

Unit 12: Magnetism and Electromagnetism

Magnetism starts with forces. A charge moving through a magnetic field feels a push that is always sideways to its motion, and an electric current in a wire feels the same kind of push. Those forces lead to the sources of magnetic fields, from a single straight wire to a solenoid. The second half of the unit is electromagnetic induction: a changing magnetic flux induces an emf, Lenz's law fixes the direction of the induced current, and inductors resist any change in current.

AP Physics 2

Magnetism and Electromagnetism

About 15 minutes to read

How to use this guide

Read it in order the first time because the topics build on each other. The magnetic force on a moving charge comes first, then the same force on a current, then the fields that currents produce. Induction comes last because it reuses everything: flux is built from the field, and the induced current's direction is checked with the same right-hand rules. Exam questions in this unit reward careful direction work far more than memorized formulas.

After the first read, use the trap boxes and the tables to review the distinctions the exam tests most often. Finish with the practice questions, then complete the recall check on the last page out loud and note any items you cannot explain yet.

What this unit is worth. Magnetism and Electromagnetism is 12 to 15 percent of the AP Physics 2 exam. The formulas here are short, but a flipped sign on a right-hand rule or a reversed Lenz's law call turns a right answer into a wrong one. This guide puts trap boxes on the exact spots where that happens.

12.1 The Magnetic Force on a Moving Charge

A **magnetic field**, written B , is a region of space where a moving electric charge feels a magnetic force. Permanent magnets and the Earth both produce magnetic fields. The field is a vector with a direction at every point, and its strength is measured in **teslas** (T).

A charge q moving with speed v through a field of strength B feels a magnetic force of magnitude $F = qvB \sin\theta$, where θ is the angle between the velocity and the field. The force is largest when the charge moves perpendicular to the field ($\theta = 90^\circ$, $\sin\theta = 1$) and zero when it moves parallel or antiparallel to the field ($\sin\theta = 0$). A charge sitting still in a magnetic field feels no magnetic force at all.

The direction of the force comes from the **first right-hand rule**. Point the fingers of your right hand in the direction of the velocity of a positive charge, then curl them toward the direction of B . Your thumb points in the direction of the magnetic force on that positive charge.

Worked setup. A proton moves to the right while the field points into the page. Fingers right, curl into the page, thumb up: the force on the proton points upward. The cross product agrees. With x to the right, y up, and z out of the page, $\hat{x} \times (-\hat{z}) = +\hat{y}$, so $F = qvB$ points up for the positive proton.

Trap. The right-hand rule gives the force on a *positive* charge. For an electron or any negative charge, the force points the opposite way. Either reverse the velocity direction before applying the rule, or apply the rule and flip the final direction. Skipping this flip is the most common sign error in the unit.

A second configuration, with an electron

An electron moves upward while the field points to the right. Do the cross product for a positive charge first: $\hat{y} \times \hat{x} = -\hat{z}$, into the page. The electron carries negative charge, so flip it: the force on the electron points out of the page. A positive charge in the same setup would feel the force into the page. If you forget the flip, the direction comes out exactly backwards.

A numerical check

An electron ($q = 1.60 \times 10^{-19}$ C) moves at $v = 2.0 \times 10^7$ m/s perpendicular to a field $B = 0.50$ T. The magnitude is $F = qvB \sin\theta = (1.60 \times 10^{-19} \text{ C})(2.0 \times 10^7 \text{ m/s})(0.50 \text{ T})(1) = 1.6 \times 10^{-12}$ N. If this electron moves to the right with the field into the page, the force points downward, opposite the proton's upward push in the first setup. The number is small because the charge of a single electron is small; macroscopic currents involve enormous numbers of charges.

One tesla is a large field. From $F = qvB$, $1 \text{ T} = 1 \text{ N}\cdot\text{s}/(\text{C}\cdot\text{m})$, which is also written $1 \text{ N}/(\text{A}\cdot\text{m})$. Laboratory electromagnets reach a few teslas; the Earth's field is tens of microteslas.

12.2 The Magnetic Force on a Current-Carrying Wire

A current is charges in motion, so a wire carrying current in a magnetic field feels a magnetic force. For a straight wire of length L carrying current I in a uniform field B , the magnitude is $F = ILB \sin\theta$, where θ is the angle between the wire, taken in the current direction, and the field. Perpendicular gives the maximum force and parallel gives zero, exactly as for a single charge.

