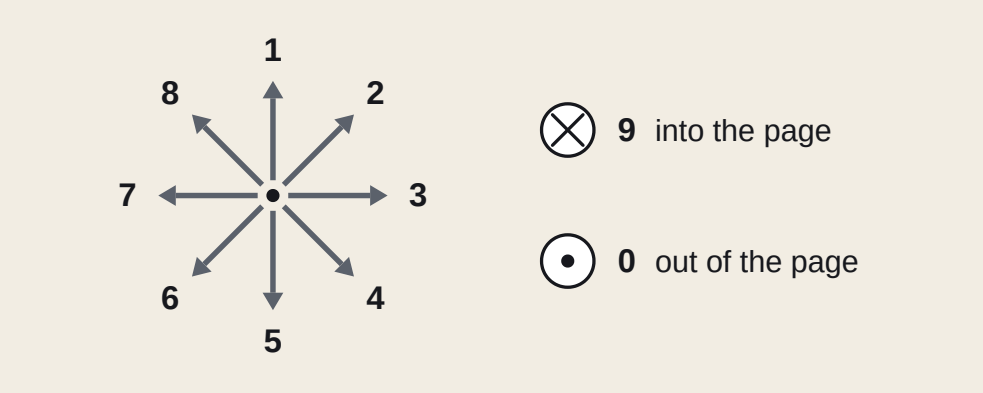
The questions go from easy to exam level. Use your data sheet. Do each one on paper, then check your answer.

Question 10.1

A proton moves at 4.0×10^{5} m/s at right angles to a uniform magnetic field of 0.250 T. The size of the magnetic force on the proton is

A. 1.60×10^{-14} N
B. 1.00×10^{5} N
C. 2.56×10^{-13} N
D. 6.40×10^{-25} N

Question 10.2



A proton is at the centre dot of the direction picture. It moves to the right. The magnetic field points into the page. The direction of the magnetic force on the proton is direction

Direction. Record the number of the direction. ☐

Question 10.3

An electron moves toward the top of the page. The magnetic field points to the right. The magnetic force on the electron is directed

A. into the page
B. to the left
C. out of the page
D. toward the bottom of the page

Question 10.4

An alpha particle (charge 3.20×10^{-19} C) moves at 2.0×10^{6} m/s through a uniform magnetic field of 0.300 T. Its velocity makes an angle of 40° with the field. The size of the magnetic force on the alpha particle is

Numerical response. Write your answer as $a.b \times 10^{-cd}$ N. Record the four digits a, b, c and d.

☐☐☐☐

Question 10.5

A charged particle moves to the right. It enters a magnetic field that points out of the page, and it is pushed toward the top of the page. The particle is

A. positive, because the force is at right angles to the field
B. negative, because a positive charge would be pushed toward the bottom of the page
C. positive, because a negative charge would be pushed toward the bottom of the page
D. neutral, because it follows the field

Question 10.6

A proton moves in the same direction as a uniform magnetic field, along a field line. The magnetic force on the proton is

A. at right angles to the field
B. in the direction of the field
C. opposite to the direction of the field
D. zero

Challenge question

A proton moves horizontally through a horizontal magnetic field of 3.0×10^{-5} T, at right angles to the field. It is not deflected, because the magnetic force balances the force of gravity. The speed of the proton is

Numerical response. Write your answer as $a.bc \times 10^{-w}$ m/s. Record the four digits a, b, c and w.

☐☐☐☐

Hint: Not deflected means the forces balance. Set the size of the magnetic force equal to the weight, then solve for v. The mass and charge of a proton are on the data sheet.

Card 10 check: hand this in

Three questions. No answers are given here. Your teacher uses them to see what to go over with you.

Check 10.1

A proton is at rest in a uniform magnetic field. The magnetic force on the proton is

A. in the direction of the field
B. zero
C. opposite to the direction of the field
D. at right angles to the field

Check 10.2

An electron moves at 3.0×10^{6} m/s at right angles to a uniform magnetic field of 0.200 T. The size of the magnetic force on the electron is

Numerical response. Write your answer as $a.b \times 10^{-cd}$ N. Record the four digits a, b, c and d.

☐☐☐☐

Check 10.3

A proton moves to the left. The magnetic field points into the page. The magnetic force on the proton is directed

A. toward the top of the page
B. out of the page
C. to the right
D. toward the bottom of the page

Need more? Go back to the lesson: Lesson B11. Then find this idea on the Videos by concept page.

Answers for card 10

Question 10.1: A. $F = qv_{\perp}B = (1.60 \times 10^{-19}\ C)(4.0 \times 10^{5}\ m/s)(0.250\ T) = 1.60 \times 10^{-14}\ N$.

Question 10.2: Record 1. Right hand flat: fingers into the page (the field), thumb to the right (the velocity). The palm faces the top of the page. A proton is positive, so the force is toward the top of the page: direction 1.

Question 10.3: C. Right hand flat: fingers to the right (the field), thumb toward the top of the page (the velocity). The palm faces into the page. That is the force on a positive charge. An electron is negative, so reverse it: out of the page.

Question 10.4: Record 1213. Only the part of the velocity across the field counts. The angle is measured from the field, so $v_{\perp} = v \sin 40° = 1.286 \times 10^{6}$ m/s. $F = qv_{\perp}B = (3.20 \times 10^{-19})(1.286 \times 10^{6})(0.300) = 1.234 \times 10^{-13}$ N. Written as $a.b \times 10^{-cd}$, that is 1.2×10^{-13} N.

Question 10.5: B. Right hand flat: fingers out of the page, thumb to the right. The palm faces the bottom of the page. That is the force on a positive charge. This particle goes the other way, so it is negative.

Question 10.6: D. Only the part of the velocity across the field gives a force. Along the field, $v_{\perp} = 0$, so $F = qv_{\perp}B = 0$. An electric field would push the proton along the field. A magnetic field does not.

Challenge: Record 3413. Not deflected means the net force is zero: $qvB = mg$. So $v = mg \div (qB) = (1.67 \times 10^{-27})(9.81) \div [(1.60 \times 10^{-19})(3.0 \times 10^{-5})] = 3.41 \times 10^{-3}$ m/s. The motion is uniform motion (principle 0).

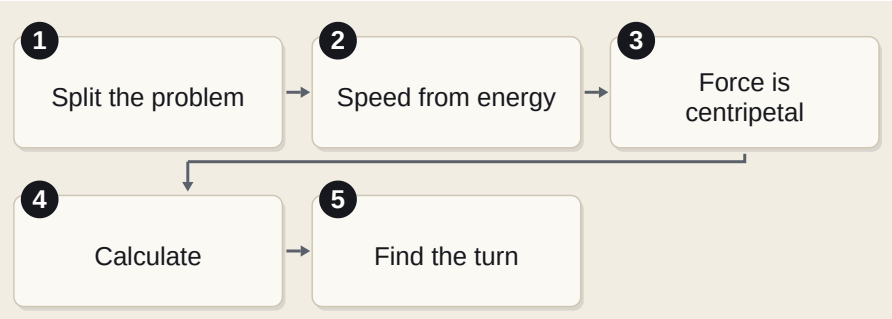
Card 11: I can solve a circular-path question: the radius, the speed, the mass or the charge

Part 2 · from lessons B12

What the question looks like

The question says a charged particle moves in a circle, or in “a circular path of radius r”, in a magnetic field. Often the particle is first “accelerated from rest through a potential difference”. It asks for the radius, the speed, the field strength, the mass or the charge. Words to look for: “circular path”, “radius”, “mass spectrometer”.

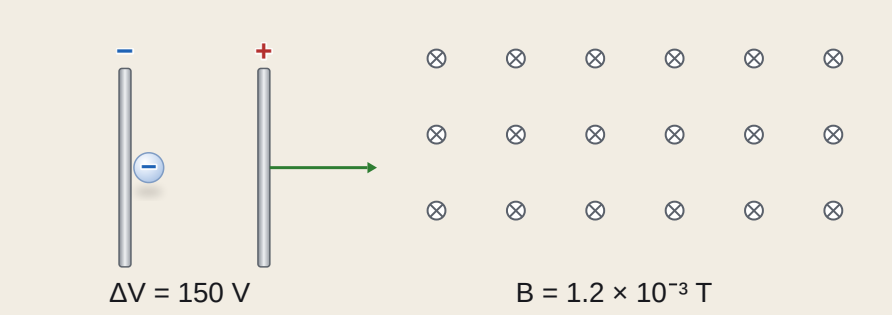
Steps: how to solve a circular-path problem



1. **Split the problem.** Is there an accelerator first? Mark the plates (energy) and the field (circle). Name the unknown.
2. **Find the speed from the energy.** $qΔV = ½mv^2$, so $v = √(2qΔV ÷ m)$, from rest. Speed given? Skip this step.
3. **Set the magnetic force equal to the centripetal force.** $qvB = mv^2/r$. Solve for the unknown: r, v, m or q. Use the size of q.
4. **Calculate with units.** Use kg, m/s, C and T. Put in the full speed from step 2.
5. **Find which way it turns.** Right-hand rule for the first force (reverse it for a negative charge). The centre is on that side.

Check: Faster or heavier means a bigger circle. More charge or field means a smaller one.

Worked example



Givens: an electron starts at rest and is accelerated through 150 V. It then enters a magnetic field of 1.2×10^{-3} T, into the page, moving to the right at right angles to the field.

Question: What is the radius of its path, and which way does it turn?

Step 1 The plates accelerate it. The field bends it. Unknowns: r and the turn.

Step 2 $v = \sqrt{(2q\Delta V \div m)} = \sqrt{(2(1.60 \times 10^{-19})(150) \div (9.11 \times 10^{-31}))} = 7.259... \times 10^{6}$ m/s. Keep the full value.

Step 3 $qvB = mv^2/r$, so $r = mv \div (qB)$. Use the size of q.

Step 4 $r = (9.11 \times 10^{-31})(7.259 \times 10^{6}) \div [(1.60 \times 10^{-19})(1.2 \times 10^{-3})] = 3.444 \times 10^{-2}$ m, so $r = 3.44 \times 10^{-2}$ m.

Step 5 A positive charge moving right through a field into the page is pushed up. The electron is pushed down, so the centre is below it and the path turns clockwise.

The common mistake

> Looking for $r = mv \div (qB)$ on the data sheet. It is not there. Start from two things that are: the magnetic force qvB and the force toward the centre of a circle, $mv^2 \div r$. Set them equal. A second mistake: thinking the particle speeds up. The magnetic force only turns the particle. Its speed stays the same.

Your turn

The questions go from easy to exam level. Use your data sheet. Do each one on paper, then check your answer.

Question 11.1

A charged particle moves at right angles to a uniform magnetic field. Its path is a circle because the magnetic force is always

A. in the direction of the velocity, so the particle speeds up
B. opposite to the velocity, so the particle slows down
C. at right angles to the velocity, so only the direction of motion changes
D. in the direction of the field, so the particle follows a field line

Question 11.2

A proton moves at 5.0×10^{5} m/s at right angles to a uniform magnetic field of 0.200 T. The radius of its circular path is

Numerical response. Write your answer as $a.bc \times 10^{-w}$ m. Record the four digits a, b, c and w.

☐☐☐☐

Question 11.3

A charged particle moves in a circle of radius r in a magnetic field. The field strength is made three times as large. The speed of the particle stays the same. The new radius is

A. ⅓ r
B. 3 r
C. ⅑ r
D. 9 r

Question 11.4

A proton starts from rest and is accelerated through a potential difference of 500 V. It then enters a uniform magnetic field of 0.0800 T, at right angles to the field. The radius of its circular path is

Numerical response. Write your answer as $a.bc \times 10^{-w}$ m. Record the four digits a, b, c and w.

☐☐☐☐

Question 11.5

A proton is accelerated from rest through a potential difference and then moves in a circle in a magnetic field. A student calculates the radius of the circle. The physics principles on the data sheet are numbered 0 to 9. Pick the two principles the student must use.

