

Magnetic Fields & Electromagnetism

AP Physics C: E&M • Unit 12

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Magnetic Fields & Electromagnetism

What we will cover

- 1 Magnetic fields
- 2 Force on a moving charge
- 3 Fields of current-carrying wires
- 4 Ampère's law



1 Magnetic fields

Magnetic Fields & Electromagnetism

↳ Magnetic fields

Magnetic fields

A **magnetic field** 磁场 $\vec{B}$ has field lines in **closed loops** – there are **no monopoles** 磁单极子. Materials differ by how their **atomic dipoles** 原子磁偶极子 align:

- **ferromagnetic** 铁磁性 – an external field aligns whole **magnetic domains** 磁畴, and the alignment **survives** the field being removed – a permanent magnet; align strongly, stay (iron)
- **paramagnetic** 顺磁性 – align weakly
- **diamagnetic** 抗磁性 – weakly oppose



Aurora magnetism

Magnetic Fields & Electromagnetism

↳ Magnetic fields

The magnetic field, and why there are no monopoles

magnetic field 磁场 $\vec{B}$ a **vector field** 矢量场 surrounding magnets, moving charges and currents; it sets the force on any *moving* charge

field lines 磁感线 run out of the north pole and into the south *outside* the magnet, and continue through it – they always **close on themselves**

Gauss's law for B $\oint \vec{B} \cdot d\vec{A} = 0$ through *any* closed surface – as many lines leave as enter

what that means no isolated **magnetic monopole** 磁单极子 has ever been found; cut a magnet in half and you get two magnets

a compass 指南针 a small **magnetic dipole** 磁偶极子 that lines up **tangent** 相切 to the local field

Compare with electric flux, which equals $Q_{\text{enc}}/\epsilon_0$ and is non-zero. The **zero** on the right is the whole difference between the two fields.

2 Moving charges

Force on a moving charge

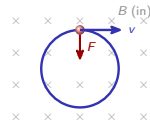
A cross product

$$\vec{F} = q \vec{v} \times \vec{B}$$

Size $qvB \sin \theta$; $\perp$ to $\vec{v}$, so it does **no work**. A wire feels $\vec{F} = I \vec{L} \times \vec{B}$.

Perpendicular entry $\Rightarrow$ a circle:

$$qvB = \frac{mv^2}{r}, \text{ so } r = \frac{mv}{qB}.$$

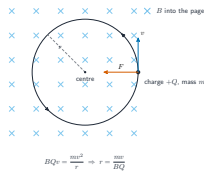


How a material answers a magnetic field

ferromagnetic 铁磁性	iron, nickel, cobalt: domains align <i>with</i> the field and stay aligned – a strong response that can be made permanent
paramagnetic 顺磁性	a weak alignment <i>with</i> the field, lost as soon as the field is removed
diamagnetic 抗磁性	present in all materials: the electronic structure produces a usually weak alignment <i>opposite</i> to the field
permeability 磁导率	the measure of that response. Free space has the constant $\mu_0 = 4\pi \times 10^{-7} \text{ T m/A}$

Diamagnetism is universal but weak, so it only shows when nothing stronger is present. The other two are extra effects layered on top of it.

A moving charge both makes and feels a field



A moving charge does **two** things: it *creates* a field, perpendicular to its velocity and circling it, and it *feels* a force in an external one. The force is perpendicular to both $\vec{v}$ and $\vec{B}$ – fingers along $\vec{v}$, curl toward $\vec{B}$, thumb gives the force on a **positive** charge – so it does no work and the path is a circle.

The velocity selector

the setup	an electric and a magnetic field, crossed, in the same region
they act independently	the two forces add as vectors: $\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$
balance them	$qE = qvB$, so only particles with $v = E/B$ pass straight through
note	the selected speed depends on neither q nor m – so it filters by speed alone

Put a **velocity selector** 速度选择器 in front of a mass spectrometer and the second stage's radius $r = mv/qB$ then measures m/q cleanly, because v is already known.