The direction comes from the **second right-hand rule**. Point your right-hand fingers in the direction of the *conventional current*, curl them toward B , and your thumb gives the force direction. Conventional current is defined as the direction positive charges would flow, which is the direction labeled I in every circuit diagram.

Trap. In a metal wire the actual moving charges are electrons, which drift opposite to the conventional current. Point your fingers along the conventional current anyway, not along the electron drift direction. Pointing along the electron flow flips every force direction.

Worked example. A 0.50 m wire carries 3.0 A to the right through a 0.20 T field pointing into the page. $F = ILB = (3.0 \text{ A})(0.50 \text{ m})(0.20 \text{ T}) = 0.30 \text{ N}$. Fingers right, curl into the page, thumb up, so the force is 0.30 N upward. If the wire instead made a 30° angle with the field, the magnitude would drop to $F = (0.30 \text{ N})(\sin 30^\circ) = 0.15 \text{ N}$ while the direction stayed the same.

12.3 Sources of Magnetic Fields

Moving charges create magnetic fields as well as respond to them. A long straight wire carrying current I produces a field that circles the wire, with strength $\mathbf{B} = \mu_0 I / (2\pi r)$ at distance r from the wire. Here $\mu_0 = 4\pi \times 10^{-7} \text{ T}\cdot\text{m/A}$ is the permeability of free space, and the field weakens as $1/r$ with distance. The **third right-hand rule** gives the circling direction: point your right thumb along the conventional current, and your curled fingers show the direction of B around the wire.

Worked example. A wire carries 5.0 A upward, and you stand 2.0 cm to the east of it. $B = \mu_0 I / (2\pi r) = (4\pi \times 10^{-7})(5.0) / (2\pi \times 0.020) = 5.0 \times 10^{-5} \text{ T}$. Thumb up, fingers curl, and on the east side they point into the page, so $B = 5.0 \times 10^{-5} \text{ T}$ into the page.

A circular loop of radius R carrying current I makes a field at its center of $\mathbf{B} = \mu_0 I / (2R)$, pointing along the loop's axis. Stack many loops into a **solenoid** and the field inside becomes nearly uniform, $\mathbf{B} = \mu_0 n I$, where n is the number of turns per unit length. Outside an ideal solenoid the field is nearly zero, which is why solenoids make tidy electromagnets.

The **fourth right-hand rule** handles loops and solenoids. Curl the fingers of your right hand in the direction of the current around the loops; your thumb points in the direction of the field inside, toward the north pole of the electromagnet.

RULE	WHAT IT FINDS	HAND SETUP
1. Force on a moving charge	F on a positive charge moving with velocity v	Fingers along v , curl toward B , thumb gives F
2. Force on a current	F on a straight current-carrying wire	Fingers along conventional current I , curl toward B , thumb gives F
3. Field around a wire	B circling a straight wire	Thumb along conventional current, curled fingers give B
4. Field of a loop or solenoid	B inside the loops	Fingers curl with the current, thumb gives B , toward the north pole

12.4 Motion of Charged Particles in Magnetic Fields

When a charged particle enters a uniform field moving perpendicular to it, the magnetic force stays perpendicular to the velocity at every instant. A force perpendicular to velocity bends the path without changing the speed, so the particle travels in a circle. Setting the magnetic force equal to the needed centripetal force, $qvB = mv^2/r$, gives the **radius $r = mv/(qB)$** .

The circling direction follows from the first right-hand rule applied moment by moment. A proton moving right into a field pointing into the page feels an upward force, so it curves upward and travels counterclockwise. An electron in the same setup curves clockwise. The period of one orbit is $T = 2\pi m/(qB)$, which does not depend on the speed: faster particles sweep out larger circles but take the same time per lap.

Worked example. A proton ($m = 1.67 \times 10^{-27}$ kg, $q = 1.60 \times 10^{-19}$ C) enters a 0.25 T field at $v = 4.0 \times 10^5$ m/s, perpendicular to the field. $r = mv/(qB) = (1.67 \times 10^{-27})(4.0 \times 10^5) / ((1.60 \times 10^{-19})(0.25)) = 6.68 \times 10^{-22} / 4.0 \times 10^{-20} = 1.67 \times 10^{-2}$ m, about 1.7 cm. Its orbital period is $T = 2\pi m/(qB) \approx 2.6 \times 10^{-7}$ s.

