

Forces on currents and moving charges in magnetic fields

Physics grades 11-12 (A Level · IB · Class 11-12) · Lesson

Quick answer: A magnetic field exerts a force on moving charges and on current-carrying wires. The force on a wire is $F = BIL \sin \theta$ and on a single charge $F = Bqv \sin \theta$. It is always perpendicular to the motion, so it bends the path into a circle of radius $r = mv/(qB)$ without changing the speed.

Level: Physics grades 11-12 (A Level · IB · Class 11-12) · **Curriculum:** IB D.3

What is a magnetic field?

A magnetic field is the region around a magnet or a moving charge where another magnet or moving charge feels a force. Compass needles, loudspeakers and the beam inside an old television tube all depend on it. Field lines run from the north pole to the south pole, and the closer they are, the stronger the field.

Definition

Magnetic flux density B measures the strength of a magnetic field. One **tesla** (T) is the flux density that produces a force of 1 N on a 1 m wire carrying 1 A at right angles to the field: $1 \text{ T} = 1 \text{ N A}^{-1} \text{ m}^{-1}$.

How big is the force on a current-carrying wire?

A current is a stream of moving charges, so a wire in a field feels the sum of all the forces on those charges. The force is largest when the wire is perpendicular to the field and zero when it is parallel to it. Its direction is perpendicular to both the wire and the field.

Formula

$$F = B I L \sin \theta$$

F = force (N), B = flux density (T), I = current (A), L = length of wire inside the field (m), θ = angle between the current and the field.



The field points into the page (crosses). The current runs to the right, so the force on the wire points up the page. Reverse either one and the force reverses.

Worked example

A straight wire 0.25 m long carries 4.0 A at right angles to a field of 0.12 T. Calculate the force.

$$F = BIL = 0.12 \times 4.0 \times 0.25 = \mathbf{0.12 \text{ N.}}$$

What force acts on a single moving charge?

Sharing the wire result among the individual carriers gives the force on one charge q moving at speed v , and the same sine rule applies. A charge at rest feels no magnetic force, and neither does a charge moving along the field lines.

Formula

$$\mathbf{F = B q v \sin \theta}$$

q = charge (C), v = speed (m/s), θ = angle between the velocity and the field. For an electron or a proton, $q = 1.60 \times 10^{-19}$ C in size.

Worked example

An electron travels at 2.0×10^6 m/s perpendicular to a field of 0.030 T. Calculate the force on it.

$$F = Bqv = 0.030 \times 1.60 \times 10^{-19} \times 2.0 \times 10^6 = \mathbf{9.6 \times 10^{-15} \text{ N.}}$$

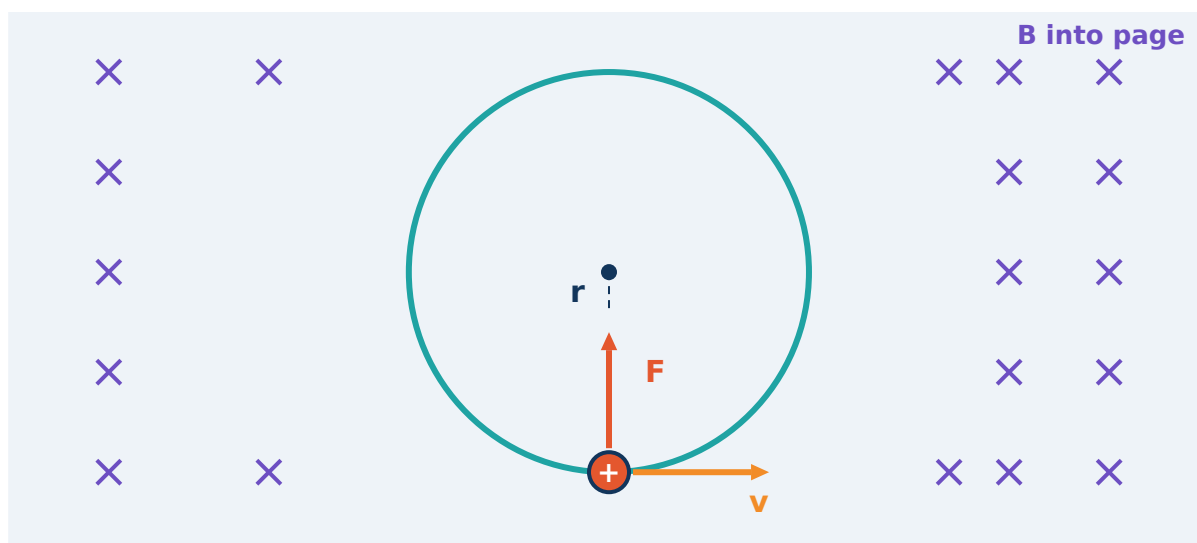
This looks tiny, but the electron's mass is only 9.11×10^{-31} kg, so the acceleration is enormous.

Why do charged particles move in circles?

