

Magnetism and Electromagnetism

Begin with poles and magnetic field maps. Follow the original route from fields around currents to forces, circular paths, motional emf, magnetic flux and Lenz’s law. The water-flow analogy and the original energy-graph reasoning stay in that sequence.

TEACHING ROUTE

The explanations follow the original lesson sequence. Connections, analogies and worked reasoning remain together. Syllabus additions appear beside the ideas they support.

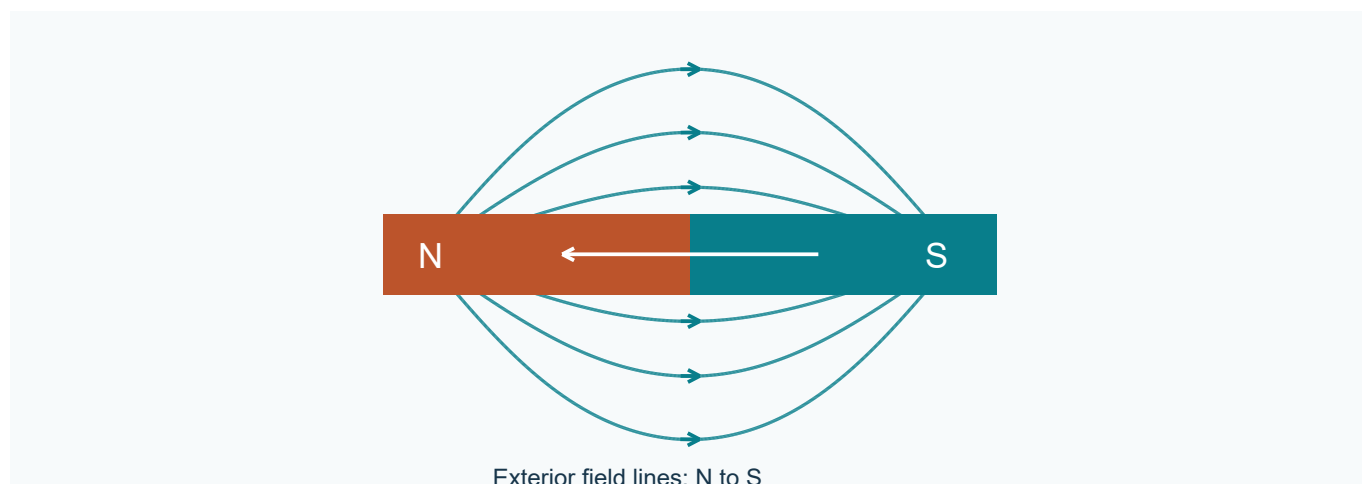
Lesson group	Focus
Fields	Poles, compasses, straight wires, loops and solenoids
Forces	Wire force, charge force, circular motion and interacting wires
Induction	Moving rod first; flux and Faraday’s law next
Applications	Lenz’s law, graph slopes, energy and experimental evidence

Predict first, draw the situation, then calculate. Use the class questions for discussion and the chapter review for independent practice. Unless stated otherwise, numerical examples use idealized models and the assumptions given on the page.

Source keys N01, N02, and so on refer to the original PDF files listed near the end of this chapter. Source page numbers count PDF pages. CED means the supplied 2026 AP Physics 2 Course and Exam Description.

Magnetic fields and magnetic materials

A compass aligns with the local magnetic field; its north-seeking end points along $\mathbf{B}$. Outside a bar magnet, field lines run from north to south, and inside they continue from south to north, forming closed loops. Cutting a magnet produces smaller dipoles rather than isolated north and south poles. Like poles repel and unlike poles attract.



The exterior field-line segments point from N to S and do not intersect. Their continuation through the magnet is omitted; the white arrow gives the internal direction from S to N.