Worked example – a proton circling in a field

A proton ($q = 1.6 \times 10^{-19} \text{ C}$, $m = 1.67 \times 10^{-27} \text{ kg}$) enters a **0.50 T field** at $2.0 \times 10^5 \text{ m/s}$, **perpendicular to it**. Find r and T .

- the magnetic force is the **centripetal force** 向心力: $qvB = \frac{mv^2}{r}$
- $r = \frac{mv}{qB} = \frac{(1.67 \times 10^{-27})(2.0 \times 10^5)}{(1.6 \times 10^{-19})(0.50)} = 4.2 \times 10^{-3} \text{ m}$
- $T = \frac{2\pi m}{qB} = 1.3 \times 10^{-7} \text{ s}$

T contains **no** v . Faster particles ride larger circles in exactly the same time – which is the principle the cyclotron is built on.

3 Wire fields

Fields of current-carrying wires

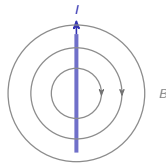
Moving charge **makes** magnetic field:

Biot-Savart law

$$d\vec{B} = \frac{\mu_0}{4\pi} \frac{I d\vec{l} \times \hat{r}}{r^2}$$

Integrate for standard results:

- long straight wire: $B = \frac{\mu_0 I}{2\pi r}$
- loop centre: $B = \frac{\mu_0 I}{2R}$



Biot-Savart, and the arc it makes easy

Biot-Savart law 毕奥-萨伐尔定律 $d\vec{B} = \frac{\mu_0}{4\pi} \frac{I d\vec{l} \times \hat{r}}{r^2}$ – the field from one current element

a straight wire gives **concentric circles** 同心圆 around it, $B = \frac{\mu_0 I}{2\pi r}$, direction from the right-hand rule

at a loop's centre every element $d\vec{l}$ is **perpendicular** to $\hat{r}$ and equally distant R – say that sentence, it is the marked step – giving $B = \frac{\mu_0 I}{2R}$

an arc a fraction of that circle contributes the same fraction: $B = \frac{\mu_0 I \theta}{4\pi R}$ for angle θ

For several wires, **superpose** 叠加: work out each field's magnitude and direction separately, then add as vectors.

The field of a current, and one measurement

Biot-Savart law The **Biot-Savart law** gives the field of a current element: $d\vec{B} = \frac{\mu_0}{4\pi} \frac{I d\vec{l} \times \hat{r}}{r^2}$ – integrate it for any geometry.

Magnetic permeability μ_0 is the **magnetic permeability** of free space, the constant that fixes the strength of the magnetic interaction.

Superposition **Superposition** does the rest: the field of several wires is the vector sum of their separate fields.

Hall effect The **Hall effect**: a magnetic field pushes the carriers to one side of a conductor, producing a transverse voltage – which reveals the *sign* of the charge carriers.

Magnetic field lines form closed loops – there is no magnetic charge for them to start on.

4 Ampere

Ampère's law

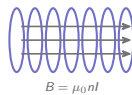
For enough symmetry, Ampère's law beats integrating Biot-Savart:

The loop integral

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 I_{enc}$$

Choose an **Amperian loop** 安培环路 where B is constant and parallel, so the integral becomes $B \times \text{length}$.

Inside a **solenoid** 螺线管: $B = \mu_0 nI$, uniform.



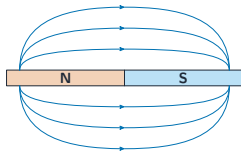
Worked example – inside a current-carrying cylinder

A solid cylinder of radius R carries current I spread uniformly over its cross-section. Find B at radius $r < R$.

