

ESAT

Physics

Magnetism and electromagnetism

Free lesson notes

Covers	P2.1 to P2.5
Format	Lesson, worked examples, self-check
Price	Free

About this lesson

Magnetism is a topic where a small number of *rules* do almost all the work, but only if you understand where each rule comes from. A magnet makes a field; a current makes a field too; two fields push on each other (the motor effect); and a *changing* field makes a current (induction). Motors, generators, loudspeakers, transformers and the National Grid are all just these four ideas arranged cleverly.

The lesson builds the chain step by step. We start with magnets and their field lines, and how an unmagnetised piece of iron is turned into a magnet by induction. We then see that a wire carrying current also has a magnetic field, learn the right-hand grip rule, and build electromagnets. Next we meet the force on a current in a field, derive the unit of field strength, use $F = BIL$ and Fleming's left-hand rule, and see how a d.c. motor uses the force to turn. We then reverse the story: moving a magnet near a coil induces an e.m.f., which explains the a.c. generator and its graph. Finally we derive the transformer equations and see why electricity is sent across the country at very high voltage. There is no calculator in the real exam, so every example uses friendly numbers.

How to use it. Draw every situation yourself and mark directions with the correct rule. Cover each worked example and try it first. Finish with the self-check and the practice set. Specification codes: P2.1 (magnets), P2.2 (field of a current), P2.3 (motor effect), P2.4 (induction and generators) and P2.5 (transformers).

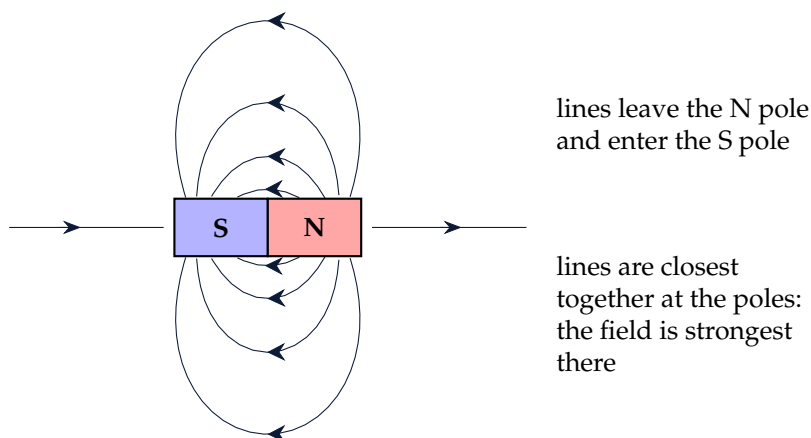
Heurisco is an independent practice provider and is not affiliated with, endorsed by, or connected to UAT-UK, Pearson VUE, the UCAT Consortium, or any university. All questions are original.

1 Magnets and magnetic fields

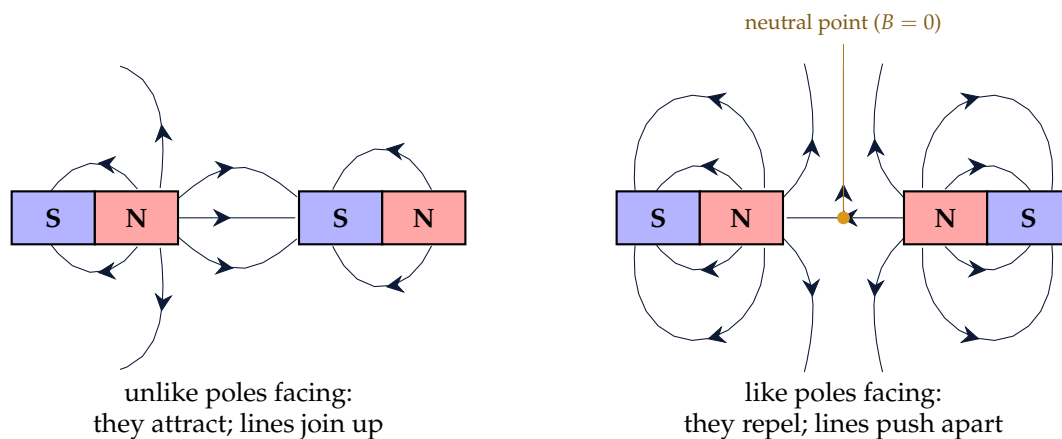
Poles and forces. A bar magnet has two ends, called **poles**, where the magnetic effect is strongest: a north-seeking pole (N) and a south-seeking pole (S). Experiments give one rule: **like poles repel, unlike poles attract**. If you hang a magnet freely it turns until its N pole points roughly to the Earth's geographic north, which is how a compass works. (The Earth behaves like a huge bar magnet whose *south* magnetic pole is near the geographic north pole, which is why the compass's N end is attracted there.)

Which materials are magnetic? Only a few metals are attracted to a magnet: **iron, steel, nickel and cobalt** (and alloys that contain them). Copper, aluminium, brass, plastic, glass and wood are not. Tiny regions inside a magnetic material act like miniature magnets. In an unmagnetised piece they point in random directions and cancel; when they are lined up, the whole piece is a magnet.