Pick two. Record the numbers of the two principles. ☐☐

Question 11.6

An electron moves at a constant speed in a circle of radius 5.29×10^{-11} m around a proton. The only force on the electron is the electric force of the proton. The speed of the electron is

Numerical response. Write your answer as $a.bc \times 10^{w}$ m/s. Record the four digits a, b, c and w.

☐☐☐☐

Challenge question

In a mass spectrometer, an ion with a charge of 1.60×10^{-19} C moves at 2.0×10^{5} m/s at right angles to a uniform magnetic field of 0.400 T. Its path is a circle of radius 0.0522 m. The mass of the ion is

Numerical response. Write your answer as $a.b \times 10^{-cd}$ kg. Record the four digits a, b, c and d.

☐☐☐☐

Hint: Start from $qvB = mv^2 \div r$, the same as for a radius. This time the unknown is the mass. One v cancels on each side.

Card 11 check: hand this in

Three questions. No answers are given here. Your teacher uses them to see what to go over with you.

Check 11.1

An electron moves in a circle in a uniform magnetic field. As it moves, its speed

A. increases
B. stays the same
C. decreases
D. increases, then decreases

Check 11.2

An electron moves at 2.0×10^7 m/s at right angles to a uniform magnetic field of 5.0×10^{-3} T. The radius of its circular path is

Numerical response. Write your answer as $a.bc \times 10^{-w}$ m. Record the four digits a, b, c and w.

☐☐☐☐

Check 11.3

An electron enters a uniform electric field at right angles to the field. An identical electron enters a uniform magnetic field at right angles to the field. Which row gives the shape of each path?

A. Electric field: circle. Magnetic field: parabola.
B. Electric field: parabola. Magnetic field: parabola.
C. Electric field: circle. Magnetic field: circle.
D. Electric field: parabola. Magnetic field: circle.

Need more? Go back to the lesson: Lesson B12. Then find this idea on the Videos by concept page.

Answers for card 11

Question 11.1: C. A force at right angles to the velocity cannot change the speed. It only turns the particle. It always points to one centre, so the path is a circle. This is uniform circular motion.

Question 11.2: Record 2612. The magnetic force is the force toward the centre: $qvB = mv^2 \div r$. So $r = mv \div (qB) = (1.67 \times 10^{-27})(5.0 \times 10^5) \div [(1.60 \times 10^{-19})(0.200)] = 2.61 \times 10^{-2}$ m.

Question 11.3: A. $r = mv \div (qB)$. The field B is on the bottom, so three times the field gives one third of the radius. A stronger field makes a tighter circle.

Question 11.4: Record 4042. Stage one, energy: $q\Delta V = \frac{1}{2}mv^2$, so $v = \sqrt{(2q\Delta V \div m)} = \sqrt{(2(1.60 \times 10^{-19})(500) \div (1.67 \times 10^{-27}))} = 3.095 \times 10^5$ m/s. Stage two, circle: $qvB = mv^2 \div r$, so $r = mv \div (qB) = (1.67 \times 10^{-27})(3.095 \times 10^5) \div [(1.60 \times 10^{-19})(0.0800)] = 4.04 \times 10^{-2}$ m.

Question 11.5: Record 25. The speed comes from conservation of energy (principle 5): $qΔV = ½mv^2$. The radius comes from uniform circular motion (principle 2): $qvB = mv^2 ÷ r$. Record 25. The order does not matter, so 52 is also right.

Question 11.6: Record 2196. The electric force is the force toward the centre: $kq_1q_2 ÷ r^2 = mv^2 ÷ r$. Multiply both sides by r and divide by m: $v = √(kq_1q_2 ÷ (mr)) = √((8.99 × 10^9)(1.60 × 10^{-19})^2 ÷ [(9.11 × 10^{-31})(5.29 × 10^{-11})]) = 2.19 × 10^6$ m/s. A circle does not need a magnetic field. It needs a force that always points to the centre.

Challenge: Record 1726. $qvB = mv^2 ÷ r$. Divide both sides by v: $qB = mv ÷ r$. So $m = qBr ÷ v = (1.60 × 10^{-19})(0.400)(0.0522) ÷ (2.0 × 10^5) = 1.670 × 10^{-26}$ kg. Written as $a.b × 10^{-cd}$, that is $1.7 × 10^{-26}$ kg.

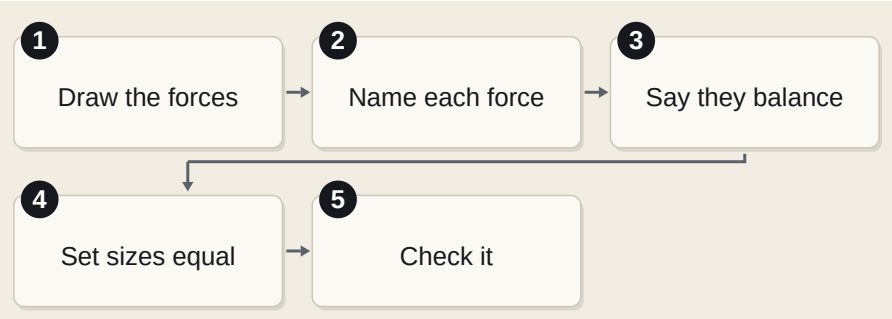
Card 12: I can solve a question with an electric field and a magnetic field together

Part 2 · from lessons B13

What the question looks like

The question shows a particle moving between charged plates, with a magnetic field in the same space. The two fields are at right angles to each other and to the velocity. The particle goes straight through, or it bends. Words to look for: “velocity selector”, “undeflected”, “passes straight through”, “perpendicular electric and magnetic fields”.

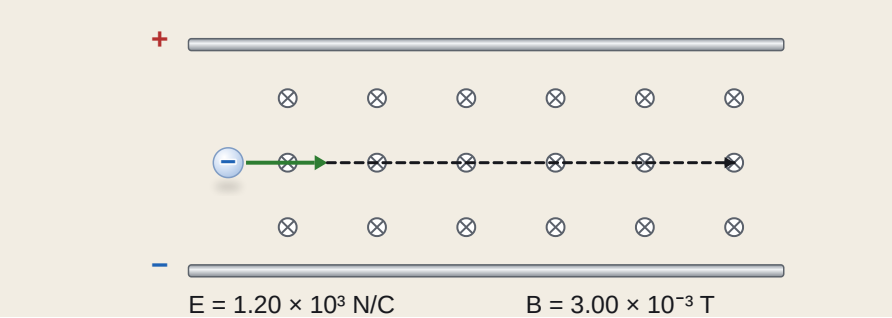
Steps: how to solve a balance-of-forces problem



1. **Draw the particle and every force.** One arrow per force: electric, magnetic or weight.
2. **Name each force’s formula.** Electric: F = qE. Magnetic: F = qvB. Sizes first. Then directions: plate signs, and the right hand reversed for a negative charge.
3. **Say if the forces balance.** Straight path or steady speed: Fnet = 0. The forces are equal and opposite.
4. **Set the sizes equal and solve.** $|qE| = |qvB|$. The q cancels. Solve: v = E/B, E = vB or B = E/v.
5. **Check the arrows and the unit.** Are the two arrows opposite? Does the unit come out right?

Check: Do the two force arrows point in opposite directions? Does N/C divided by T give m/s?

Worked example



Givens: an electron goes straight through crossed fields with $E = 1.20 \times 10^{3}$ N/C and $B = 3.00 \times 10^{-3}$ T. The top plate is positive and B points into the page.

Question: What is the speed of the electron that goes straight through?

Step 1 The electron moves right. E points down, so the electric force is up. The magnetic force is down. The arrows are opposite.

Step 2 Electric force: $F = qE$. Magnetic force: $F = qvB$, where v is the unknown.

Step 3 The path is straight, so $F_{net} = 0$ and the sizes are equal.

Step 4 $qE = qvB$, so $v = E/B = (1.20 \times 10^{3}) \div (3.00 \times 10^{-3}) = 4.00 \times 10^{5}$ m/s.

Step 5 Check: $(1.60 \times 10^{-19})(1.20 \times 10^{3}) = 1.92 \times 10^{-16}$ N and $(1.60 \times 10^{-19})(4.00 \times 10^{5})(3.00 \times 10^{-3}) = 1.92 \times 10^{-16}$ N. They match, and N/C ÷ T is m/s.

The common mistake

> Mixing up the two forces. The electric force is $F = qE$. It acts along the field, on any charge, moving or not. The magnetic force is $F = qvB$. It acts across the field, only on a moving charge. Draw both arrows before you write an equation. A second mistake: setting the forces equal when the path is not straight. Equal forces mean a straight path at a constant speed.

Your turn

The questions go from easy to exam level. Use your data sheet. Do each one on paper, then check your answer.

Question 12.1

A velocity selector has an electric field of 4.50×10^{3} N/C and a magnetic field of 1.50×10^{-2} T. The fields are at right angles to each other. The speed of the particles that pass straight through is

A. 67.5 m/s
B. 3.33×10^{-6} m/s
C. 3.00×10^{5} m/s
D. 6.75×10^{1} m/s

Question 12.2

Charged particles of many kinds enter a velocity selector. The particles that pass straight through all have the same

A. mass
B. charge
C. kinetic energy
D. speed

Question 12.3

Two parallel plates are 0.0200 m apart, with a potential difference of 300 V across them. A magnetic field fills the space between the plates. Electrons moving at 2.5×10^{6} m/s pass straight through. The strength of the magnetic field is

Numerical response. Write your answer as $a.bc \times 10^{-w}$ T. Record the four digits a, b, c and w.



Question 12.4

The top plate of a velocity selector is positive, and the magnetic field points into the page. A proton moving to the right at the speed E ÷ B passes straight through. A second proton enters, moving to the right at a higher speed. Which row gives the larger force on the second proton and the way it bends?

A. The electric force is larger. It bends toward the bottom of the page.
B. The magnetic force is larger. It bends toward the top of the page.
C. The magnetic force is larger. It bends toward the bottom of the page.
D. The electric force is larger. It bends toward the top of the page.

Question 12.5

An electron moves at 6.00×10^{5} m/s through an electric field of 1.00×10^{3} N/C and a magnetic field of 2.50×10^{-3} T. The electric force and the magnetic force on the electron are in opposite directions. The size of the acceleration of the electron is

Numerical response. Write your answer as $a.b \times 10^{cd}$ m/s². Record the four digits a, b, c and d.



Question 12.6

A proton is held at rest in a space that has an electric field and a magnetic field. Which statement is correct?

A. Both fields exert a force on the proton.
B. Neither field exerts a force on the proton.
C. Only the electric field exerts a force on the proton.
D. Only the magnetic field exerts a force on the proton.

Challenge question

A proton starts from rest and is accelerated through a potential difference. It then passes straight through a velocity selector that has an electric field of 2.00×10^{3} N/C and a magnetic field of 4.00×10^{-3} T. The potential difference that accelerated the proton is

Numerical response. Write your answer as $a.bc \times 10^{w}$ V. Record the four digits a, b, c and w.

□□□□

Hint: There are two cues, so there are two equations. “Straight through” gives the speed. “Accelerated from rest through a potential difference” links that speed to the voltage.

Card 12 check: hand this in

Three questions. No answers are given here. Your teacher uses them to see what to go over with you.

Check 12.1

A charged particle passes straight through an electric field and a magnetic field at a constant speed. The net force on the particle is

A. equal to the electric force
B. zero
C. equal to the magnetic force
D. the sum of the two forces

Check 12.2

A velocity selector has an electric field of 9.0×10^{2} N/C and a magnetic field of 3.0×10^{-3} T. The speed of the particles that pass straight through is

Numerical response. Write your answer as $a.bc \times 10^{w}$ m/s. Record the four digits a, b, c and w.