Trap. A magnetic force can never do work on a charged particle, because it is always perpendicular to the velocity. It changes the direction of motion, never the speed or the kinetic energy. A question that asks how a magnetic field speeds up a charge has a trick built in: it cannot, so the answer involves an electric field or no speed change at all.

12.5 Magnetic Flux

Magnetic flux measures how much magnetic field passes through a surface: $\Phi = BA \cos\theta$, where A is the area and θ is the angle between the field and the *normal* to the surface, the line perpendicular to it. Flux is largest when the field hits the surface head-on ($\theta = 0$) and zero when the field runs parallel to the surface ($\theta = 90^\circ$). The unit is the **weber** (Wb), equal to $\text{T}\cdot\text{m}^2$.

Flux changes whenever B , A , or the orientation θ changes. Turning a loop, sliding it into a stronger-field region, and ramping the field up or down all change the flux, and that change is what the next section is about.

Worked example. A loop of area 0.030 m^2 sits in a 0.40 T field, with the field making 30° with the loop's normal. $\Phi = BA \cos\theta = (0.40)(0.030)(\cos 30^\circ) = (0.012)(0.866) \approx 0.010 \text{ Wb}$.

Trap. Faraday's law cares about the *rate of change* of flux, not the flux itself. A huge steady flux through a coil induces zero emf because nothing is changing. When a question gives you a flux value and asks for the emf, the flux alone is never enough; you need how fast it changes.

12.6 Faraday's Law and Lenz's Law

A changing magnetic flux through a coil induces an **emf**: $\epsilon = -N \Delta\Phi/\Delta t$. This is **Faraday's law**. The fraction $\Delta\Phi/\Delta t$ is the rate of change of flux through one turn, N is the number of turns, and the minus sign carries **Lenz's law**.

Lenz's law says the induced current flows in the direction that creates a magnetic field opposing the *change* in flux. Worked direction example: the field through a loop points into the page and is getting stronger. The induced field must point out of the page to fight the increase, and by the fourth right-hand rule that means a counterclockwise current. If instead the into-the-page field were weakening, the induced field would point into the page to prop up the fading flux, giving a clockwise current.

Trap. Lenz's law opposes the *change*, not the field. Many students pick the current that fights the existing field direction, which is right only when the field is increasing. When the field is decreasing, the induced current supports the existing field direction to resist the decrease. Always ask first whether the flux is growing or shrinking.

Worked example. A 150-turn coil, each turn of area $4.0 \times 10^{-3} \text{ m}^2$, sits perpendicular to a field that rises from 0.020 T to 0.140 T in 0.50 s. The flux change per turn is $\Delta\Phi = A\Delta B = (4.0 \times 10^{-3})(0.120) = 4.8 \times 10^{-4} \text{ Wb}$. Then $\epsilon = N \Delta\Phi/\Delta t = (150)(4.8 \times 10^{-4}) / (0.50) = 0.144 \text{ V}$, about 0.14 V.

Trap. The N in Faraday's law is the number of *turns*, and the emf scales with it. Computing $\Delta\Phi/\Delta t$ for one loop and stopping there misses a factor of N , which here would give 0.00096 V instead of 0.144 V. When a coil is described, multiply by the turn count.

12.7 Motional EMF

A conductor moving through a magnetic field develops an emf across its ends even with no coil and no changing field. Each charge q in a rod moving at speed v perpendicular to B feels the magnetic force qvB , so charges pile up at one end until their electric field balances the magnetic push: $qE = qvB$, so $E = vB$. Across a rod of length L the potential difference is $\mathcal{E} = EL = BLv$.

Worked example. A 0.40 m metal rod slides at 2.5 m/s perpendicular to a 0.30 T field. $\mathcal{E} = BLv = (0.30)(0.40)(2.5) = 0.30$ V. For motion to the right with the field into the page, positive charges are pushed to the top end, since $\mathbf{v} \times \mathbf{B}$ points up, so the top of the rod is positive. The emf exists whether or not the rod is part of a closed circuit.

12.8 Inductance and RL Circuits

An **inductor** is a coil that opposes *changes* in its own current. When the current tries to rise, the changing flux induces a **back emf** that fights the rise; when the current tries to fall, the back emf fights the fall. The current through an inductor cannot change instantaneously.