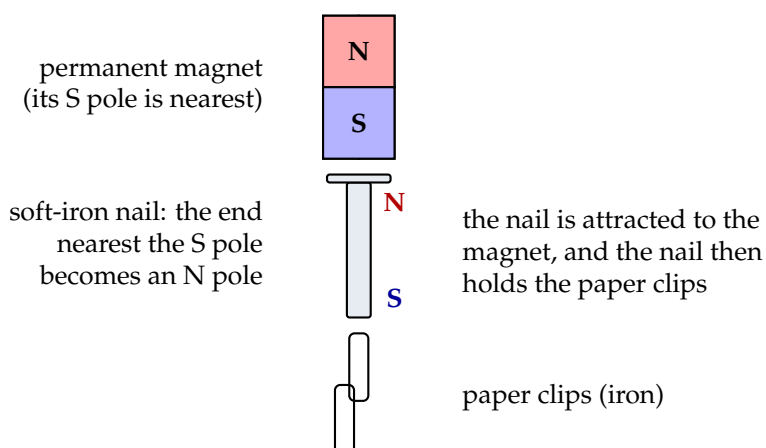
The magnetic field. A **magnetic field** is a region where a magnetic material or a moving charge feels a force. We draw it with **field lines**. The rules are: lines have arrows pointing from **N to S** (the direction a tiny N pole would be pushed); lines never cross; and where the lines are **closest together the field is strongest**. A plotting compass placed anywhere lines up along the field line through it, which is how field patterns are mapped in the laboratory.



Two magnets together. When unlike poles face each other the lines run straight across the gap from N to S: the two magnets are pulled together. When like poles face each other the lines bend away and squeeze apart, and there is a *neutral point* between them where the two fields cancel and the field is zero. A very useful special case is the **uniform field** between two flat opposite poles close together: the lines are parallel, equally spaced and straight, meaning the field has the same strength and direction everywhere in the gap. Most diagrams later in this lesson use such a field.



Permanent and induced magnets. A **permanent magnet** always has its own field. An **induced magnet** is a magnetic material that becomes magnetic only while it is in another magnet's field. Bring the S pole of a magnet near a piece of soft iron: the field lines the magnet produces line up the tiny magnets in the iron, so the end nearest the S pole becomes a N pole (the opposite pole) and the far end a S pole. The nearest pole is always *opposite*, so the attraction wins and the iron is pulled towards the magnet. This is why an unmagnetised nail picks up paper clips, and why a magnet can pick up a *chain* of clips: each clip is magnetised by the one above it. Take the magnet away and a soft iron nail loses almost all its magnetism.



Hard and soft magnetic materials. **Soft** magnetic materials such as pure **iron** are easy to magnetise *and* easy to demagnetise: they are ideal for electromagnet cores, relays and transformer cores because the magnetism must switch on and off quickly. **Hard** magnetic materials such as **steel** are harder to magnetise but *keep* their magnetism, so they are used for permanent magnets, compass needles and fridge magnets. A magnet can be demagnetised by heating it, dropping or hammering it, or placing it in a decreasing alternating field.

Worked example: is it a magnet?

A steel rod is attracted when *either* of its ends is brought near the N pole of a bar magnet. Is the rod itself a magnet? What test would settle it?

Attraction happens between a magnet and an unmagnetised magnetic material (through induced magnetism) as well as between unlike poles of two magnets, so attraction alone proves nothing. A rod that is a magnet would be attracted at one end and *repelled* at the other by the same pole. Here both ends are attracted, so the rod is unmagnetised. **Repulsion is the only reliable test for a magnet.**

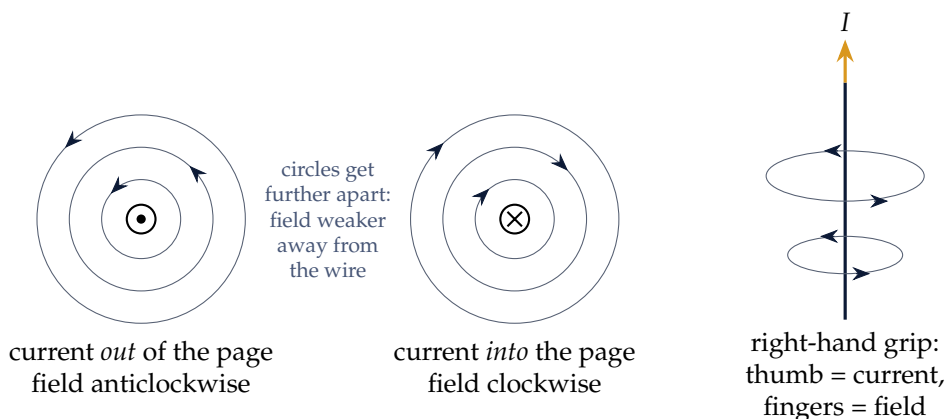
Common mistakes

- Saying a magnet attracts all metals. Only iron, steel, nickel and cobalt are magnetic; aluminium and copper are not.
- Drawing field-line arrows from S to N. They go from N to S outside the magnet.
- Drawing lines that cross or stop in mid-air. Lines are continuous and never cross.
- Using attraction as the test for a magnet. Only repulsion shows that an object is a magnet.