□□□□

Check 12.3

A particle enters a velocity selector moving slower than the speed E ÷ B. Compared with the electric force on the particle, the magnetic force is

A. smaller, because the magnetic force depends on the speed
B. larger, because the magnetic force depends on the speed
C. the same size, because the charge cancels
D. zero, because the particle is too slow

Need more? Go back to the lesson: Lesson B13. Then find this idea on the Videos by concept page.

Answers for card 12

Question 12.1: C. Straight through means the forces balance: qE = qvB. The charge cancels, so v = E ÷ B = $(4.50 \times 10^{3}) \div (1.50 \times 10^{-2}) = 3.00 \times 10^{5}$ m/s.

Question 12.2: D. From qE = qvB, the charge cancels and the mass never appears: v = E ÷ B. Only the speed matters.

Question 12.3: Record 6003. Electric field: E = ΔV ÷ Δd = 300 ÷ 0.0200 = 1.50×10^{4} V/m. Straight through: qE = qvB, so B = E ÷ v = $(1.50 \times 10^{4}) \div (2.5 \times 10^{6}) = 6.00 \times 10^{-3}$ T.

Question 12.4: B. The electric field points from the positive top plate down, so the electric force qE on a proton is down. Right hand flat: fingers into the page, thumb right, palm up: the magnetic force qvB is up. A higher speed makes qvB larger. qE does not change. The net force is up, so the proton bends toward the top of the page.

Question 12.5: Record 8813. Electric force: qE = $(1.60 \times 10^{-19})(1.00 \times 10^{3}) = 1.60 \times 10^{-16}$ N. Magnetic force: qvB = $(1.60 \times 10^{-19})(6.00 \times 10^{5})(2.50 \times 10^{-3}) = 2.40 \times 10^{-16}$ N. They are opposite, so subtract: Fnet = 0.80×10^{-16} N, in the direction of the magnetic force. a = Fnet ÷ m = $(8.0 \times 10^{-17}) \div (9.11 \times 10^{-31}) = 8.782 \times 10^{13}$ m/s². Written as $a.b \times 10^{cd}$, that is 8.8×10^{13} m/s².

Question 12.6: C. An electric field pushes any charge, at rest or moving: F = qE. A magnetic field pushes only a charge that moves across it: F = qv⊥B, and here v = 0.

Challenge: Record 1303. Work backward. Straight through: v = E ÷ B = $(2.00 \times 10^{3}) \div (4.00 \times 10^{-3}) = 5.00 \times 10^{5}$ m/s. Energy: qΔV = ½mv², so ΔV = mv² ÷ (2q) = $(1.67 \times 10^{-27})(5.00 \times 10^{5})^{2} \div [2(1.60 \times 10^{-19})] = 1.30 \times 10^{3}$ V.

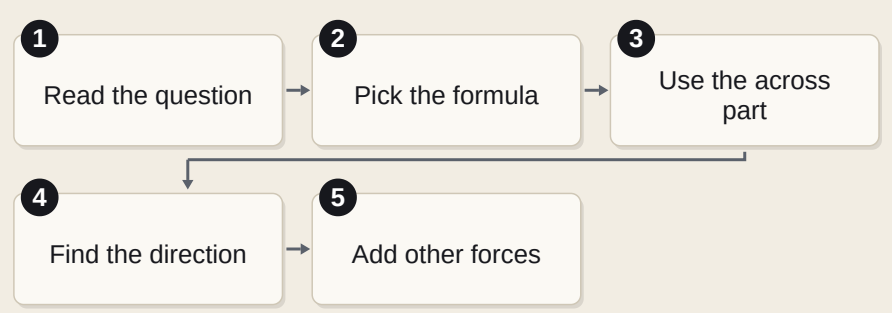
Card 13: I can find the force on a wire that carries a current in a magnetic field, and explain a motor

Part 2 · from lessons B14

What the question looks like

The question shows a wire, a rod or a loop that carries a current between the poles of a magnet. It asks for the force on the wire, the direction it is pushed, or the current that holds it up. Words to look for: “current-carrying conductor”, “length of wire in the field”, “suspended”, “balance”, “motor”.

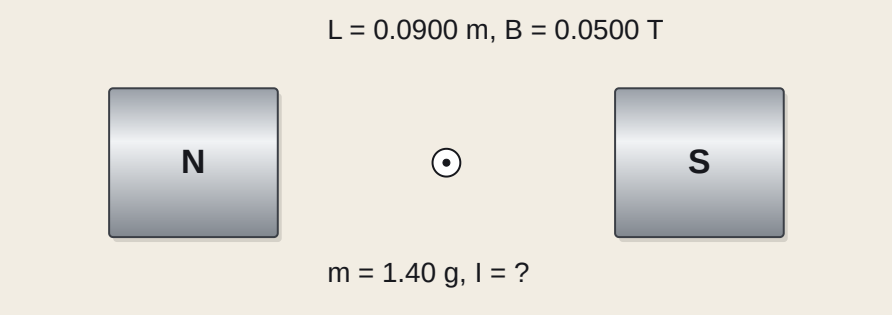
Steps: how to choose the tool for a wire in a field



1. **Read the question.** Write what is asked and every given. Note if the wire is at rest.
2. **Pick the formula.** A current in a wire: F = ILB. One moving charge: F = qvB, from lesson B11.
3. **Use the part across the field.** Use only the length in the field, and L sin θ if the wire is slanted. Change grams to kilograms.
4. **Find the direction.** Right hand: fingers along the field, thumb along conventional current, palm shows the force. Electron flow? Reverse it first.
5. **Add the other forces.** Gravity pulls down with mg. A wire at rest has Fnet = 0, so ILB = mg. Otherwise subtract the smaller force from the larger.

Check: Units: A·m·T gives N. Do the two forces point opposite ways? Is a wire at rest balanced?

Worked example



Givens: a horizontal wire of mass 1.40 g hangs still between a north pole on the left and a south pole on the right. 0.0900 m of its length is in the field, the field is 0.0500 T and the current is toward you.

Question: What current holds the wire still, and which way is the magnetic force?

Step 1 Asked: the current that holds the wire still. Given: m = 1.40 g, L = 0.0900 m, B = 0.0500 T. The wire is at rest.

Step 2 A current in a wire, so use F = ILB, not qvB.

Step 3 The wire is at right angles to the field, so L = 0.0900 m. Change the mass: 1.40 g = 1.40×10^{-3} kg.

Step 4 The field points right, from north to south. Fingers right, thumb toward you, palm up: the magnetic force is up and gravity is down.

Step 5 At rest, so Fnet = 0 and ILB = mg. Keep the full value: mg = $(1.40 \times 10^{-3})(9.81) = 1.3734 \times 10^{-2}$ N. I = $1.3734 \times 10^{-2} \div [(0.0900)(0.0500)] = 3.052$ A, so I = 3.05 A.

The common mistake

> Using the whole length of the wire. Only the length inside the field counts. A second mistake: forgetting gravity. A wire that hangs still has two forces that balance: ILB = mg. Change the mass from grams to kilograms first.

Your turn

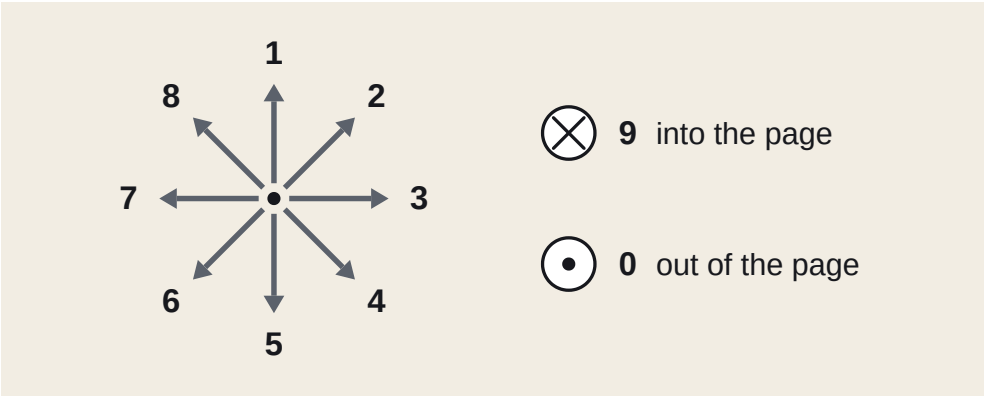
The questions go from easy to exam level. Use your data sheet. Do each one on paper, then check your answer.

Question 13.1

A wire carries a current of 5.0 A. A 0.150 m length of the wire lies at right angles to a uniform magnetic field of 0.400 T. The size of the magnetic force on the wire is

A. 0.0300 N
B. 3.00 N
C. 13.3 N
D. 0.300 N

Question 13.2



A wire lies in the plane of the page and passes through the centre dot of the direction picture. It carries conventional current to the right. The magnetic field points out of the page. The direction of the magnetic force on the wire is direction

Direction. Record the number of the direction. ☐

Question 13.3

A horizontal wire of mass 2.50 g hangs still in a uniform magnetic field of 0.0700 T. A 0.100 m length of the wire is in the field, at right angles to it. The magnetic force on the wire points up. The current in the wire, in amperes, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Question 13.4

A vertical wire lies in the plane of the page. Electrons flow through it toward the bottom of the page. The magnetic field points into the page. The magnetic force on the wire is directed

A. to the right
B. to the left
C. out of the page
D. toward the top of the page

Question 13.5

A student puts a wire on a balance, in a magnetic field that pushes the wire down. A 0.0500 m length of the wire is in the field. She changes the current I and records the balance reading F. The line of best fit for a graph of F against I passes through (1.00 A, 0.260 N) and (5.00 A, 0.340 N). The strength of the magnetic field, in teslas, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Question 13.6

The coil of a direct current motor keeps turning in one direction because the split ring

A. reverses the current in the coil every half turn
B. makes the magnetic field stronger every half turn
C. stops the current when the coil is level
D. reverses the poles of the magnet every half turn

Challenge question

A horizontal wire of mass 4.00×10^{-3} kg carries a current of 2.50 A. A 0.200 m length of the wire is in a uniform magnetic field of 0.150 T, at right angles to it. The magnetic force on the wire points up. The wire is free to move. The size of the acceleration of the wire, in m/s², is

Numerical response. Record your three-digit answer. ☐☐☐☐

Hint: The wire is not at rest, so the two forces are not equal. Find each force. Subtract the smaller from the larger. Then use Fnet = ma.

Card 13 check: hand this in

Three questions. No answers are given here. Your teacher uses them to see what to go over with you.

Check 13.1

A wire that carries a current hangs still in a magnetic field. The magnetic force on the wire is

A. zero, because the wire is not moving
B. larger than the weight of the wire
C. equal in size to the weight of the wire, and opposite in direction
D. in the same direction as the weight of the wire

Check 13.2

A wire carries a current of 2.0 A. A 0.25 m length of the wire lies at right angles to a uniform magnetic field of 0.60 T. The size of the magnetic force on the wire, in newtons, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Check 13.3

Two long straight wires are side by side. They carry conventional current in opposite directions. The wires

A. attract each other
B. do not affect each other
C. attract, then repel
D. repel each other

Need more? Go back to the lesson: Lesson B14. Then find this idea on the Videos by concept page.

Answers for card 13

Question 13.1: D. $F = IL\perp B = (5.0\ A)(0.150\ m)(0.400\ T) = 0.300\ N$.

Question 13.2: Record 5. Right hand flat: fingers out of the page (the field), thumb to the right (the conventional current). The palm faces the bottom of the page. That is direction 5.

Question 13.3: Record 3.50. The wire is at rest, so the forces balance: $ILB = mg$. Change the mass: $2.50\ g = 2.50 \times 10^{-3}\ kg$. $I = mg \div (LB) = (2.50 \times 10^{-3})(9.81) \div [(0.100)(0.0700)] = 3.50\ A$.