In an **RL circuit** the current therefore climbs gradually toward its final value after the switch closes, and if the battery is disconnected the current keeps flowing in the same direction while it decays away through the resistor. While current flows, energy is stored in the inductor's magnetic field.

Confusions That Cost Points

PAIR	HOW TO KEEP THEM STRAIGHT
Right-hand rule for $+q$ vs $-q$	The rule gives the force on positive charge. For electrons, flip the result. Electron flow in a wire is opposite to conventional current, so point your fingers with the labeled current.
Lenz's law: oppose the field vs oppose the change	Growing into-the-page flux induces an out-of-the-page field, so counterclockwise current. Shrinking into-the-page flux induces an into-the-page field, so clockwise current. Ask whether flux is growing or shrinking first.
$F = qvB$ vs $F = ILB$	qvB is for a single moving charge; ILB is for a current-carrying wire. Both need the $\sin\theta$ factor when the directions are not perpendicular.
Flux Φ vs $\Delta\Phi/\Delta t$	Flux is $BA \cos\theta$, a snapshot. Only its rate of change induces emf. Steady flux, however large, induces nothing.
Electric force vs magnetic force	qE points along the field and does work. qvB is perpendicular to both v and B and never does work; it only bends the path.

Practice Questions

Original questions written for this guide in the style of the AP exam. Answers and explanations are on the next page, so complete the questions before checking them.

1. An electron moves to the right through a uniform magnetic field pointing into the page. What is the direction of the magnetic force on the electron?

1. Upward
2. Downward
3. Into the page
4. Out of the page

2. An electron travels at 3.0×10^6 m/s perpendicular to a uniform 0.20 T magnetic field. What is the magnitude of the magnetic force on the electron? ($e = 1.60 \times 10^{-19}$ C)

1. 9.6×10^{-14} N
2. 9.6×10^{-13} N
3. 4.8×10^{-14} N
4. 0 N

3. A long straight wire carries conventional current upward. At a point directly east of the wire, the magnetic field points

1. upward, parallel to the current
2. east, directly away from the wire
3. into the page
4. out of the page

4. A proton ($m = 1.67 \times 10^{-27}$ kg, $q = 1.60 \times 10^{-19}$ C) enters a uniform 0.40 T magnetic field at 2.0×10^5 m/s, moving perpendicular to the field. What is the radius of its circular path?

1. 0.52 mm
2. 5.2 cm
3. 2.6 mm
4. 5.2 mm

5. A 50-turn coil of area 0.020 m^2 sits perpendicular to a magnetic field. The field strength drops from 0.30 T to 0.10 T in 0.25 s . What is the magnitude of the induced emf?

1. 0.20 V
2. 1.2 V
3. 0.80 V
4. 0.016 V

6. The magnetic field through a conducting loop points into the page and its strength is decreasing. What is the direction of the induced current?

1. Counterclockwise
2. There is no induced current, because the flux is decreasing
3. Impossible to tell without the area of the loop
4. Clockwise

7. A 0.50 m metal rod moves at 4.0 m/s perpendicular to a uniform 0.25 T magnetic field, with the velocity also perpendicular to the rod. What is the emf across the ends of the rod?

1. 0.50 V
2. 0.13 V
3. 1.0 V
4. 0 V , because there is no complete circuit

8. In a series RL circuit the current has been steady for a long time. The switch is then flipped so the battery is removed and the resistor and inductor form a closed loop. Just after the switch flips, the current

1. remains at its steady value forever
2. continues in the same direction and decreases gradually
3. drops to zero instantly
4. immediately reverses direction