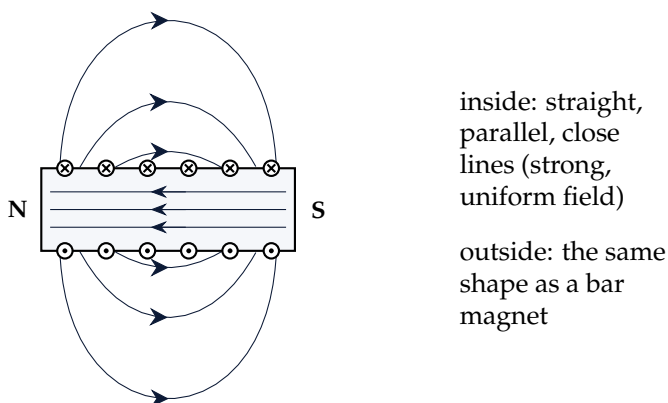
2 The magnetic field of a current

A current has a magnetic field. In 1820 Ørsted noticed that a compass needle beside a wire deflected when a current was switched on. Moving charge makes a magnetic field. Around a long straight wire the field lines are **concentric circles** centred on the wire, in planes at right angles to it. The field is *strongest close to the wire*, so the circles drawn for equal increases in strength are more and more widely spaced as you move away, and the field gets stronger when the current is increased. Reversing the current reverses the direction of the field.

Direction: the right-hand grip rule. Grip the wire with your right hand, with the **thumb pointing along the (conventional) current**. Your **fingers curl in the direction of the field**. Seen end-on, a current coming *out* of the page (drawn as a dot, like the tip of an arrow coming towards you) gives an *anticlockwise* field, and a current going *into* the page (drawn as a cross, like the tail feathers of an arrow going away) gives a *clockwise* field.



Coils and solenoids. A single loop of wire concentrates the field in its middle. A long coil with many turns is called a **solenoid**. Every turn adds its field, so inside the solenoid the field is strong, *uniform* and parallel to the axis, while outside it has the same shape as the field of a bar magnet: one end acts as a N pole and the other as a S pole. To find which is which, use the grip rule again: **curl the fingers of your right hand round the coil in the direction of the current; the thumb points to the N end.** (Check with the figure below. At the top the current goes into the page and at the bottom it comes out, so the current circulates so that the thumb points left, and the left end is N.)



cross-section: current into the page along the top wires, out along the bottom wires

Electromagnets. An **electromagnet** is a solenoid wound on a core of soft iron. The iron is magnetised by induction and

adds its own field to the coil's, making the electromagnet far stronger than the coil alone. It can be switched on and off, and its strength can be varied. The strength increases if you (1) **increase the current**, (2) **use more turns** of wire, or (3) **insert a soft iron core** (using a coil that is shorter and wider for the same wire also helps). Reversing the current swaps its poles.

Uses. A scrapyard crane uses a large electromagnet to lift steel and then release it by switching off. In a **relay**, a small current in a coil attracts an iron armature, which closes a second switch in a separate circuit that can carry a large current: a small, safe switch controls a big, dangerous current. In an **electric bell**, the electromagnet pulls the hammer onto the gong, which breaks the circuit, so the electromagnet switches off and the spring pulls the hammer back, which remakes the circuit, and so on.

Worked example: which end is north?

A solenoid is connected so that, looking at the left end, the current goes round the coil anticlockwise. Which end is N? How could you double the strength of the field in the middle?

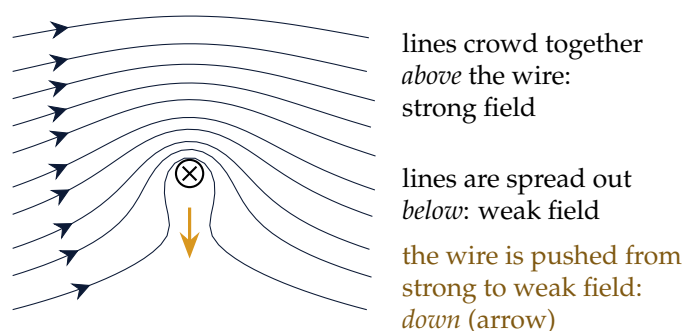
Grip with the right hand so the fingers curl anticlockwise as seen from the left. The thumb then points towards the viewer, i.e. out of the left end. So the left end is N (the field leaves from it). To double the field you could double the current, or double the number of turns on the same length, or add an iron core (which does much more than double it).

Common mistakes

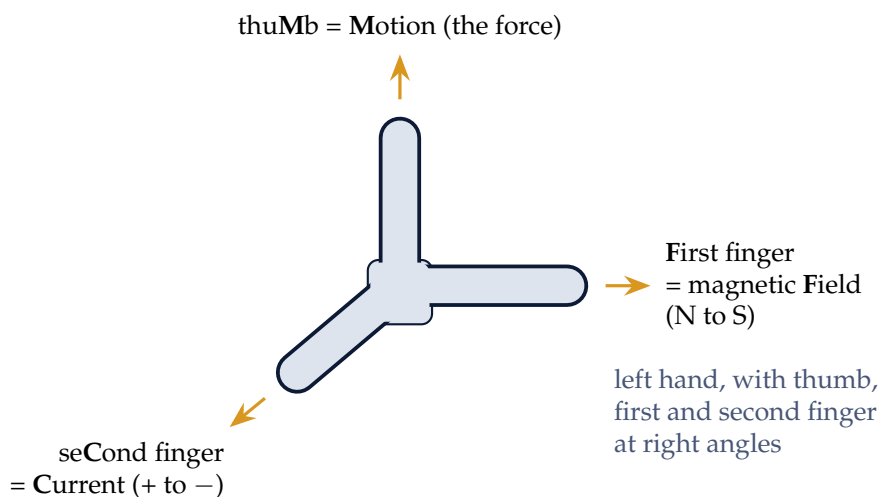
- Using the *left* hand for the field of a current. Right hand for fields from currents; left hand for the force on a current (next section).
- Saying the field of a wire points along the wire. It circles around it.
- Giving a solenoid a steel core for an electromagnet. Steel stays magnetised; soft iron is used so that the electromagnet switches off.
- Forgetting that the current direction (conventional) is from + to –.