Question 13.4: B. Electrons flow toward the bottom of the page, so conventional current flows toward the top. Right hand flat: fingers into the page, thumb toward the top of the page. The palm faces left.

Question 13.5: Record 0.40. The reading is the magnetic force plus the weight: $F = (LB)I + mg$. Compare it with $y = mx + b$: the slope equals LB. Slope $= (0.340 - 0.260) \div (5.00 - 1.00) = 0.0200\ N/A$. $B = \text{slope} \div L = 0.0200 \div 0.0500 = 0.400\ T$. For an answer below 1, the zero in front counts as a digit, so record 0.40.

Question 13.6: A. The two sides of the coil are wires in a field. They are pushed in opposite directions, so the coil turns. After half a turn the sides have changed places. The split ring reverses the current, so the push still turns the coil the same way. A motor changes electrical energy into motion.

Challenge: Record 8.94. Magnetic force, up: $ILB = (2.50)(0.200)(0.150) = 0.07500\ N$. Weight, down: $mg = (4.00 \times 10^{-3})(9.81) = 0.03924\ N$. The forces are opposite and not equal, so subtract: $F_{net} = 0.03576\ N$, up. $a = F_{net} \div m = 0.03576 \div (4.00 \times 10^{-3}) = 8.94\ m/s^2$, up.

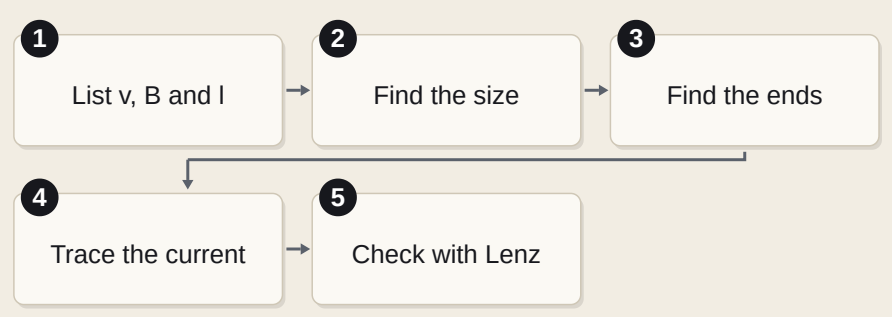
Card 14: I can find an induced voltage and its direction, and use Lenz’s law

Part 2 · from lessons B15

What the question looks like

The question shows a metal rod pulled through a magnetic field, a rod that slides on rails, or a magnet moved into a coil. It asks for the potential difference, which end is positive, which way the current goes, or why something is hard to move. Words to look for: “induced”, “generator”, “moves through a magnetic field”, “Lenz’s law”.

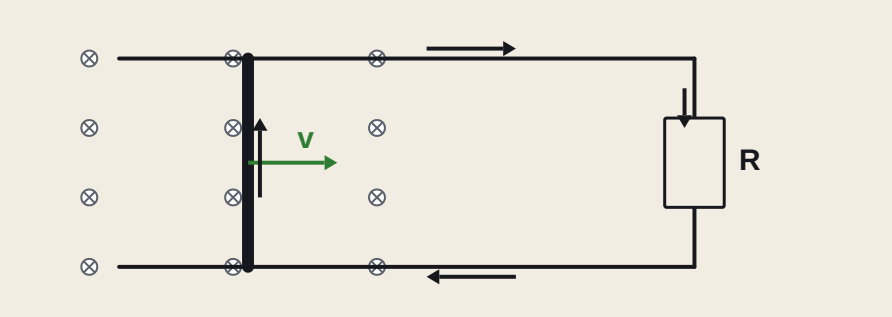
Steps: how to find an induced voltage and its direction



1. **List v, B and I.** All at right angles. Units: m/s, T, m.
2. **Find the size.** ΔV = BIv. Keep every digit.
3. **Find the ends.** Right hand, then reverse for electrons. They gather at the negative end.
4. **Trace the current.** It leaves the positive end. Say clockwise or counterclockwise.
5. **Check with Lenz’s law.** The force on the rod’s current opposes v.

Check: Volts. Reverse v or B: every direction flips. Stop the rod: ΔV = 0.

Worked example



Givens: a 0.40 m rod is pulled to the right at 3.0 m/s through a field of 0.250 T that points into the page, and it is part of a closed circuit with a resistor.

Question: What is the potential difference between the ends of the rod? Which end is positive, and which way does the current go around the circuit?

Step 1 v, B and l are at right angles.

Step 2 $\Delta V = (0.250\ T)(0.40\ m)(3.0\ m/s) = 0.300\ V$.

Step 3 Fingers in, thumb right: palm up. Electrons go down. Bottom is negative, top is positive.

Step 4 Current leaves the top end: top rail, resistor, bottom rail. Clockwise.

Step 5 In the rod the current goes up. The force is left, opposite to v. Lenz's law agrees.

The common mistake

> Expecting a current when nothing moves. A magnet at rest in a coil gives no current. Only motion gives a potential difference. A second mistake: forgetting which way Lenz's law points. The induced current always makes a force that **opposes** the motion. If it helped the motion, energy would come from nothing.

Your turn

The questions go from easy to exam level. Use your data sheet. Do each one on paper, then check your answer.

Question 14.1

A metal rod of length 0.50 m moves at 4.0 m/s through a uniform magnetic field of 0.300 T. The rod, its velocity and the field are all at right angles to each other. The potential difference between the ends of the rod is

A. 0.038 V
B. 0.60 V
C. 2.4 V
D. 6.7 V

Question 14.2

A vertical metal rod is pulled to the right through a magnetic field that points into the page. Which row gives the direction the electrons in the rod are pushed and the end of the rod that becomes positive?

A. Electrons: toward the top. Positive end: the bottom.
B. Electrons: toward the top. Positive end: the top.
C. Electrons: toward the bottom. Positive end: the top.
D. Electrons: toward the bottom. Positive end: the bottom.

Question 14.3

A metal rod of length 0.25 m moves through a uniform magnetic field of 0.400 T. The rod, its velocity and the field are all at right angles to each other. The potential difference between the ends of the rod is 1.20 V. The speed of the rod, in m/s, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Question 14.4

The north pole of a bar magnet is pushed toward one end of a coil. The coil is part of a closed circuit. The end of the coil nearest the magnet becomes a

A. south pole, which attracts the magnet
B. north pole, which attracts the magnet
C. south pole, which repels the magnet
D. north pole, which repels the magnet

Question 14.5

A hand-cranked generator is easy to turn when nothing is connected to it. It is harder to turn when it lights a lamp. This is because the current in the generator’s coil

A. is in a magnetic field, so it feels a force that opposes the turning
B. makes the magnets weaker
C. is in a magnetic field, so it feels a force that helps the turning
D. makes the coil heavier

Question 14.6

A strong magnet is dropped through three tubes of the same size: **1** a copper tube, **2** a plastic tube, **3** an aluminium tube. Copper conducts electricity better than aluminium. Plastic is an insulator. Put the tubes in order from the one the magnet falls through in the shortest time to the one it falls through in the longest time.

Put in order. Record the three numbers in order. ☐☐☐

Challenge question

An airplane flies level at 864 km/h. Its metal wings are 35.0 m from tip to tip. The part of the Earth's magnetic field that points straight down is 5.0×10^{-5} T. The potential difference between the wing tips, in volts, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Hint: The wings act like a metal rod pulled through a magnetic field. Change km/h to m/s before you calculate: divide by 3.6.

Card 14 check: hand this in

Three questions. No answers are given here. Your teacher uses them to see what to go over with you.

Check 14.1

A metal rod is at rest in a uniform magnetic field. The potential difference between the ends of the rod is

A. zero, because the rod is not moving
B. equal to Blv
C. largest when the field is strongest
D. equal to the field strength

Check 14.2

A metal rod of length 0.30 m moves at 5.0 m/s through a uniform magnetic field of 0.200 T. The rod, its velocity and the field are all at right angles to each other. The potential difference between the ends of the rod, in volts, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Check 14.3

Oersted and Faraday made the two discoveries that link electricity and magnetism. Which row gives each discovery?

A. Oersted: a magnet has two poles. Faraday: a current makes a magnetic field.
B. Oersted: a current makes a magnetic field. Faraday: a changing magnetic field can make a current.
C. Oersted: a changing magnetic field can make a current. Faraday: a current makes a magnetic field.
D. Oersted: charge is quantized. Faraday: a changing magnetic field can make a current.

Need more? Go back to the lesson: Lesson B15. Then find this idea on the Videos by concept page.

Answers for card 14

Question 14.1: B. $\Delta V = Blv = (0.300\ T)(0.50\ m)(4.0\ m/s) = 0.60\ V$. This is not on the data sheet. It comes from $qvB = qE$ and $E = \Delta V \div l$.

Question 14.2: C. Right hand flat: fingers into the page, thumb to the right, palm toward the top of the page. That is the force on a positive charge. Electrons are pushed the other way, toward the bottom. The bottom gains electrons and is negative. The top is positive.

Question 14.3: Record 12.0. $\Delta V = Blv$, so $v = \Delta V \div (Bl) = 1.20 \div [(0.400)(0.25)] = 12.0$ m/s.

Question 14.4: D. Lenz's law: the induced current opposes the motion. The magnet is moving closer, so the coil must push it back. A north pole repels a north pole, so the near end becomes a north pole.

Question 14.5: A. With the lamp connected, a current flows in the coil. A current in a magnetic field feels a force. By Lenz's law that force opposes the motion. The extra work the hand does becomes electrical energy in the lamp. Energy is conserved.

Question 14.6: Record 231. A moving magnet makes currents flow in a tube that conducts. Those induced currents make a force on the magnet that opposes its motion. Plastic has no current, so the magnet falls fastest (2). Aluminium has some current (3). Copper conducts best, so it has the largest current and the slowest fall (1). The order is 2, 3, 1.

Challenge: Record 0.42. Change the speed to m/s: 864 km/h ÷ 3.6 = 240 m/s. The wings are a rod that moves through a field: $\Delta V = Blv = (5.0 \times 10^{-5}\ \text{T})(35.0\ \text{m})(240\ \text{m/s}) = 0.420$ V. For an answer below 1, the zero in front counts as a digit, so record 0.42.

Practice unit check

Do this when your cards are done. It mixes the whole unit, like the unit final. Give yourself about 30 minutes, with your data sheet. Then check your answers. Each answer names the card to go back to.

Unit check 1

A positive rod is brought near a neutral metal sphere on an insulating stand. The rod does not touch the sphere. The side of the sphere nearest the rod becomes

A. positive, because protons move away from the rod
B. negative, because electrons move toward the rod
C. positive, because electrons move away from the rod
D. negative, because protons move toward the rod

Unit check 2

Two identical electroscopes are both charged negative, so their leaves stand apart. A student holds a metal rod in her bare hand and touches it to the knob of electroscope 1. She holds a glass rod in her bare hand and touches it to the knob of electroscope 2. Afterwards, the leaves of

A. both electroscopes fall together
B. electroscope 1 stay apart, and the leaves of electroscope 2 fall together
C. both electroscopes stay apart
D. electroscope 1 fall together, and the leaves of electroscope 2 stay apart

Unit check 3

A +3.0 μC point charge and a +4.0 μC point charge are 0.20 m apart. The size of the electric force on each charge, in newtons, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Unit check 4

Charge B is on a line between charge A and charge C. The force of A on B is 0.50 N [east]. The force of C on B is 0.20 N [west]. The net electric force on B is

A. 0.70 N [east]
B. 0.30 N [west]
C. 0.54 N [east]
D. 0.30 N [east]

Unit check 5

A −5.0 μC point charge is the source of an electric field. The size of the electric field 0.30 m from the charge is

Numerical response. Write your answer as a.bc × 10^{w} N/C. Record the four digits a, b, c and w.
☐☐☐☐

Unit check 6

The electric field strength E between two parallel plates is measured for several potential differences ΔV. The distance Δd between the plates stays the same. A graph of E against ΔV is a straight line. The slope of the line equals

A. 1 ÷ Δd
B. Δd
C. ΔV ÷ Δd
D. E × Δd

Unit check 7

An electron starts from rest and is accelerated through a potential difference of 400 V. The final speed of the electron is

Numerical response. Write your answer as a.bc × 10^{w} m/s. Record the four digits a, b, c and w.