Answer Key

- 1. B.** The first right-hand rule for a positive charge gives fingers right, curl into the page, thumb up. The electron carries negative charge, so flip it: the force points downward. A is the answer you get when you forget the sign flip. C confuses the force direction with the field direction. D would require a different velocity or field arrangement entirely.
- 2. A.** $F = qvB = (1.60 \times 10^{-19})(3.0 \times 10^6)(0.20) = 9.6 \times 10^{-14} \text{ N}$. B is a decimal slip of one power of ten. C halves the answer, as if $\sin\theta$ were $1/2$ instead of 1 for perpendicular motion. D misreads "magnetic forces do no work" as "magnetic forces do not exist"; the force is real, it just points perpendicular to the motion.
- 3. C.** Point the right thumb up along the conventional current; the fingers curl around the wire, and on the east side they point into the page. D reverses the curl. A confuses the field direction with the current direction; the field circles the wire rather than running along it. B treats the magnetic field like a radial electric field, which it is not.
- 4. D.** $r = mv/(qB) = (1.67 \times 10^{-27})(2.0 \times 10^5) / ((1.60 \times 10^{-19})(0.40)) = 3.34 \times 10^{-22} / 6.4 \times 10^{-20} = 5.2 \times 10^{-3} \text{ m} = 5.2 \text{ mm}$. A and B are decimal slips in opposite directions. C halves the radius, possibly from mixing radius with diameter or dropping a factor of 2 in the algebra.
- 5. C.** The flux change per turn is $\Delta\Phi = A\Delta B = (0.020)(0.30 - 0.10) = 4.0 \times 10^{-3} \text{ Wb}$. Then $\varepsilon = N \Delta\Phi/\Delta t = (50)(4.0 \times 10^{-3}) / (0.25) = 0.80 \text{ V}$. D forgets the turn count N . A forgets to divide by the time interval. B uses the final field 0.30 T instead of the change 0.20 T .
- 6. D.** The into-the-page flux is shrinking, so the induced field must point into the page to oppose the decrease. By the fourth right-hand rule, a clockwise current produces an into-the-page field inside the loop. A opposes the field instead of the change; it would be correct if the field were increasing. B is wrong because a decreasing flux is still a changing flux, and change is what induces emf. C is wrong because the area sets the size of the emf, not the direction of the current.
- 7. A.** $\varepsilon = BLv = (0.25)(0.50)(4.0) = 0.50 \text{ V}$. B drops the velocity factor, computing only BL . C doubles the correct value. D is the trap: charge separation and the resulting emf appear across the rod whether or not it is part of a closed circuit; a closed loop is needed for a sustained current, not for the emf.
- 8. B.** The inductor opposes the change in current, so the current cannot vanish instantly; it keeps its direction and decays gradually as the resistor dissipates the stored energy. C ignores the inductor entirely. D confuses the back emf, which opposes the change, with a reversal of the current. A ignores the resistor, which drains the energy and brings the current to zero over time.

When you check your answers, note which distinction each miss came from. Make a flashcard for that distinction and drill it spaced out over the next few days instead of rereading the whole section. If you missed one of these questions, the same distinction is worth practicing again in Rycal, where the Magnetism and Electromagnetism deck has flashcards for it and more practice questions use the same kinds of traps.

One-Page Recall Check

Say each answer out loud before you look back, and mark the ones you cannot finish. Anything you cannot say out loud yet belongs in your flashcard deck. In Rycal, add those items to the Magnetism and Electromagnetism deck and let spaced review bring them back over the next few days.

- State $F = qvB \sin\theta$ and say when the force is largest and when it is zero.
- State the first right-hand rule and explain the sign flip for negative charges.
- State the second right-hand rule and explain why you point along conventional current.
- State the third right-hand rule and write $B = \mu_0 I / (2\pi r)$, naming each symbol.
- State the fourth right-hand rule for a loop and a solenoid.
- Derive $r = mv / (qB)$ starting from $qvB = mv^2 / r$.
- Explain why a magnetic force does no work on a charged particle.
- Write $\Phi = BA \cos\theta$ and say what the angle θ is measured from.
- Explain the difference between flux and the rate of change of flux for induction.
- State Faraday's law and explain the roles of N and the minus sign.
- State Lenz's law in terms of opposing the change, for both the increasing and decreasing cases.
- Write $\varepsilon = BLv$ and explain where it comes from.
- Describe what an inductor does when current tries to rise and when it tries to fall.

Where to go next. Turn every missed item above into flashcards and drill them spaced out over several days rather than in one sitting. In Rycal, open the Magnetism and Electromagnetism deck under AP Physics 2. The deck covers the terms in this guide, and its practice questions target the same traps named here. If you have a test date, add it in the Test Planner. You can also start your next review with a Brain Dump, then check what you missed against this guide.

Key terms for this unit

Magnetic field, Tesla, Magnetic force on a moving charge, Right-hand rule, Conventional current, Electron flow, Magnetic force on a current-carrying wire, Permeability of free space (μ_0), Magnetic field of a long straight wire, Magnetic field at the center of a current loop, Solenoid, Magnetic flux, Weber, Faraday's law, Lenz's law, Induced emf, Motional emf, Inductor, Back emf, RL circuit.

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