The magnetic force is always at right angles to the velocity, so it changes the direction of motion but never the speed. It plays the role of the centripetal force, and setting $Bqv = mv^2/r$ gives the radius of the path.

Key law

$r = m v / (q B)$ and the period is $T = 2\pi m / (q B)$, independent of the speed.



The magnetic force always points to the centre of the circle, at right angles to the velocity, so the speed stays constant while the direction keeps changing.

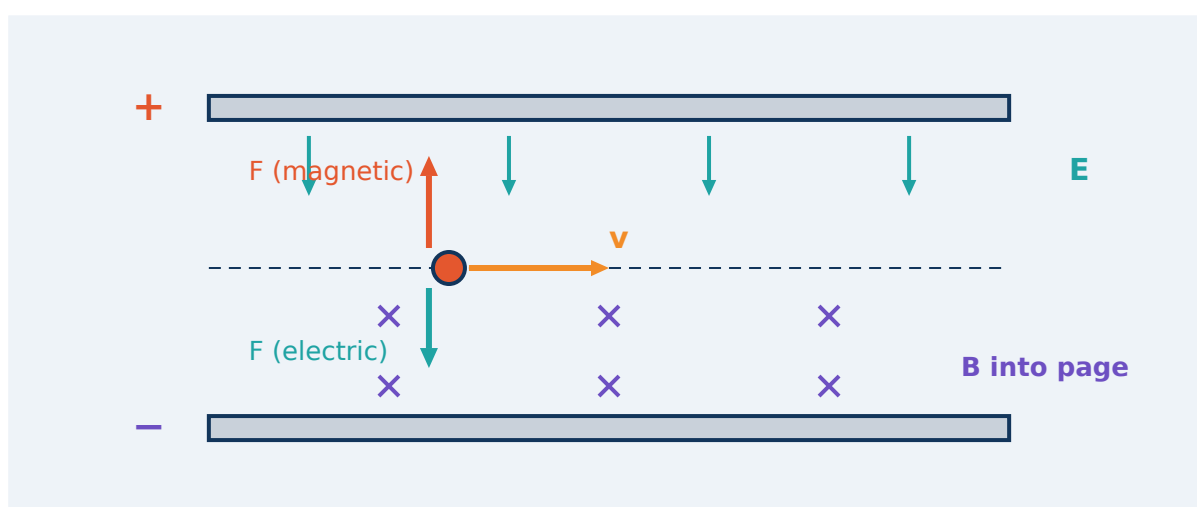
Worked example

A proton moves at 3.0×10^6 m/s perpendicular to a 0.50 T field. Calculate the radius of its path.

$$r = mv/(qB) = (1.67 \times 10^{-27} \times 3.0 \times 10^6) / (1.60 \times 10^{-19} \times 0.50) = \mathbf{6.3 \text{ cm.}}$$

How does a velocity selector choose one speed?

Place an electric field and a magnetic field at right angles to each other. For a positive particle the electric force can point one way and the magnetic force the opposite way. They balance when $qE = qvB$, so only particles with $v = E / B$ go straight.



Only particles with the speed $v = E / B$ pass straight through, because the two forces cancel exactly.

How do the three situations compare?

Situation	Force formula	Direction of force	Work done
Wire in a field	$F = BIL \sin \theta$	perpendicular to wire and field	none on the charges
Moving charge	$F = Bqv \sin \theta$	perpendicular to v and B	zero
Circular path	$r = mv/(qB)$	towards the centre	zero, speed constant

Common mistake

Students say a magnetic force speeds a particle up. It does not: the force is at right angles to the motion, so it does no work and the kinetic energy stays constant.

Lina's tip

To find a force direction, point your fingers along the current (or the velocity of a positive charge), curl them towards B , and your thumb gives the force. Reverse the answer for an electron.

Key points to remember

- Wire: $F = BIL \sin \theta$, largest when the wire is perpendicular to B .
- Moving charge: $F = Bqv \sin \theta$, zero when v is parallel to B .
- Circular path: $r = mv/(qB)$ and $T = 2\pi m/(qB)$.
- Velocity selector: $v = E/B$.
- Magnetic force does no work and never changes speed.

Forces on currents and moving charges in magnetic fields: frequently asked questions

What is a tesla?

A tesla is the unit of magnetic flux density. One tesla gives a force of 1 N on a 1 m wire carrying 1 A at right angles to the field.

Why does a magnetic force not change a particle's speed?

The force is perpendicular to the velocity, so it does no work. It only changes the direction of motion, which is why the path is circular.

How do you find the direction of the force on a wire?

Use Fleming's left-hand rule: first finger along the field, second finger along the current, thumb gives the force. The force is perpendicular to both.

Does the period of a circular orbit depend on speed?

No. $T = 2\pi m/(qB)$ contains only the mass, the charge and the field. Faster particles travel on a larger circle but take the same time per turn.

What happens when a charge moves parallel to the field?

Nothing: $\sin 0^\circ = 0$, so there is no force. If the velocity has a component along the field, the path becomes a spiral.