Unit check 8

A proton enters the uniform electric field between two parallel plates. It is moving parallel to the plates when it enters. Its path between the plates is

A. a circle
B. a straight line parallel to the plates
C. a parabola that curves toward the negative plate
D. a parabola that curves toward the positive plate

Unit check 9

An oil drop of mass 2.45 × 10^{-15} kg is held at rest in a uniform electric field of 5.00 × 10^{4} N/C. The number of extra electrons on the drop is

A. 1
B. 2
C. 3
D. 30

Unit check 10

A solenoid is joined to a battery. To make the magnetic field inside the solenoid stronger, a student could

A. use fewer turns of wire
B. put an iron core inside the solenoid
C. make the current smaller
D. turn the battery around

Unit check 11

An electron moves at 6.0×10^{5} m/s at right angles to a uniform magnetic field of 0.150 T. The size of the magnetic force on the electron is

Numerical response. Write your answer as $a.b \times 10^{-cd}$ N. Record the four digits a, b, c and d.

☐☐☐☐

Unit check 12

An electron moves at 4.0×10^{6} m/s at right angles to a uniform magnetic field of 2.0×10^{-3} T. The radius of its circular path is

Numerical response. Write your answer as $a.bc \times 10^{-w}$ m. Record the four digits a, b, c and w.

☐☐☐☐

Unit check 13

An electron passes straight through a velocity selector. The electric field in the selector is made stronger, and nothing else changes. To pass straight through now, an electron must move

A. faster, because v = E ÷ B
B. slower, because v = B ÷ E
C. at the same speed, because the charge cancels
D. slower, because the electric force is larger

Unit check 14

A horizontal wire of mass 1.20 g hangs still in a uniform magnetic field of 0.0500 T. A 0.0800 m length of the wire is in the field, at right angles to it. The magnetic force on the wire points up. The current in the wire, in amperes, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Unit check 15

A bar magnet is held at rest inside a coil that is joined to a sensitive meter. The meter reads

A. a steady current, because the field inside the coil is strong
B. a current that grows, because the magnet stays in the coil
C. a current in one direction, then the other
D. zero, because nothing is moving

Answers for the practice unit check

Unit check 1: B. Only electrons move. The positive rod attracts them, so they shift to the near side. That side is negative. This is charge separation. The sphere is still neutral. *Wrong? Go back to card 1.*

Unit check 2: D. Metal is a conductor. The extra electrons move through the metal rod and the student to the ground, so electroscope 1 loses its charge and its leaves fall. Glass is an insulator. Electrons cannot move through it, so electroscope 2 keeps its charge and its leaves stay apart. *Wrong? Go back to card 1.*

Unit check 3: Record 2.70. $F = kq_1q_2 \div r^2 = (8.99 \times 10^9)(3.0 \times 10^{-6})(4.0 \times 10^{-6}) \div (0.20)^2 = 2.70$ N. The charges are alike, so they repel. *Wrong? Go back to card 2.*

Unit check 4: D. The forces are on one line and opposite. East is +: (+0.50) + (−0.20) = +0.30 N, which is 0.30 N [east]. *Wrong? Go back to card 3.*

Unit check 5: Record 4995. $E = kq \div r^2 = (8.99 \times 10^9)(5.0 \times 10^{-6}) \div (0.30)^2 = 4.99 \times 10^5$ N/C. The source is negative, so the field points toward it. *Wrong? Go back to card 4.*

Unit check 6: A. $E = \Delta V \div \Delta d = (1 \div \Delta d) \times \Delta V$. Compare it with y = mx. E plays y and ΔV plays x. The number that multiplies ΔV is the slope: 1 ÷ Δd. *Wrong? Go back to card 5.*

Unit check 7: Record 1197. Energy is conserved: $q\Delta V = \frac{1}{2}mv^2$. $v = \sqrt{(2q\Delta V \div m)} = \sqrt{(2(1.60 \times 10^{-19})(400) \div (9.11 \times 10^{-31}))} = 1.19 \times 10^7$ m/s. *Wrong? Go back to card 6.*

Unit check 8: C. The field points from the positive plate to the negative plate. A proton is positive, so the force is along the field, toward the negative plate. A constant force at right angles to the starting velocity gives a parabola. *Wrong? Go back to card 7.*

Unit check 9: C. At rest, qE = mg. $q = mg \div E = (2.45 \times 10^{-15})(9.81) \div (5.00 \times 10^4) = 4.81 \times 10^{-19}$ C. n = q ÷ e = 3.00, so 3 extra electrons. *Wrong? Go back to card 8.*

Unit check 10: B. The field is stronger with more current, more turns, or an iron core. The domains in the iron line up with the field and add to it. Turning the battery around reverses the poles. It does not change the strength. *Wrong? Go back to card 9.*

Unit check 11: Record 1414. $F = qv\perp B = (1.60 \times 10^{-19})(6.0 \times 10^5)(0.150) = 1.44 \times 10^{-14}$ N. Written as $a.b \times 10^{-cd}$, that is 1.4×10^{-14} N. *Wrong? Go back to card 10.*

Unit check 12: Record 1142. $qvB = mv^2 \div r$, so $r = mv \div (qB) = (9.11 \times 10^{-31})(4.0 \times 10^6) \div [(1.60 \times 10^{-19})(2.0 \times 10^{-3})] = 1.14 \times 10^{-2}$ m. *Wrong? Go back to card 11.*

Unit check 13: A. Straight through means qE = qvB, so v = E ÷ B. A larger E with the same B gives a larger speed. A faster electron feels a larger magnetic force, which balances the larger electric force. *Wrong? Go back to card 12.*

Unit check 14: Record 2.94. At rest, ILB = mg. Change the mass: 1.20 g = 1.20×10^{-3} kg. $I = mg \div (LB) = (1.20 \times 10^{-3})(9.81) \div [(0.0800)(0.0500)] = 2.94$ A. *Wrong? Go back to card 13.*

Unit check 15: D. Electromagnetic induction needs motion. A current flows only while the magnet and the coil move past each other. At rest, there is no induced current. *Wrong? Go back to card 14.*

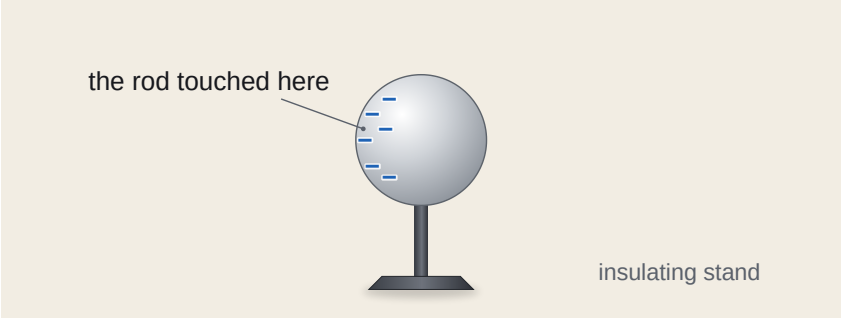
Exam-style question sets

The diploma exam often gives one situation and then asks several questions about it. The questions can come from different cards. Read the box first. Then answer each question in the set. Each answer names the card to go back to.

Set 1: A charged sphere

Use the following information to answer the questions in set 1.

A negatively charged rod touches a neutral sphere that sits on an insulating stand. The rod is taken away. The picture shows where the extra charge is on the sphere afterwards. During the touch, the sphere gained 2.0×10^{10} electrons.



Set 1, question 1

Which row gives the way the sphere was charged and the kind of material the sphere is made of?

A. Charged by induction. The sphere is a conductor.
B. Charged by induction. The sphere is an insulator.
C. Charged by contact. The sphere is a conductor.
D. Charged by contact. The sphere is an insulator.

Set 1, question 2

The same rod touches a metal sphere of the same size on an insulating stand. Afterwards, the extra charge on the metal sphere is

A. spread evenly over its surface, because electrons can move through a metal and they repel each other
B. in one patch where the rod touched, because the stand is an insulator
C. at the centre of the sphere, because the electrons attract each other
D. gone, because a metal cannot hold a charge

Set 1, question 3

The size of the charge on the sphere is

Numerical response. Write your answer as $a.bc \times 10^{-w}$ C. Record the four digits a, b, c and w.



Set 1, question 4

Treat the sphere as a point charge. The size of the electric field 0.30 m from the centre of the sphere is

Numerical response. Write your answer as a.bc × 10^{w} N/C. Record the four digits a, b, c and w.

□□□□

Answers for set 1

Set 1, question 1: D. The rod touched the sphere, and the sphere ended with the same sign as the rod. That is charging by contact (conduction). The extra charge stayed in one patch, where the rod touched. On a conductor it would spread over the whole surface. So the sphere is an insulator. *Wrong? Go back to card 1.*

Set 1, question 2: A. In a metal, electrons can move through the whole object. The extra electrons repel each other, so they spread out as far apart as they can: evenly over the surface. *Wrong? Go back to card 1.*

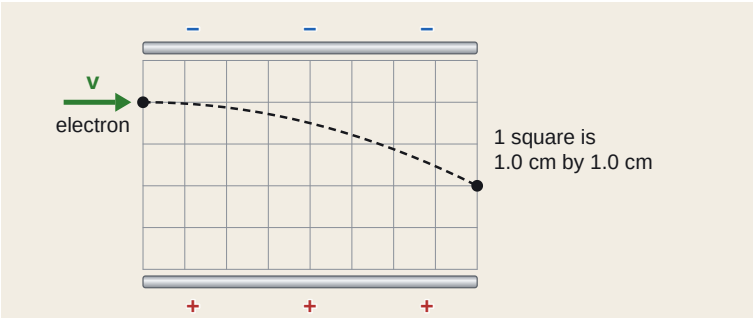
Set 1, question 3: Record 3209. $q = ne = (2.0 \times 10^{10})(1.60 \times 10^{-19}\ C) = 3.20 \times 10^{-9}\ C$. The sphere gained electrons, so the charge is negative. *Wrong? Go back to card 1.*

Set 1, question 4: Record 3202. $E = kq \div r^2 = (8.99 \times 10^{9})(3.20 \times 10^{-9}) \div (0.30)^2 = 3.20 \times 10^{2}$ N/C. The charge is negative, so the field points toward the sphere. *Wrong? Go back to card 4.*

Set 2: Measuring the path of an electron

Use the following information to answer the questions in set 2.

An electron enters the uniform electric field between two parallel plates. It enters at 4.0×10^{6} m/s, moving parallel to the plates. The picture shows its path, drawn to scale on a grid. Each square of the grid is 1.0 cm wide and 1.0 cm tall in the real apparatus. The two dots mark where the electron enters the grid and where it leaves. Gravity is too small to matter.



Set 2, question 1

Use the grid to find how far the electron moves along the plates between the two dots. The time the electron takes to move between the two dots is

Numerical response. Write your answer as a.bc × 10^{-w} s. Record the four digits a, b, c and w.

□□□□

Set 2, question 2

Use the grid to find how far the electron moves across the plates between the two dots. The size of the acceleration of the electron is

Numerical response. Write your answer as a.b × 10^{cd} m/s². Record the four digits a, b, c and d.

☐☐☐☐

Set 2, question 3

The strength of the electric field between the plates is

Numerical response. Write your answer as a.bc × 10^{w} N/C. Record the four digits a, b, c and w.