- loop: a circle of radius r , concentric – B is constant on it and parallel to it by symmetry
- enclosed current scales with area:
 $I_{enc} = I \frac{\pi r^2}{\pi R^2} = I \frac{r^2}{R^2}$
- $B(2\pi r) = \mu_0 I \frac{r^2}{R^2}$, so $B = \frac{\mu_0 I r}{2\pi R^2}$

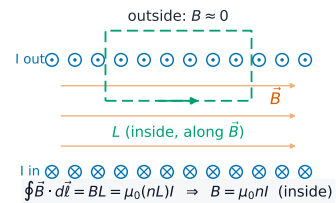
Inside, B grows **linearly** with r ; outside it falls as $1/r$, so the field peaks at the surface. Check both limits agree at $r = R$.

Closed loops, and what that means



Field lines run N to S outside the magnet and close on themselves inside it. That is **Gauss's law for magnetism** – the second of **Maxwell's equations** 麦克斯韦方程组: the net flux through *any* closed surface is zero, as many lines leaving as entering. It is the same statement as “no isolated **magnetic monopole** 磁单极子 has ever been found”.

Ampère's Law, continued



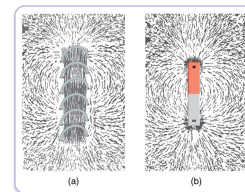
A rectangular Amperian loop derives the uniform field inside a solenoid

Every Ampère's-law answer earns its marks in the setup

1. **name the loop** say which **Ampèrian loop** 安培环路 you chose and where it runs
2. **justify it** why B is **constant** on it and **parallel** to it – by symmetry, in words
3. **count I_{enc}** only current *through* the loop; for a spread-out current use the **current density** 电流密度 and the enclosed area
4. **solve** $\oint \vec{B} \cdot d\vec{l} = \mu_0 I_{enc}$, giving $B(2\pi r) = \mu_0 I_{enc}$ for a circular loop

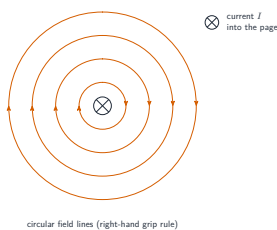
For symmetric distributions this beats Biot-Savart by a long way – but only when the symmetry argument is **stated**, not assumed.

Magnetic Fields of Current-Carrying Wires



A current-carrying coil (solenoid) makes a magnetic field shaped just like a bar magnet's

Concentric circular field lines surround a straight



Concentric circular field lines surround a straight current-carrying wire

Exam tips

- The magnetic force $\vec{F} = q\vec{v} \times \vec{B}$ is **perpendicular** to velocity – use the right-hand rule and note it does **no work**.
- A charge in a uniform field moves in a circle with $r = \frac{mv}{qB}$.
- Find the field of currents with **Biot-Savart** $d\vec{B} = \frac{\mu_0}{4\pi} \frac{I d\vec{l} \times \vec{r}}{r^2}$ or **Ampère's law** $\oint \vec{B} \cdot d\vec{l} = \mu_0 I_{enc}$ when there is symmetry.
- Force on a wire is $\vec{F} = I\vec{L} \times \vec{B}$; keep the cross-product direction straight.
- Distinguish the force **on** a charge from the field the current **creates**.

5

Recap

Unit 12 – key takeaways

1 Fields

lines in closed loops; no magnetic monopoles

2 Force

$\vec{F} = q\vec{v} \times \vec{B}$, does no work; circle
 $r = mv/qB$

3 Wire fields

Biot-Savart; long wire $\mu_0 I / 2\pi r$

4 Ampère

$\oint \vec{B} \cdot d\vec{l} = \mu_0 I_{enc}$; solenoid $\mu_0 nI$

Check yourself

- 1 Why does the magnetic force on a moving charge do no work?
- 2 Which law gives the field of a symmetric current quickly?
- 3 Double the distance from a straight wire – what happens to B ?
- 4 Is the field inside an ideal solenoid uniform?



Answers 1. it is perpendicular to $\vec{v}$ 2. Ampère's law 3. it halves 4. yes