3 The motor effect

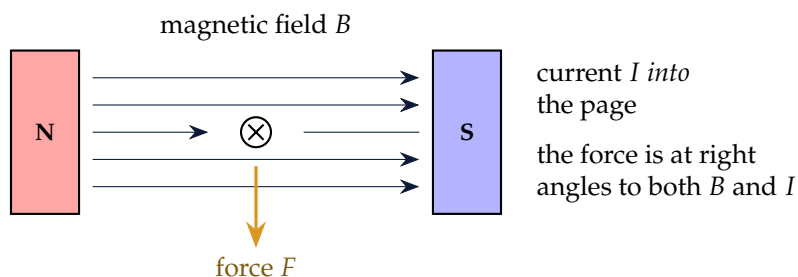
A current in a magnetic field feels a force. Put a wire carrying current between the poles of a magnet. The wire has its own circular field, and the magnet has its field. Add the two: on one side of the wire the fields point the same way and the field is *stronger*; on the other side they oppose and it is *weaker*. The wire is pushed from the strong side to the weak side. This is called the **motor effect**, and the picture below (sometimes called the “catapult field”) shows why the force on this wire is downwards.



Direction: Fleming's left-hand rule. Hold the thumb, first finger and second finger of your **left** hand at right angles to each other. Point the **F**irst finger along the magnetic **F**ield (N to S) and the **se**Cond finger along the **C**urrent (conventional, + to –). Then the **thu**Mb points in the direction of the force or **M**otion.



In the next figure the field points left to right, the current goes into the page, and the rule gives a force *downwards*. The force is always at right angles to *both* the field and the current. Reverse the current *or* the field and the force reverses; reverse both and it does not change. If the wire is *parallel* to the field there is no force at all.



Size of the force. For a straight wire at right angles to a uniform field,

$$F = BIL,$$

where B is the **magnetic flux density** (field strength) in tesla (T), I is the current in amperes, and L is the length of wire *inside the field* in metres. This is how field strength is *defined*: $B = \frac{F}{IL}$, so $1 \text{ T} = 1 \text{ N}/(\text{A m})$, the field that exerts 1 N on each metre of wire carrying 1 A. The formula makes sense: the force is proportional to the current (more moving charge), to the length in the field (more wire being pushed) and to the field strength.

Worked example: force on a wire

A wire carries 5 A at right angles to a uniform field of 0.4 T. 0.25 m of the wire lies in the field. Find the force. What field strength would give a force of 0.12 N on a 0.20 m length carrying 3.0 A?

$$F = BIL = 0.4 \times 5 \times 0.25 = 0.50 \text{ N. Rearranged, } B = \frac{F}{IL} = \frac{0.12}{3.0 \times 0.20} = \frac{0.12}{0.6} = 0.20 \text{ T.}$$

Worked example: direction with the left-hand rule

A wire lies at right angles to a field running from a N pole on the left to a S pole on the right. The current goes into the page. In which direction is the force?

First finger points right (field). Second finger points into the page (current). The thumb then points *down the page*. Check with vectors: with x to the right, y up the page and z out of the page, the force is along $\mathbf{I} \times \mathbf{B} = (-z) \times x = -y$, down.

Worked example: a wire on a balance

A horizontal wire carrying 2 A has 0.1 m lying in a horizontal field of 0.5 T, and the force is vertical and downward. By how much would a balance supporting the magnet change its reading? ($g = 10 \text{ N/kg}$.)

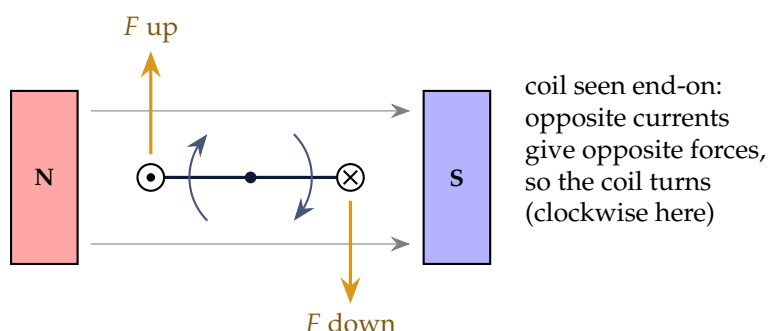
$F = 0.5 \times 2 \times 0.1 = 0.1 \text{ N}$ on the wire. By Newton's third law the wire pushes the magnet with an equal and opposite force of 0.1 N, *upwards*. The reading goes down by $m = F/g = 0.1/10 = 0.01 \text{ kg} = 10 \text{ g}$.

Common mistakes

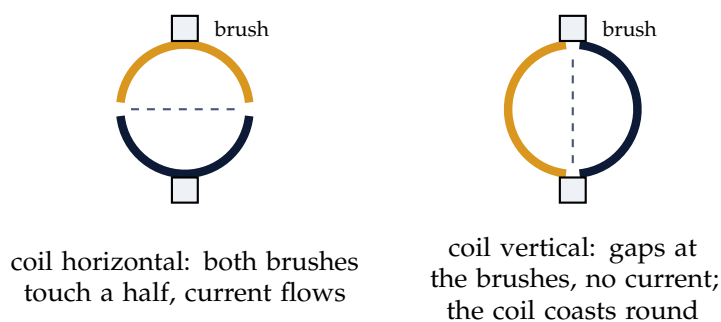
- Using the right hand for the force on a current. Right hand for field of a current, *left* hand for force on a current.
- Using the length of the whole wire in $F = BIL$ rather than the length that lies in the field.
- Forgetting that reversing both the current and the field leaves the force unchanged.
- Using electron flow instead of conventional current in the left-hand rule.