☐☐☐☐

Set 2, question 4

The physics principles on the data sheet are numbered 0 to 9. Pick the two principles that were used to find the acceleration of the electron from the picture.

Pick two. Record the numbers of the two principles. ☐☐

Answers for set 2

Set 2, question 1: Record 2008. Count the squares between the dots: 8 squares along, so L = 8.0 cm = 0.080 m. Along the plates the speed is constant: t = L ÷ v_x = 0.080 ÷ (4.0 × 10^{6}) = 2.00 × 10^{-8} s. *Wrong? Go back to card 7.*

Set 2, question 2: Record 1014. Count the squares: 2 squares across, so Δd = 2.0 cm = 0.020 m. The starting across speed is 0, so Δd = ½at². a = 2Δd ÷ t² = 2(0.020) ÷ (2.00 × 10^{-8})² = 1.00 × 10^{14} m/s². Written as a.b × 10^{cd}, that is 1.0 × 10^{14} m/s². *Wrong? Go back to card 7.*

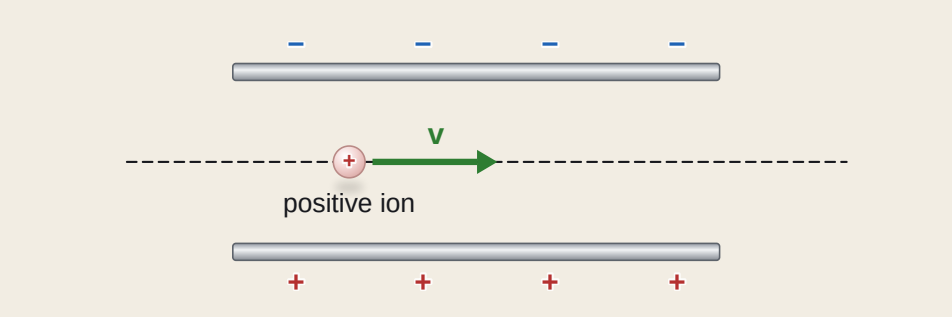
Set 2, question 3: Record 5692. The electric force is the net force: qE = ma. E = ma ÷ q = (9.11 × 10^{-31}) (1.00 × 10^{14}) ÷ (1.60 × 10^{-19}) = 5.69 × 10^{2} N/C. On the exam you measure with a ruler tool, so a small range of answers is marked right. *Wrong? Go back to card 7.*

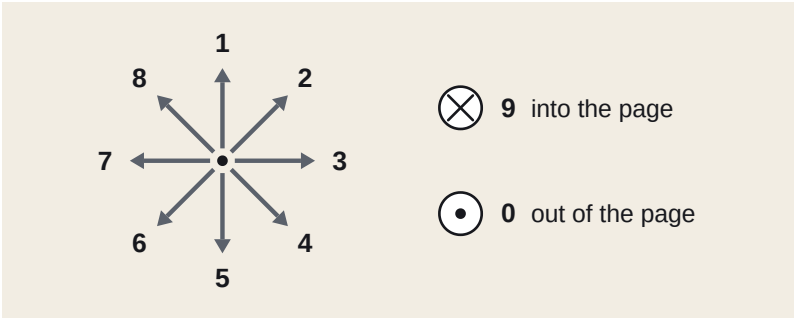
Set 2, question 4: Record 01. Along the plates: uniform motion (principle 0) gives the time. Across the plates: accelerated motion (principle 1) gives the acceleration. Record 01. The order does not matter. *Wrong? Go back to card 7.*

Set 3: A velocity selector

Use the following information to answer the questions in set 3.

> A positive ion moves to the right between two parallel plates. The top plate is negative and the bottom plate is positive. A uniform magnetic field fills the space between the plates. The ion passes through at a constant speed, and its path is a straight line. The electric field between the plates is 2.4 × 10^{4} N/C. The magnetic field is 0.060 T. Use the direction picture for question 1.





Set 3, question 1

Four directions are needed, in this order: the electric force on the ion, the electric field between the plates, the magnetic force on the ion, the magnetic field between the plates. The four directions are

Direction. Record the four direction numbers in order. ☐☐☐☐

Set 3, question 2

The speed of the ion is

Numerical response. Write your answer as a.bc × 10ʷ m/s. Record the four digits a, b, c and w.

☐☐☐☐

Set 3, question 3

An electron enters the same fields, moving to the right at the same speed as the ion. The electron

A. bends toward the top plate, because the electric force on it is reversed
B. bends toward the bottom plate, because it is attracted to the positive plate
C. passes straight through, because both forces on it are reversed and still balance
D. moves in a circle, because it has much less mass

Set 3, question 4

The plates are disconnected, so the electric field between them is zero. The magnetic field stays. The positive ion enters as before. At the moment it enters, the ion

A. keeps moving in a straight line, because a magnetic field does not push a charge
B. starts to curve toward the top plate
C. speeds up to the right, along its velocity
D. starts to curve toward the bottom plate

Answers for set 3

Set 3, question 1: Record 1150. Electric force: a positive ion is pulled toward the negative plate, at the top: direction 1. Electric field: it points the way a positive charge is pushed, from the positive plate to the negative plate: direction 1. Magnetic force: the path is straight, so the net force is zero and the magnetic force is opposite to the electric force: direction 5. Magnetic field: right hand flat, thumb to the right (the velocity), palm toward the bottom of the page (the force). The fingers point out of the page: direction 0. *Wrong? Go back to card 12.*

Set 3, question 2: Record 4005. A straight path means qE = qvB. The charge cancels: v = E ÷ B = (2.4 × 10^4) ÷ (0.060) = 4.00 × 10^5 m/s. *Wrong? Go back to card 12.*

Set 3, question 3: C. For a negative charge the electric force and the magnetic force both reverse. They are still equal in size and opposite, because v = E ÷ B does not depend on the charge or the mass. *Wrong? Go back to card 12.*

Set 3, question 4: D. Only the magnetic force acts now. From question 1 it points toward the bottom of the page. A force at right angles to the velocity turns the ion into a circular path, starting toward the bottom plate. *Wrong? Go back to card 10.*

Set 4: An experiment with a wire in a magnetic field

Use the following information to answer the questions in set 4.

> Students put a stiff wire between the poles of a magnet. The wire is at right angles to the magnetic field. A power supply sends a current through the wire, and a meter reads the current. The magnet sits on a balance, so the students can find the size of the magnetic force on the wire. They can change the current. They can also swap the magnet for a wider one, so that a longer piece of the wire is in the field.

Set 4, question 1

The students choose this research question: “Does the size of the current affect the size of the magnetic force on the wire?” Which row names the variables for this question?

A. Manipulated: the magnetic force. Responding: the current. Controlled: the length of wire in the field.
B. Manipulated: the current. Responding: the magnetic force. Controlled: the length of wire in the field.
C. Manipulated: the length of wire in the field. Responding: the magnetic force. Controlled: the current.
D. Manipulated: the current. Responding: the length of wire in the field. Controlled: the magnetic force.

Set 4, question 2

The students then ask: “Does the length of wire in the field affect the size of the magnetic force?” For a fair test, they must keep the same

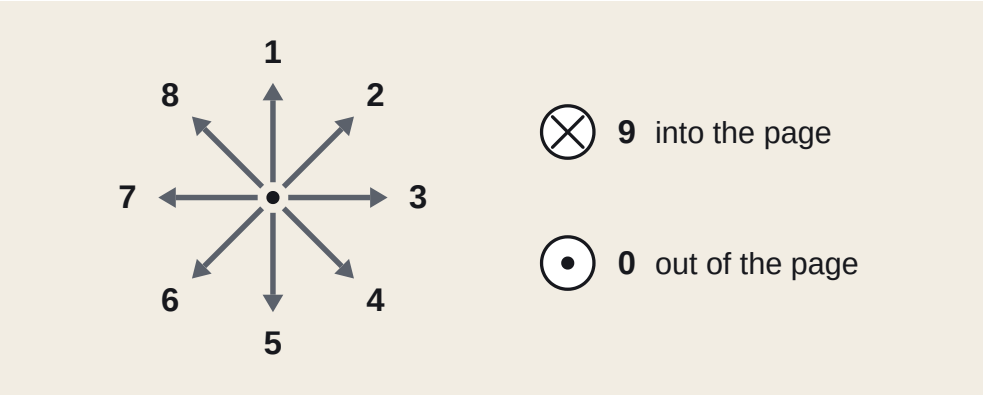
A. length of wire in the field
B. magnetic force
C. balance reading
D. current and field strength

Set 4, question 3

The students graph the magnetic force F against the current I. The line of best fit passes through (2.0 A, 0.064 N) and (4.0 A, 0.128 N). The length of wire in the field is 0.080 m. The strength of the magnetic field, in teslas, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Set 4, question 4



The wire is at the centre dot of the direction picture. The magnetic field points to the right. The students want the magnetic force on the wire to point toward the top of the page. The direction the electrons must flow in the wire is direction

Direction. Record the number of the direction. ☐

Answers for set 4

Set 4, question 1: B. The question asks what the current does to the force. So the current is changed (manipulated) and the force is measured (responding). Everything else must stay the same: the length of wire in the field and the field strength. *Wrong? Go back to card 13.*

Set 4, question 2: D. Now the length is the one thing they change, and the force is what they measure. The current and the field strength must be held fixed, so that only the length can change the force. *Wrong? Go back to card 13.*

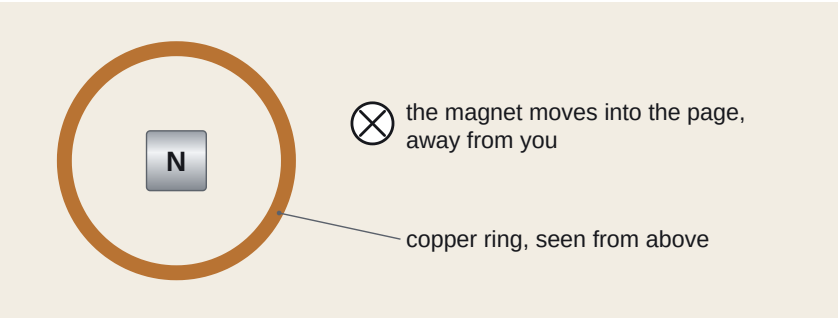
Set 4, question 3: Record 0.40. $F = (LB)I$, so the slope equals LB. Slope = (0.128 − 0.064) ÷ (4.0 − 2.0) = 0.032 N/A. B = slope ÷ L = 0.032 ÷ 0.080 = 0.40 T. For an answer below 1, the zero in front counts as a digit, so record 0.40. *Wrong? Go back to card 13.*

Set 4, question 4: Record 9. Work backward with the flat right hand. Fingers to the right (the field). Palm toward the top of the page (the force). The thumb then points out of the page. The thumb shows the conventional current: out of the page, direction 0. Electrons flow the opposite way: into the page, direction 9. *Wrong? Go back to card 13.*

Set 5: A falling magnet, a ring and two plates

Use the following information to answer the questions in set 5.

Part 1. A copper ring lies flat on a table. A bar magnet is dropped from above, with its north pole first, toward the centre of the ring. The picture shows the ring seen from above: the magnet is moving away from you, into the page.
Part 2. In a second experiment, the ends of a coil of wire are joined to two metal plates that stand side by side. A small positive ball hangs on a thread between the plates. When the north pole of a magnet is pushed quickly toward the coil, the left plate becomes positive and the right plate becomes negative.



Set 5, question 1

In Part 1, which row gives the pole that the top of the ring becomes and the direction of the force on the falling magnet?

A. A south pole. The force on the magnet is down.
B. A south pole. The force on the magnet is up.
C. A north pole. The force on the magnet is up.
D. A north pole. The force on the magnet is down.