Magnetism originates in moving charge and intrinsic magnetic properties of particles. In a ferromagnetic material, many microscopic magnetic moments can align within domains. An unmagnetized sample has domains whose contributions largely cancel. An applied field can align domains and magnetize it. Some materials retain much of that alignment after the external field is removed.

RELATIONSHIP AND CONDITIONS

Magnetic field B is measured in teslas: $1 \text{ T} = 1 \text{ N}/(\text{A}\cdot\text{m})$.

Permeability μ characterizes magnetic response. In air/vacuum classroom problems, $\mu \approx \mu_0 \approx 4\pi \times 10^{-7} \text{ T}\cdot\text{m}/\text{A}$.

Superpose magnetic fields as vectors. A zero net field can occur where two nonzero contributions cancel. Magnetic field lines are a representation, not physical threads. The density of drawn lines communicates relative strength only when the drawing uses a consistent convention.

Checkpoint

An iron nail attracted by either pole of a magnet need not have been a permanent magnet initially. Induced domain alignment can produce attraction. Magnetic attraction alone does not identify a permanent pole.

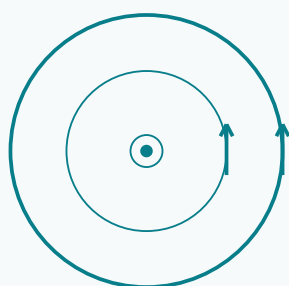
Magnetic fields made by currents

RELATIONSHIP AND CONDITIONS

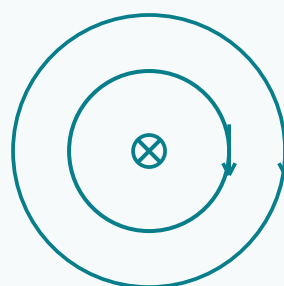
Long straight wire: $B = \mu_0 I / (2\pi r)$

r is the perpendicular distance from the wire; the wire is long compared with r .

Point the right thumb along conventional current; curled fingers give the circulating B direction. For a loop, curl fingers with current and the thumb gives the field direction through the center. A solenoid combines the fields of many turns, producing an approximately uniform interior field in a long-coil model. Its ends behave like north and south poles.



I out: B counterclockwise



I in: B clockwise

Look directly along the wire: a dot is current toward you; a cross is current away from you.

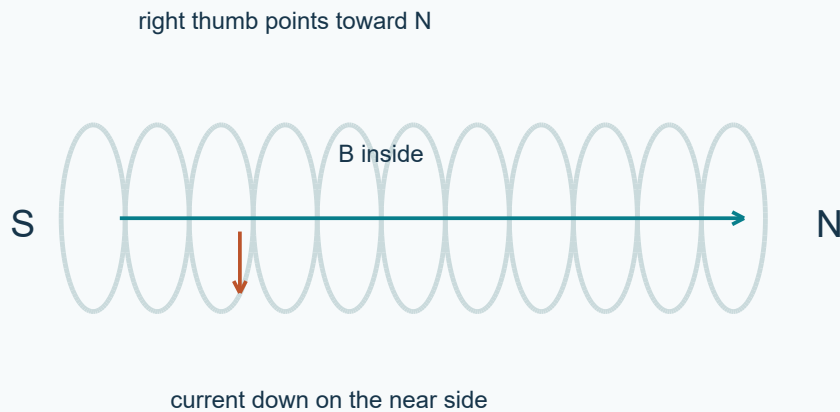
Worked example: field cancellation

Two long parallel wires carry equal 4.0 A currents upward and are 0.10 m apart. At their midpoint, each field magnitude is $\mu_0(4.0)/(2\pi \cdot 0.050) = 1.60 \times 10^{-5} \text{ T}$. The directions oppose, so $\mathbf{B}_{\text{net}} = \mathbf{0}$. If one current reverses, the fields add to $3.20 \times 10^{-5} \text{ T}$.

For unequal same-direction currents, the cancellation point lies between the wires and closer to the weaker-current wire. Solve $I_1/r_1 = I_2/r_2$, with $r_1 + r_2$ equal to the separation. For opposite currents, fields between the wires add rather than cancel.