4 The d.c. motor and the loudspeaker

Why a coil turns. Now take a rectangular coil in a uniform field. Seen end-on, current goes *out of the page* in one side of the coil and *into the page* in the other (it flows round the loop). The field is the same for both sides but the currents are opposite, so the forces are *opposite*: one side is pushed up and the other down. These two forces together turn the coil.



The problem and its solution. When the coil has turned a quarter of a turn to the vertical position, the forces on the two sides act along the line joining them and just pull on the axle: no turning effect. If the coil kept its current direction past this point, the forces would reverse their turning effect and try to turn it back. The solution is the **split-ring commutator**: a ring cut into two halves, each joined to one end of the coil, which rubs against two fixed carbon **brushes** connected to the cell. Each half turn, the halves swap brushes, which *reverses the current in the coil*, so the forces keep turning it the *same way*. As the coil passes the vertical, the gaps in the ring are at the brushes for an instant and no current flows; the coil's momentum carries it past.



amber and black: the two halves of the split ring, each joined to one end of the coil (dashed line = the coil). After half a turn the halves have swapped brushes, so the current in each side reverses.

Making a motor faster or more powerful. Increase the current (force $\propto I$), use a stronger magnet (force $\propto B$), or use more turns in the coil (each turn adds force). To reverse the direction of rotation, reverse the current *or* the magnet's poles (but not both). Real motors use many coils and curved pole-pieces so the turning effect is smooth.

The loudspeaker uses the same effect in a different way. A coil attached to a paper cone sits in the field of a permanent magnet. The audio signal is an alternating current in the coil, so the force on the coil alternates and the cone vibrates to and fro, pushing air and making sound waves at the frequency of the current.

Worked example: motor changes

A motor turns clockwise. State what happens to the speed and direction if (a) the cell is reversed, (b) both the cell and the magnet are reversed, (c) the current is doubled.

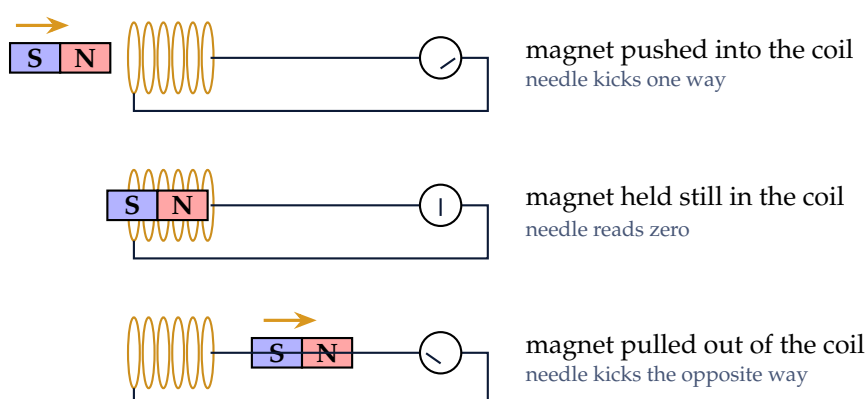
(a) The current reverses but the field does not, so the force reverses: the motor turns anticlockwise. (b) Both reverse, so the force is unchanged: still clockwise. (c) The force doubles, so the coil turns faster (and still clockwise).

Common mistakes

- Saying the commutator “keeps the current the same”. It *reverses* the current in the coil every half turn so the force keeps the same turning direction.
- Thinking the commutator is needed to make the current flow. It is needed to *reverse* it at the right moment.
- Saying the coil stops at the vertical position. It coasts through on its momentum.

5 Electromagnetic induction

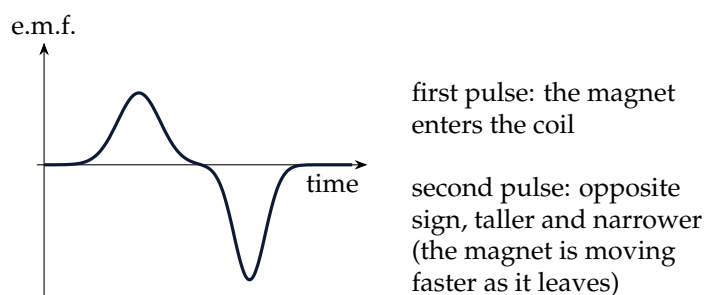
The reverse effect. A current in a field makes a force; Faraday showed that the reverse also happens. If a conductor is moved so that it **cuts magnetic field lines**, an e.m.f. is **induced** in it. If it is part of a complete circuit, a current flows. The same happens if a magnet moves into or out of a coil: the field through the coil changes. This is **electromagnetic induction**. Nothing is induced if the wire and the field are at rest relative to each other, or if the wire moves *along* the field lines (cutting none).