Set 5, question 2

In Part 1, seen from above, the electrons in the ring move

A. counterclockwise
B. toward the centre of the ring
C. away from the centre of the ring
D. clockwise

Set 5, question 3

In Part 2, while the magnet is pushed toward the coil, the positive ball

A. swings toward the right plate, because the electric field between the plates points to the right
B. swings toward the left plate, because the electric field between the plates points to the left
C. does not move, because a magnetic field does not push a charge at rest
D. swings toward the left plate, because it is attracted to the positive plate

Set 5, question 4

In Part 2, the magnet is then pulled quickly away from the coil. The positive ball

A. swings toward the right plate again
B. swings toward the left plate
C. hangs straight down
D. swings toward the right plate, but more slowly

Set 5, question 5

In Part 2, the magnet is held at rest inside the coil. The positive ball

A. stays pushed toward the right plate
B. swings back and forth
C. is pulled toward the coil
D. hangs straight down

Answers for set 5

Set 5, question 1: C. Lenz's law: the induced current opposes the motion. The north pole is moving toward the ring, so the ring must push it back. A north pole repels a north pole, so the top of the ring becomes a north pole and the force on the magnet is up. *Wrong? Go back to card 14.*

Set 5, question 2: D. The top of the ring is a north pole, so the field inside the ring points up, out of the page. Grip the ring with the right hand so that the fingers inside the ring point out of the page. The thumb, and so the conventional current, goes counterclockwise. Electrons flow the opposite way: clockwise. *Wrong? Go back to card 14.*

Set 5, question 3: A. The moving magnet induces a potential difference in the coil, which charges the plates. The field between the plates points from the positive left plate to the negative right plate. A positive ball is pushed along the field: toward the right plate. *Wrong? Go back to card 4.*

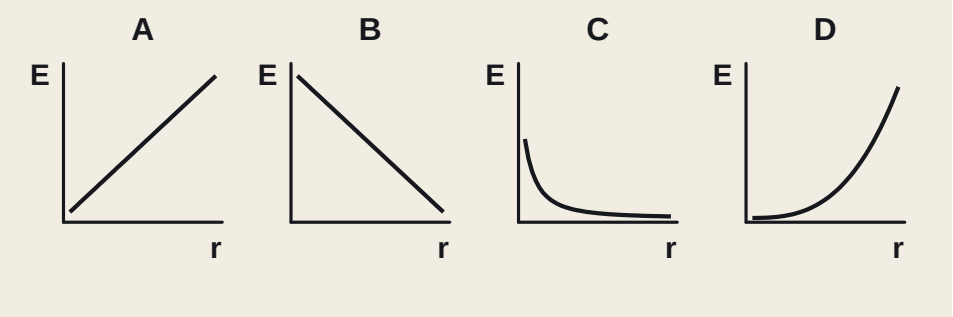
Set 5, question 4: B. Pulling the magnet away reverses the induced current. Now the left plate is negative and the right plate is positive. The field between the plates points to the left, so the positive ball swings toward the left plate. *Wrong? Go back to card 14.*

Set 5, question 5: D. Induction needs motion. With the magnet at rest there is no induced current, so the plates lose their charge and there is no electric field between them. Only gravity and the thread act, so the ball hangs straight down. *Wrong? Go back to card 14.*

Set 6: Mapping the space around a charge

Use the following information to answer the questions in set 6.

A student maps the space around one small positive charge in two ways.
Map 1. At many points she finds the size and the direction of the electric force on a small positive test charge.
Map 2. At many points she finds the electric potential energy that each coulomb of charge would have there. This quantity has a size but no direction.
She also measures the electric field strength E at several distances r from the charge.



Set 6, question 1

Which row gives the kind of field that each of the two maps shows?

A. Map 1 is a scalar field. Map 2 is a scalar field.
B. Map 1 is a scalar field. Map 2 is a vector field.
C. Map 1 is a vector field. Map 2 is a scalar field.
D. Map 1 is a vector field. Map 2 is a vector field.

Set 6, question 2

Which of the four graphs shows how the electric field strength E changes with the distance r from the charge?

A. Graph A
B. Graph B
C. Graph C
D. Graph D

Set 6, question 3

The student moves a charge from one point to another point where each coulomb has the same electric potential energy. The potential difference between the two points, and the work she must do, are

A. zero, and zero
B. zero, and qE
C. not zero, and zero
D. not zero, and qΔV

Answers for set 6

Set 6, question 1: C. A vector field has a size and a direction at every point. Map 1 records a force, with a direction, so it is a vector field. A scalar field has only a size at every point. Map 2 records energy for each coulomb, with no direction, so it is a scalar field. *Wrong? Go back to card 4.*

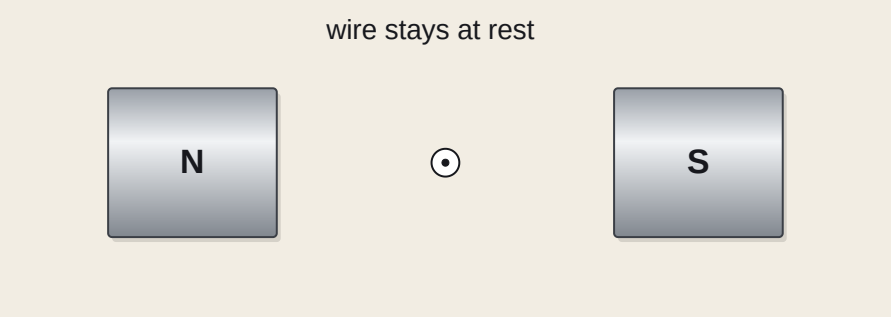
Set 6, question 2: C. $E = kq \div r^2$. The field is very strong close to the charge and drops quickly as r grows: double the distance gives one quarter of the field. It gets closer and closer to zero without reaching it. That is the curve in graph C. A straight line would mean E changes by the same amount for each step in r. *Wrong? Go back to card 5.*

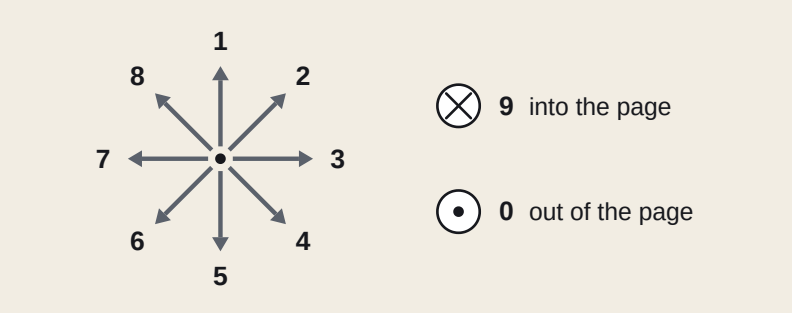
Set 6, question 3: A. The energy for each coulomb is the same at both points, so the potential difference ΔV is zero. The energy change is $\Delta E = q\Delta V = 0$, so no work is needed. *Wrong? Go back to card 6.*

Set 7: A wire between the poles of a magnet

Use the following information to answer the questions in set 7.

A straight wire is held between the poles of a magnet. The north pole is on the left and the south pole is on the right, so the field of the magnet points to the right. The picture shows the wire seen end-on. The dot means that the conventional current in the wire comes out of the page, toward you. Point P is just above the wire. Point Q is just below the wire.





Set 7, question 1

Think only about the magnetic field that the current in the wire makes. The wire is at the centre dot of the direction picture. The direction of this field at point P, above the wire, is direction

Direction. Record the number of the direction. ☐

Set 7, question 2

Fields add as vectors. Compared with the field of the magnet alone, the net magnetic field is

A. stronger at P and stronger at Q
B. stronger at P and weaker at Q
C. weaker at P and weaker at Q
D. weaker at P and stronger at Q

Set 7, question 3

The direction of the magnetic force on the wire is direction

Direction. Record the number of the direction. ☐

Set 7, question 4

In 20.0 s, 7.5×10^{19} electrons pass a point in the wire. A 0.0500 m length of the wire is in the magnet's field of 0.0800 T, at right angles to it. The size of the magnetic force on the wire is

Numerical response. Write your answer as $a.bc \times 10^{-w}$ N. Record the four digits a, b, c and w.
☐☐☐☐

Answers for set 7

Set 7, question 1: Record 7. Grip the wire with the right hand, thumb out of the page (the conventional current). The fingers curl counterclockwise. P is at 12 o'clock, where a counterclockwise circle goes to the left: direction 7. *Wrong? Go back to card 9.*

Set 7, question 2: D. The magnet's field points to the right everywhere. At P the wire's field points to the left, opposite to it, so the two partly cancel: weaker. At Q, below the wire, the wire's field points to the right, the same way, so they add: stronger. *Wrong? Go back to card 9.*

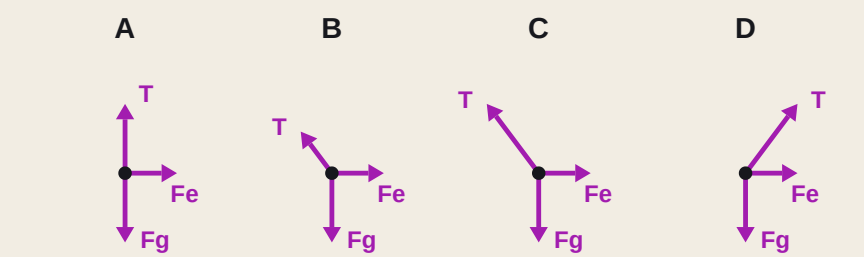
Set 7, question 3: Record 1. Right hand flat: fingers to the right (the magnet's field), thumb out of the page (the conventional current). The palm faces the top of the page: direction 1. This fits the last question: the wire is pushed from the side where the net field is stronger toward the side where it is weaker. *Wrong? Go back to card 13.*

Set 7, question 4: Record 2403. Two steps. Current: $q = ne = (7.5 \times 10^{19})(1.60 \times 10^{-19}) = 12.0$ C, so $I = q \div t = 12.0 \div 20.0 = 0.600$ A. Force: $F = IlB = (0.600)(0.0500)(0.0800) = 2.40 \times 10^{-3}$ N. *Wrong? Go back to card 13.*

Set 8: Coulomb's balance and a hanging ball

Use the following information to answer the questions in set 8.

> **Part 1.** Coulomb measured the electric force with a torsion balance. A light rod hangs level from a thin fibre. Charged ball A is on one end of the rod. Charged ball B is held near ball A. Both balls are positive, so ball A is pushed away. The rod turns and twists the fibre until the rod stops.
> **Part 2.** A small charged ball hangs at rest on a thread. Three forces act on it: its weight of 0.040 N, straight down; an electric force of 0.030 N, to the right; and the tension in the thread.



Fg is the weight. Fe is the electric force. T is the tension.

Set 8, question 1

In Part 1, the angle that the fibre twists through tells Coulomb the size of the

A. charge on ball A
B. electric force between the two balls
C. mass of ball A
D. distance between the two balls

Set 8, question 2

In Part 1, ball B is touched to a neutral ball of the same size, so ball B keeps half of its charge. Ball B is put back at the same distance from ball A. Compared with before, the twist of the fibre is

A. half as large
B. one quarter as large
C. the same
D. twice as large

Set 8, question 3

In Part 2, which of the four free-body diagrams is drawn to scale for the ball?

A. Diagram A
B. Diagram B
C. Diagram C
D. Diagram D

Set 8, question 4

In Part 2, the size of the tension in the thread is

Numerical response. Write your answer as a.bc × 10^{-w} N. Record the four digits a, b, c and w.