Extension: a long air-core solenoid has $B \approx \mu_0 nI$, where n is turns per length. Use this only when the long-solenoid approximation is appropriate; the CED emphasizes field directions and the long straight-wire relation.

The solenoid: a coil acts like a bar magnet



Curl the right fingers with conventional current around the turns. The thumb points along the interior field and toward the north end.

The field contributions of neighboring turns reinforce inside a long coil. Outside, the field returns from the north end to the south end. A compass aligns with the local field rather than pointing toward every nearby north pole.

RELATIONSHIP AND CONDITIONS

Long-solenoid extension: $B \approx \mu_0 nI$, where $n = N/L$
 N is total turns; n is turns per unit length.

With N and I fixed, stretching the coil to twice its length approximately halves its interior field in the long-coil model. Doubling both N and L leaves n unchanged. Adding an iron core can strengthen the field by aligning magnetic domains, though real core response is not simply a universal constant.

PAUSE AND EXPLAIN

A student knows the coil current but looks from the opposite end. Does the north end change? No. The words clockwise and counterclockwise change with viewpoint; the physical field does not.

Magnetic response of matter

Response	Microscopic explanation	After the field is removed
Ferromagnetic	Groups of aligned moments form domains; an applied field changes their collective alignment. Iron, nickel and cobalt are examples.	Substantial magnetization can remain.
Paramagnetic	Existing atomic moments align weakly with an applied field; thermal motion competes with alignment. Aluminum is an example.	Alignment is not retained in the simple model.
Diamagnetic	The applied field induces a weak response opposing it. This contribution occurs in all matter, but stronger responses can mask it.	The induced response disappears.

Magnetic permeability describes the material's magnetic response. It depends on composition and can vary with temperature, field strength and orientation; it is not generally one fixed number for every condition. Treat a stated constant permeability as a model valid over the specified range.

Earth and the dipole model

Earth's large-scale field is approximately dipolar. A compass aligns with the local field, so its north-seeking tip points toward the geographically northern region, which acts roughly like a magnetic south pole. Geographic and magnetic axes are not identical. A dipole field becomes weaker farther from its source.

Compare three ideas

A permanent magnet retains alignment; induced magnetization is created by an applied field; permeability describes the response of the material. None of these means that an isolated north or south magnetic pole has been produced.

A current-carrying wire in an external field

RELATIONSHIP AND CONDITIONS

$F = ILB \sin \theta$; use the wire length actually inside the field.

The force on a wire results from magnetic forces on its moving charge carriers transmitted to the material. Use the field created by other sources, not the wire's own field in the simple straight-wire force equation. The direction follows the cross product of conventional current direction with B .

THE ORIGINAL LEFT-HAND MNEMONIC

Fleming's left-hand motor rule: first finger points along B , second finger along conventional I , and thumb along force. It gives the same result as the right-hand cross product $I \times B$. Keep it distinct from the right-hand curl rule used to find the field around a current.

Worked example

A horizontal wire of length 0.20 m carries 3.0 A to the right in a uniform 0.50 T field into the page. Its force is **0.30 N upward**. If it supports a mass at equilibrium with no other vertical forces, $m = F/g =$ **0.0306 kg**. Reversing the current reverses the magnetic force.

A current loop in a uniform magnetic field can experience a torque even if its net force is zero. Forces on opposite sides can cancel as vectors while forming a turning pair. This supplies useful physical intuition for motors without requiring advanced torque formulas here.

Force on a moving charge

RELATIONSHIP AND CONDITIONS

$$F_B = |q|vB \sin \theta; \text{ direction from } q(\mathbf{v} \times \mathbf{B})$$

θ is the angle between velocity and field. For $q > 0$ use the right-hand cross-product direction; reverse it for $q < 0$.