What controls the size of the e.m.f.? The e.m.f. depends on how fast the field lines are cut. It increases if you (1) **move the magnet (or wire) faster**, (2) **use a stronger magnet**, (3) **use more turns of wire** (each turn has its own e.m.f. and they add), or (4) use a coil with a larger area. A thicker wire does not change the e.m.f. (it only lowers the resistance, so the current is larger).

Direction of the induced current. Reversing the motion, or the magnet, reverses the induced e.m.f. The general rule (Lenz's law) is that *the induced current always acts to oppose the change that causes it*. Push the N pole of a magnet towards a coil and the end of the coil nearest the magnet becomes N too, so it repels the magnet, and you have to do work to push it in: that work is where the energy comes from. If it did the opposite, the magnet would be pulled in faster and faster, creating energy from nothing, which is impossible. Pull the magnet away and the nearer end becomes S, attracting the magnet back and again opposing you.

Reading an e.m.f.-time graph. Drop a magnet through a coil. As it enters, the field through the coil is increasing and a pulse of e.m.f. appears. When the magnet is at the middle the field is momentarily steady, so the e.m.f. drops to zero. As it leaves, the field is decreasing, so the pulse has the *opposite* sign. Because gravity makes the magnet go *faster* by the time it leaves, the second pulse is *taller and narrower*. Remember that the area under each pulse is about the same, because the total change in field is the same.



Worked example: changing the pulse

When a magnet is pushed into a coil at a steady speed the voltmeter reads 4 mV. What does it read if (a) the magnet is pushed in at twice the speed, (b) the magnet is pulled out at the original speed, (c) a coil with 3 times the turns is used, with the original speed?

(a) The rate of cutting doubles, so 8 mV. (b) The same size but *opposite* direction: -4 mV, i.e. 4 mV the other way. (c) Three times the turns gives three times the e.m.f.: 12 mV.

Exam tip

For any induction question ask three things: Is the field through the circuit *changing* (or is a wire cutting lines)? How *fast*? Then use "faster, stronger, more turns $\Rightarrow$ bigger e.m.f." and "reverse the motion $\Rightarrow$ reverse the e.m.f.".

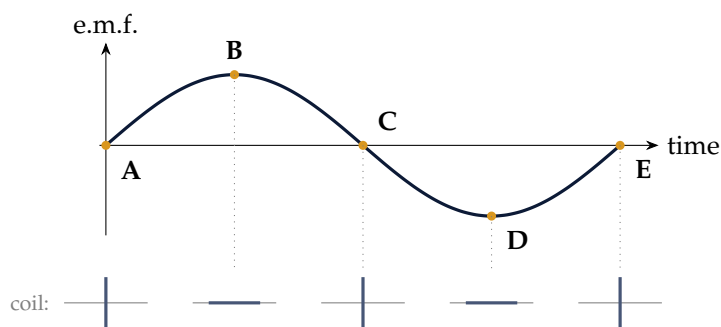
Common mistakes

- Saying a magnet at rest inside a coil induces a steady current. Only a *changing* field induces an e.m.f.
- Thinking a thicker wire gives a bigger e.m.f.
- Confusing the motor effect (current in a field makes a force) with induction (a moving field or conductor makes an e.m.f.).
- Forgetting that pulling the magnet out gives the opposite sign to pushing it in.

6 The a.c. generator

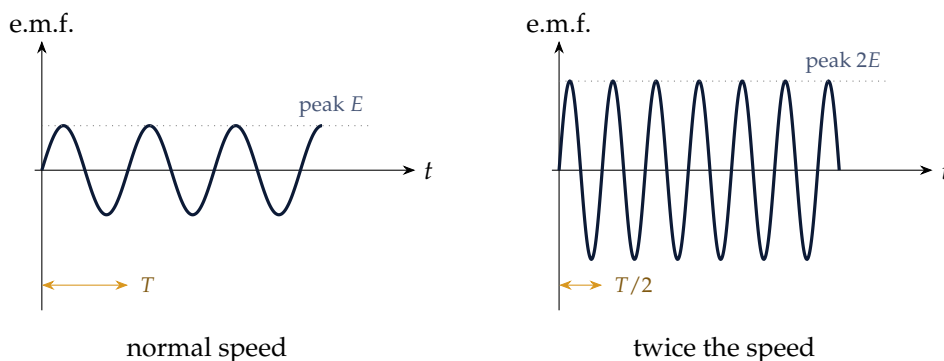
A rotating coil. Spin a rectangular coil in a uniform field. Its sides keep cutting field lines, so an e.m.f. is induced. The coil's ends are connected to **slip rings**, two complete metal rings that turn with the coil and rub against fixed **brushes**. The brushes connect to the outside circuit. Unlike the commutator of the motor, the slip rings do *not* reverse anything; the e.m.f. produced alternates by itself, so the generator gives **alternating current (a.c.)**. (A dynamo is the same thing with a commutator instead, giving d.c.)

Why the graph is a sine wave. Look at the coil end-on. When its plane is **parallel to the field lines** (horizontal in the figure) its sides are moving at right angles to the field, so they cut field lines at the fastest possible rate: the e.m.f. is a maximum (positions B and D; the signs are opposite because one side is going up and then the other). When the plane is **perpendicular to the field** (vertical) the sides move *along* the lines and cut none: the e.m.f. is zero (A, C and E), and the sign changes as it passes through. One full turn is one full cycle.



coil edge-on to the field lines (which run left to right): cuts them fastest, maximum e.m.f. (B and D). Coil face-on to the field: cuts none, zero e.m.f. (A, C, E).