□□□□

Answers for set 8

Set 8, question 1: B. The electric force turns the rod. The fibre twists until its pull back balances that force. A bigger force gives a bigger twist, so the twist angle measures the electric force. Coulomb could not measure a charge directly. He measured the distance with a scale. *Wrong? Go back to card 2.*

Set 8, question 2: A. $F = kq_1q_2 \div r^2$. The force is proportional to the product of the two charges. One charge is halved and the distance is the same, so the force is halved. The twist measures the force, so the twist is halved. *Wrong? Go back to card 2.*

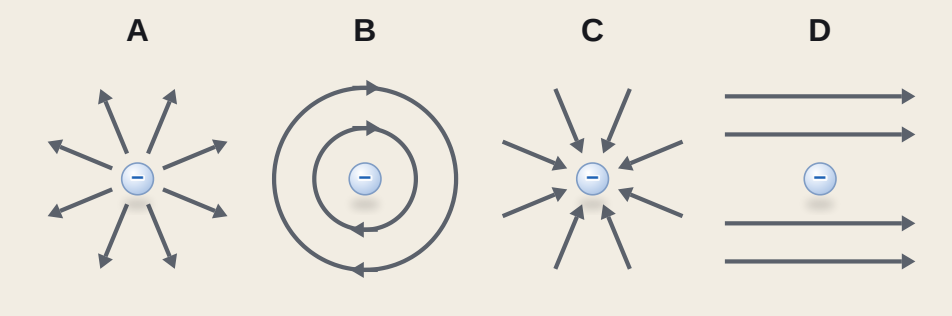
Set 8, question 3: C. The ball is at rest, so the net force is zero. The tension must cancel both other forces. It needs an upward part of 0.040 N to cancel the weight and a leftward part of 0.030 N to cancel the electric force. So the tension points up and to the left, and its size is $\sqrt{(0.030^2 + 0.040^2)} = 0.050$ N: longer than both other arrows. That is diagram C. In A the tension has no leftward part. In B the tension is too short. In D the tension points to the right, the same side as the electric force. *Wrong? Go back to card 3.*

Set 8, question 4: Record 5002. The weight and the electric force are at right angles. The tension balances both: $T = \sqrt{(0.030^2 + 0.040^2)} = 5.00 \times 10^{-2}$ N. *Wrong? Go back to card 3.*

Set 9: Plotting a field, and a fast proton

Use the following information to answer the questions in set 9.

Part 1. Students want to plot the electric field around a small sphere that has a negative charge. In the lab they have: a small positive test charge on an insulating thread, a compass, a balance and a stopwatch.
Part 2. A machine uses an electric field to speed up a proton from rest. The proton leaves the machine with a kinetic energy of 2.50 MeV.



Set 9, question 1

In Part 1, which piece of equipment shows the direction of the electric field at a point, and why?

A. The compass: its needle lines up with an electric field.
B. The balance: it reads the size of the charge on the sphere.
C. The stopwatch: a stronger field gives a shorter time.
D. The test charge on its thread: the field points the way a positive test charge is pushed.

Set 9, question 2

In Part 1, the students do these four steps, listed here in mixed order:
1 Join the arrows into smooth field lines.
2 Hold the test charge at one point near the sphere.
3 Move the test charge to a new point and do the same again, until there are arrows all around the sphere.
4 Draw a small arrow at that point, in the direction the test charge is pushed.
Put the four steps in the order the students do them.

Put in order. Record the four numbers in order. ☐☐☐☐

Set 9, question 3

Which of the four pictures shows the electric field around the negative sphere?

A. Picture A
B. Picture B
C. Picture C
D. Picture D

Set 9, question 4

In Part 2, the kinetic energy of the proton, in joules, is

Numerical response. Write your answer as $a.b \times 10^{-cd}$ J. Record the four digits a, b, c and d.
☐☐☐☐

Set 9, question 5

In Part 2, the speed of the proton as it leaves the machine is

Numerical response. Write your answer as $a.bc \times 10^{w}$ m/s. Record the four digits a, b, c and w.
☐☐☐☐

Answers for set 9

Set 9, question 1: D. The direction of an electric field at a point is the direction of the electric force on a small positive test charge there. A compass is the test object for a magnetic field, not for an electric field. *Wrong? Go back to card 4.*

Set 9, question 2: Record 2431. First put the test charge at a point (2). Then draw an arrow the way it is pushed (4). Repeat at many points (3). Last, join the arrows into field lines (1). The order is 2, 4, 3, 1. *Wrong? Go back to card 4.*

Set 9, question 3: C. A positive test charge is attracted to a negative sphere from every side. So the field lines are straight lines that point toward the sphere: picture C. Picture A is the field of a positive charge. Circles (picture B) are the shape of the magnetic field around a wire. Parallel lines (picture D) are the field between two charged plates. *Wrong? Go back to card 4.*

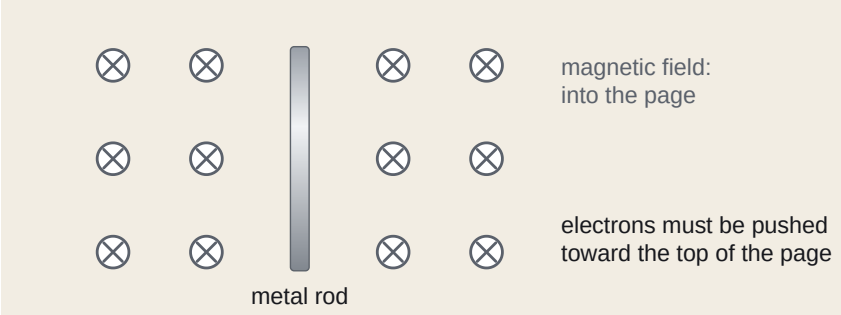
Set 9, question 4: Record 4013. The prefix M (mega) means 10^6, so 2.50 MeV = 2.50×10^6 eV. From the data sheet, 1 eV = 1.60×10^{-19} J. Ek = $(2.50 \times 10^6)(1.60 \times 10^{-19}) = 4.00 \times 10^{-13}$ J. Written as $a.b \times 10^{-cd}$, that is 4.0×10^{-13} J. *Wrong? Go back to card 6.*

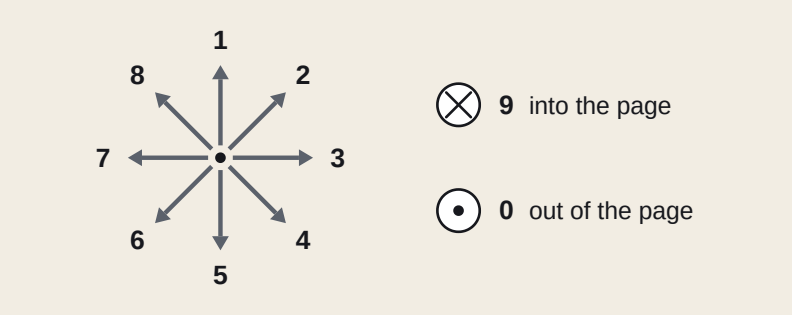
Set 9, question 5: Record 2197. $Ek = \frac{1}{2}mv^2$, so $v = \sqrt{(2Ek \div m)} = \sqrt{[2(4.00 \times 10^{-13}) \div (1.67 \times 10^{-27})]} = 2.19 \times 10^7$ m/s. The mass of a proton is on the data sheet. Use the energy in joules, not in MeV. *Wrong? Go back to card 6.*

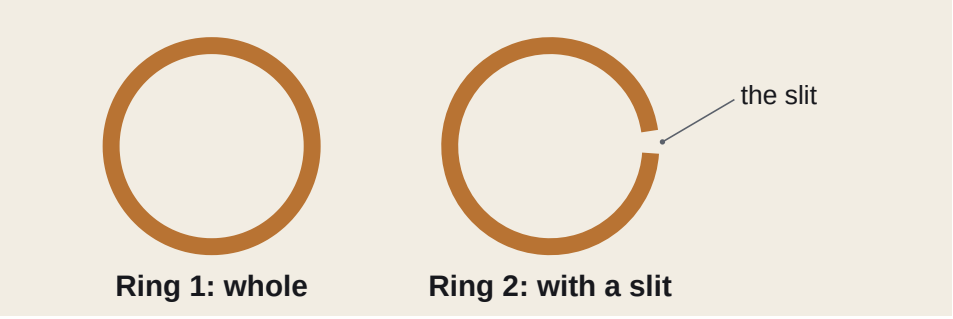
Set 10: A moving rod, two rings and a hospital scanner

Use the following information to answer the questions in set 10.

Part 1. A vertical metal rod is in a uniform magnetic field that points into the page. The rod will be moved through the field. The rod must move so that the electrons in it are pushed toward the top of the page. Use the direction picture for question 1.
Part 2. Two copper rings of the same size lie flat. Ring 1 is whole. Ring 2 has a slit cut through it. A bar magnet is dropped, north pole first, through the centre of each ring.
Part 3. An MRI scanner makes pictures of the inside of the body. It uses a very strong magnetic field from a large coil.







Set 10, question 1

In Part 1, the rod is at the centre dot of the direction picture. The direction the rod must move is direction

Direction. Record the number of the direction. ☐

Set 10, question 2

In Part 1, students test how the speed of the rod changes the potential difference between its ends. Their four steps are listed here in mixed order:
1 Graph the potential difference against the speed.
2 Move the rod through the field at one steady speed and record the voltmeter reading.
3 Connect a voltmeter to the two ends of the rod.
4 Do the same again at several other speeds.
Put the four steps in the order the students do them.

Put in order. Record the four numbers in order. ☐☐☐☐

Set 10, question 3

In Part 2, which row describes ring 2, the ring with the slit, as the magnet falls toward it?

A. A current goes around the ring. The ring slows the magnet.
B. No current can go around the ring. The ring does not slow the magnet.
C. No current can go around the ring. The ring slows the magnet.
D. A current goes around the ring. The ring speeds up the magnet.

Set 10, question 4

In Part 2, the magnet passes through ring 1 more slowly than it passes through ring 2. The kinetic energy that the magnet does not gain at ring 1 becomes

A. thermal energy in ring 1, because the induced current warms the copper
B. gravitational potential energy of the magnet
C. extra magnetism in the magnet
D. nothing: that energy is lost

Set 10, question 5

In Part 3, a hospital is deciding whether to buy an MRI scanner. Which row gives one benefit and one risk that both come from its strong magnetic field?

A. Benefit: it uses no electrical energy. Risk: copper wires in the room are pulled toward the scanner.
B. Benefit: it takes away static charge from the patient. Risk: the field stops if the patient moves.
C. Benefit: it shields the patient from every electric field. Risk: the patient becomes a permanent magnet.
D. Benefit: it makes pictures of the inside of the body without cutting. Risk: iron and steel objects in the room are pulled hard toward the scanner.

Answers for set 10

Set 10, question 1: Record 7. Work backward. Electrons must be pushed toward the top, so a positive charge would be pushed toward the bottom of the page. Right hand flat: fingers into the page (the field), palm toward the bottom of the page (the force on a positive charge). The thumb then points to the left. The thumb shows the velocity: direction 7. *Wrong? Go back to card 14.*

Set 10, question 2: Record 3241. Set up the meter first (3). Take one measurement at one speed (2). Repeat at other speeds (4). Then graph the results (1). The order is 3, 2, 4, 1. *Wrong? Go back to card 14.*

Set 10, question 3: B. A current needs a closed path. The slit breaks the path, so no current can go around ring 2. With no current, the ring makes no magnetic field of its own, so it does not push back on the magnet. In ring 1 the path is closed. A current goes around it, and by Lenz's law that current opposes the motion of the magnet. *Wrong? Go back to card 14.*

Set 10, question 4: A. Energy is conserved. The induced current in ring 1 carries electrical energy, and the current warms the copper. That energy comes from the falling magnet, so the magnet gains less kinetic energy. *Wrong? Go back to card 14.*

Set 10, question 5: D. The strong field is what lets the scanner make pictures of the inside of the body. The same field pulls iron and steel objects with a large force, so they must be kept out of the room. To judge a technology, list its benefits and its risks, then decide whether the benefits are worth the risks. Copper is not pulled by a magnet, and the scanner uses a lot of electrical energy. *Wrong? Go back to card 13.*