The force is perpendicular to both velocity and magnetic field. It vanishes for a stationary charge and for motion parallel or antiparallel to B . The magnetic part of the force does no work on a point charge: it can change the direction of velocity without changing speed or kinetic energy. An electric field, including an induced electric field, can change kinetic energy.

Velocity and B	Positive charge force	Negative charge force
v right, B into page	Up	Down
v up, B right	Into page	Out of page
v parallel to B	Zero	Zero

Worked example

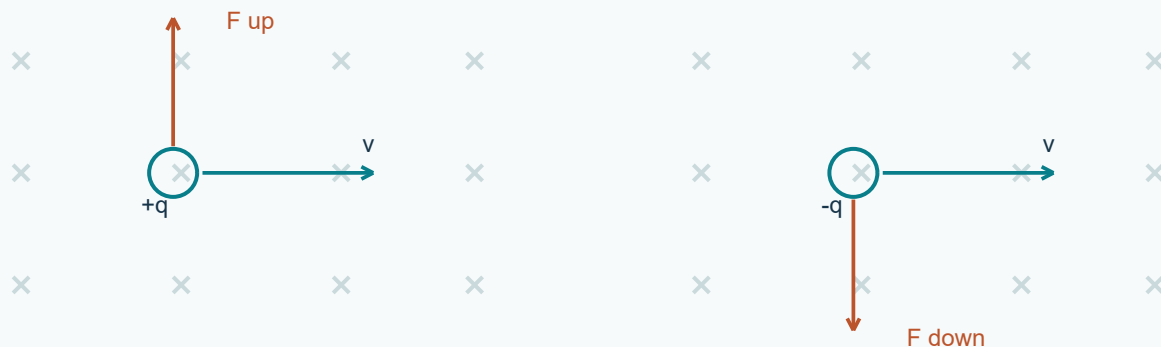
A proton moves at 2.0×10^6 m/s perpendicular to $B = 0.20$ T. $F = (1.60 \times 10^{-19})(2.0 \times 10^6)(0.20) = \mathbf{6.40 \times 10^{-14} \text{ N}}$. **Extension:** if the angle becomes 30° , the force is $\mathbf{3.20 \times 10^{-14} \text{ N}}$. Doubling mass alone would not change magnetic force for the same q , v , B and angle.

Crossed electric and magnetic fields

A particle passes undeflected if the electric and magnetic forces are equal and opposite. With mutually perpendicular fields and velocity, $|q|E = |q|vB$ gives $\mathbf{v = E/B}$. The speed condition does not by itself guarantee cancellation: first check the directions of both forces. Reversing the charge reverses both forces, so the same selected velocity can still be undeflected.

CED boundary: numerical magnetic-force questions on moving charges are restricted to 0° , 90° and 180° . Other angles are treated qualitatively; numerical 30° examples here are labeled extensions.

Two hand rules answer two different questions



Same v and B ; opposite charge $\rightarrow$ opposite force

With velocity right and B into the page, a positive charge feels force upward and a negative charge downward.

Question	Inputs	Procedure
What B does this current produce?	Current and observation point	Right thumb along I ; curled fingers follow B
What force does an existing B produce?	Charge sign, velocity and B	Use $q(\mathbf{v} \times \mathbf{B})$; reverse for negative q
What force acts on this wire?	Conventional current and external B	Use $I \times B$, or the equivalent left-hand motor rule

THE ZERO-FORCE CHECK

A charge can be in a nonzero magnetic field and feel zero magnetic force if it is stationary or moves parallel to B . Unlike electric force qE , magnetic force depends on velocity.

Class question: reverse both the charge sign and velocity while keeping B fixed. The two reversals cancel: the magnetic force points in the same direction as before.