Effect of speed. If the coil is turned twice as fast: the sides cut lines twice as fast, so the **peak e.m.f. doubles**; and each rotation takes half as long, so the **period halves** and the **frequency doubles**. The mains frequency of 50 Hz means that the generators in a power station complete 50 turns every second, giving a period $T = 1/50 = 20$ ms. A stronger magnet or more turns also increases the peak e.m.f., but not the frequency.



Worked example: reading the generator graph

A generator produces a sinusoidal e.m.f. with peak value 6 V and period 10 ms. Find its frequency. What peak value and period result if the coil is turned at three times the speed with the same magnet and coil?

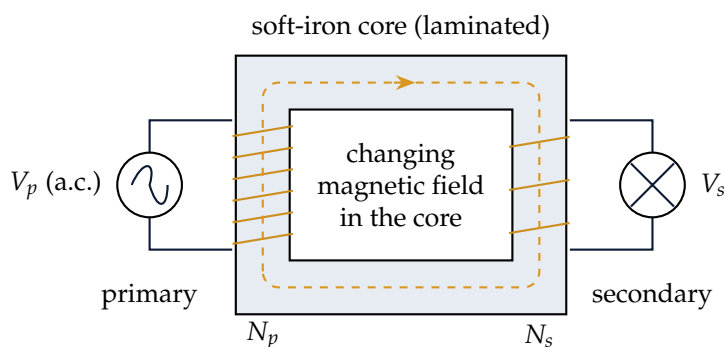
$f = \frac{1}{T} = \frac{1}{0.010} = 100 \text{ Hz}$. At three times the speed the peak is $3 \times 6 = 18 \text{ V}$ and the period is $\frac{10}{3} \approx 3.3 \text{ ms}$ (frequency 300 Hz).

Common mistakes

- Saying the e.m.f. is largest when the coil is perpendicular to the field. That is when it is zero; the largest e.m.f. is when the coil is *parallel* to the field lines.
- Doubling the speed and saying only the frequency changes. The peak value changes too.
- Confusing slip rings (a.c.) with a split-ring commutator (d.c.).

7 Transformers and the National Grid

How a transformer works. A transformer has two coils, the **primary** and the **secondary**, wound on a **soft-iron core**. The core is a closed loop so it carries the changing field from one coil to the other. The steps are: (1) an alternating voltage across the primary drives an alternating current in it; (2) this produces a continually changing magnetic field in the core; (3) the changing field passes through the secondary coil and, by electromagnetic induction, induces an alternating e.m.f. in it. A transformer works *only with a.c.*: a steady d.c. current gives a steady field, which does not change, so nothing is induced. (Connect a battery and you would see a reading only at the instant you make or break the connection.)



The transformer equation. The same changing field passes through every turn of both coils, so each turn has the same induced e.m.f. The secondary voltage is therefore proportional to its number of turns, and so is the primary voltage:

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

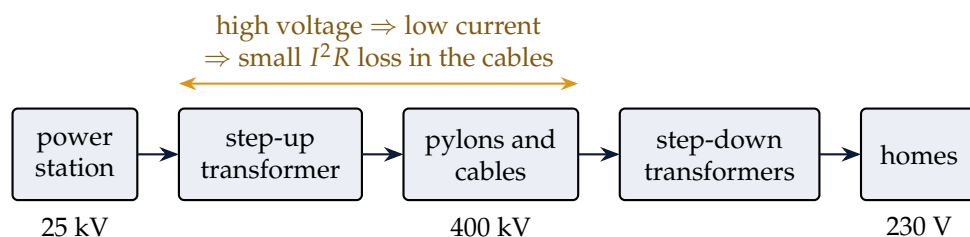
If $N_s > N_p$ the voltage is stepped *up* (a step-up transformer); if $N_s < N_p$ it is stepped *down*. So a transformer with $N_p = 100$ and $N_s = 500$ steps 12 V up to 60 V.

Energy and power. A transformer cannot create energy. For an *ideal* (100% efficient) transformer the power output equals the power input:

$$V_p I_p = V_s I_s$$

Combining with the turns equation, a step-up transformer increases the voltage by the turns ratio but decreases the current by the same factor. In the example above, the secondary is at 5 times the voltage, so it can only supply one fifth of the current. Real transformers are 95 % to 99 % efficient; the losses come from the resistance of the coils (heating), **eddy currents** induced in the iron core (reduced by making the core from thin insulated sheets, i.e. *laminated*), and some magnetic field not passing through the secondary.

Transmitting electricity. Power stations send electrical energy across the country along cables of significant resistance. The power wasted as heat in a cable of resistance R carrying current I is $P = I^2R$. For a given power delivered, $P = VI$, so the current is $I = P/V$. If the voltage is increased tenfold the current falls to a tenth, and the energy wasted ($\propto I^2$) falls to one hundredth. That is why step-up transformers raise the voltage to hundreds of thousands of volts for transmission, and step-down transformers reduce it again to a safe 230 V for homes.



Worked example: a step-down transformer

A transformer has 2000 turns on its primary and 100 turns on its secondary. The primary is connected to 230 V a.c. A lamp of 23 W is run from the secondary. Find the secondary voltage, the current in the lamp, and the current in the primary (ideal transformer).

$V_s = 230 \times \frac{100}{2000} = 11.5 \text{ V}$. The lamp takes $I_s = \frac{23}{11.5} = 2 \text{ A}$. The input power is also 23 W, so $I_p = \frac{23}{230} = 0.1 \text{ A}$. (Check with the current ratio: $2 \times \frac{100}{2000} = 0.1$.)