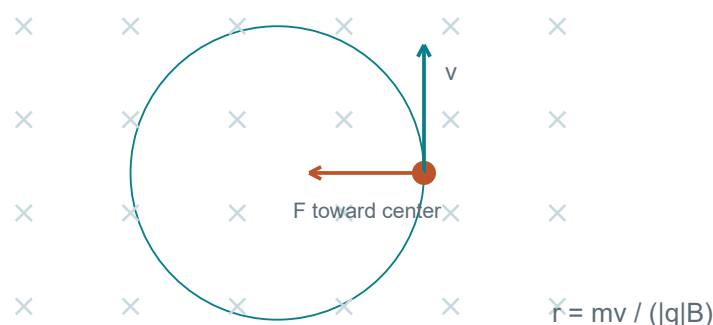
Circular paths and charge-to-mass ratio

RELATIONSHIP AND CONDITIONS

$$|q|vB = mv^2/r \rightarrow r = mv/(|q|B)$$

Period $T = 2\pi m/(|q|B)$, for uniform perpendicular motion at nonrelativistic speed.

+q; B into page



A positive charge moves counterclockwise in a field into the page. At the rightmost point its velocity is upward and the force is leftward, toward the center.

The centripetal force is not an extra force: it is the inward net force, supplied here by the magnetic interaction. At fixed B , a larger momentum produces a larger radius. At fixed speed and field, a larger mass gives a larger radius, while a larger charge magnitude gives a smaller radius. The direction of curvature identifies the sign of charge only when the velocity and B direction are known.

Worked example

For the proton in the preceding example, $r = (1.67 \times 10^{-27})(2.0 \times 10^6)/[(1.60 \times 10^{-19})(0.20)] = \mathbf{0.104 \text{ m}}$. The period is $\mathbf{3.28 \times 10^{-7} \text{ s}}$. Doubling its speed doubles r but leaves the nonrelativistic period unchanged.

If the velocity has a component parallel to B , that component remains constant while the perpendicular component rotates, giving a helical path. Use $v_{\text{perpendicular}}$ in the radius formula. Relativistic corrections are beyond this chapter's ordinary charged-particle examples.

RELATIONSHIP AND CONDITIONS

Accelerate from rest through voltage magnitude V , then bend in B :

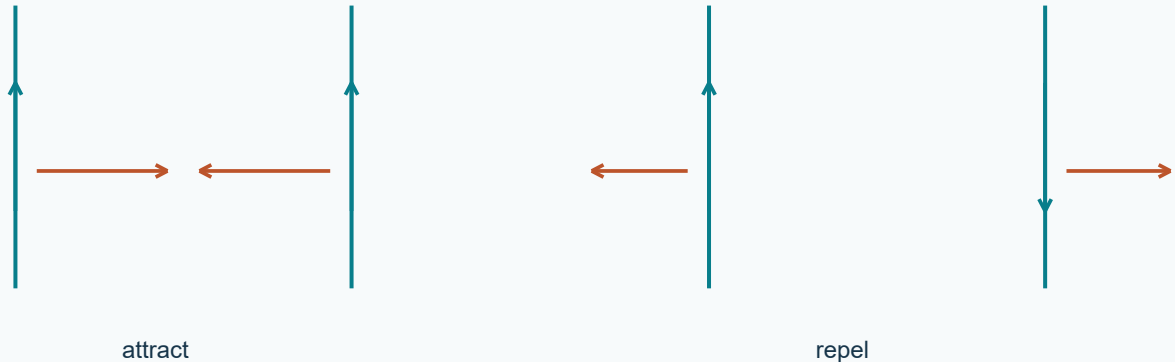
$$|q|V = \frac{1}{2}mv^2 \text{ and } r = mv/(|q|B) \rightarrow m/|q| = B^2 r^2 / (2V).$$

Parallel wires: field first, force second

RELATIONSHIP AND CONDITIONS

Straight wire segment in uniform external B: $F = ILB \sin \theta$

Two long parallel wires: $F/L = \mu_0 I_1 I_2 / (2\pi d)$.