Worked example: why high voltage

A power station sends 100 kW through cables of total resistance 5Ω . Find the power wasted if the transmission voltage is (a) 1000 V, (b) 10 000 V.

(a) $I = \frac{100000}{1000} = 100 \text{ A}$, so the loss is $I^2R = 10000 \times 5 = 50 \text{ kW}$, which is half of the power! (b) $I = \frac{100000}{10000} = 10 \text{ A}$, so the loss is $100 \times 5 = 500 \text{ W}$, only 0.5 % of the power.

Exam tip

In transformer problems write down $V_s/V_p = N_s/N_p$ and $V_p I_p = V_s I_s$ before putting in numbers. The side with the higher voltage always has the smaller current. In transmission problems, calculate the current from $P = VI$ first, then the loss from I^2R with the *cable's* resistance.

Common mistakes

- Using a transformer with a d.c. supply: it will not work.
- Calculating the cable loss as V^2/R using the transmission voltage. The voltage *across the cable* is far less than the supply voltage; use I^2R .
- Forgetting that when the voltage is stepped up the current is stepped *down*.
- Using N_p over N_s instead of N_s over N_p .

8 Putting it together: direction rules and exam reasoning

Two ideas cause most mistakes in magnetism: choosing the correct hand, and being sure what is being asked. This table sums up the four situations you must separate. In every case draw the picture, mark the direction of the current (conventional) and the field, and do not guess.

Situation	Rule	Result
Field made by a wire or coil	Right-hand grip: thumb = current, fingers = field (or fingers = current round coil, thumb = N)	Circles around a wire; N end of a solenoid
Force on a current in a field	Left hand: first finger = field, second = current, thumb = force	Force $F = BIL$ at right angles to both
Moving conductor or changing field	Faraday: e.m.f. $\propto$ rate of cutting field lines; Lenz: it opposes the change	Larger for faster, stronger, more turns
Transformer	$V_s/V_p = N_s/N_p$, $V_p I_p = V_s I_s$	Works with a.c. only

Estimating and scaling. ESAT often asks “what happens if...” without numbers. Write the proportionalities: $F \propto B, I, L$; induced e.m.f. $\propto$ speed, field strength and turns; $P_{\text{loss}} \propto I^2$; $V_s \propto N_s$. Then scale. For example, if the current in a wire in a field is doubled and the length in the field is halved, the force is unchanged ($2 \times \frac{1}{2} = 1$). If the transmission voltage is multiplied by 20, the loss in the cable is divided by $20^2 = 400$.

Worked example: scaling with proportionalities

A wire in a field experiences a force of 0.30 N. The current is tripled, a stronger magnet doubles B , and half as much wire lies in the field. What is the new force?
 $F \propto BIL$, so the new force is $0.30 \times 2 \times 3 \times \frac{1}{2} = 0.90$ N.

Exam tip

Look out for *energy sanity checks*: a transformer cannot give more power out than in; an induced current always opposes the change; a generator turned faster needs more effort. If an answer contradicts these, check it again.

Common mistakes

- Mixing up the *motor* (electrical energy to movement) with the *generator* (movement to electrical energy). Both use a coil in a field, but the motor needs a supply while the generator needs to be turned.
- Treating a transformer as if it increased power. It changes voltage and current in opposite directions.

Check yourself

Try these without looking back, then compare with the answers on the next page.

1. A steel bar is brought towards a magnet. How can you prove the bar is itself a magnet?
2. A straight wire carries a current out of the page. Describe the shape and direction of the magnetic field.
3. Give three ways to make an electromagnet stronger.
4. A 0.40 m length of wire carries 6 A at right angles to a field of 0.50 T. What is the force?
5. What does the split-ring commutator in a d.c. motor do?
6. A magnet is pulled out of a coil twice as quickly as it was pushed in. Compare the e.m.f.
7. A generator coil turns at 25 revolutions per second. State the frequency and period of the e.m.f., and what happens to the peak e.m.f. if the speed is doubled.
8. A transformer has 400 turns on the primary and 50 on the secondary. It is connected to 240 V a.c. Find the secondary voltage, and the primary current when the secondary current is 4 A.

Answers to the self-check

1. Hold the same pole of the test magnet near each end of the bar in turn. A magnet will be *repelled* at one end. Attraction at both ends only shows that the bar is magnetic, not that it is a magnet.
2. Concentric circles around the wire, anticlockwise (right-hand grip rule), further apart as the distance from the wire increases.
3. Increase the current; add more turns; use a soft iron core.
4. $F = BIL = 0.5 \times 6 \times 0.4 = 1.2 \text{ N}$.
5. It reverses the current in the coil every half turn, so that the forces keep turning the coil the same way.
6. Twice the magnitude and in the opposite direction.
7. $f = 25 \text{ Hz}$, $T = 1/25 = 0.04 \text{ s}$. The peak e.m.f. doubles (and f doubles to 50 Hz).
8. $V_s = 240 \times \frac{50}{400} = 30 \text{ V}$. Power = $30 \times 4 = 120 \text{ W}$, so $I_p = 120/240 = 0.5 \text{ A}$.

Next step

Heurisco's *ESAT Physics: Magnetism and Electromagnetism Practice Set* has twenty original exam-style questions on this lesson, with field diagrams, circuits and graphs, in order of difficulty, with a full worked solution for each.