Each wire feels the field produced by the other wire. Same-direction currents attract; opposite-direction currents repel.

Parallel currents in the same direction attract; currents in opposite directions repel. Derive this in two stages: first find the field of wire 1 at wire 2 using the curl rule, then find the force on wire 2 using $I \times B$. The forces on the wires have equal magnitude and opposite direction even when the currents differ.

Worked example: interacting wires

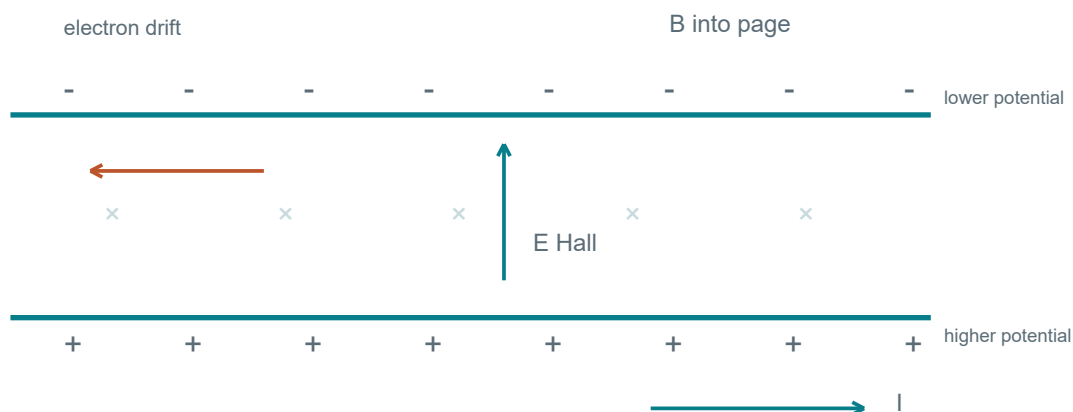
$I_1 = 2.0 \text{ A}$ and $I_2 = 5.0 \text{ A}$ flow in the same direction, $d = 0.040 \text{ m}$. $F/L = (2 \times 10^{-7})(2)(5)/0.040 = \mathbf{5.0 \times 10^{-5} \text{ N/m}}$, attractive. Increasing both currents by a factor of two multiplies the force per length by four.

UNEQUAL CURRENTS, EQUAL INTERACTION FORCES

The original comparison uses 1 A and 3 A. Wire 2 feels $B_1 \propto I_1$ but its own current is I_2 ; wire 1 feels $B_2 \propto I_2$ but its own current is I_1 . Both force magnitudes contain the same product $I_1 I_2$. A stronger field at one wire does not mean a larger interaction force on that wire.

Moving charges and the Hall effect

A moving point charge also produces a magnetic field. In the slow-motion model, its direction follows $q(\mathbf{v} \times \mathbf{r})$, where $\mathbf{r}$ points from the charge toward the observation point. The field is perpendicular to both vectors, greatest for perpendicular geometry and zero along the line of motion. At a fixed geometry it grows with speed and weakens with distance. Distinguish the field a charge creates from the force another field exerts on it.



Electron carriers drift left while conventional current is right. With B into the page, electrons accumulate at the top edge. The resulting Hall field points upward; its force on electrons is downward.

The Hall effect is a transverse potential difference across a current-carrying conductor in a perpendicular magnetic field. Charge separation builds an electric force that eventually balances the sideways magnetic force. In this diagram the top edge is negative and at lower electric potential than the bottom edge.

RELATIONSHIP AND CONDITIONS

At transverse equilibrium in the simple model: $|q|E = |q|v_d B$.

Thus $E = v_d B$. Across width w , $|V_H| = Ew = v_d Bw$.

The Hall-voltage polarity, together with known current and magnetic-field directions, can identify the carrier sign. Reversing current or magnetic field reverses the polarity. The core requirement is explaining the charge separation; the voltage expression follows directly from electric and magnetic force balance.

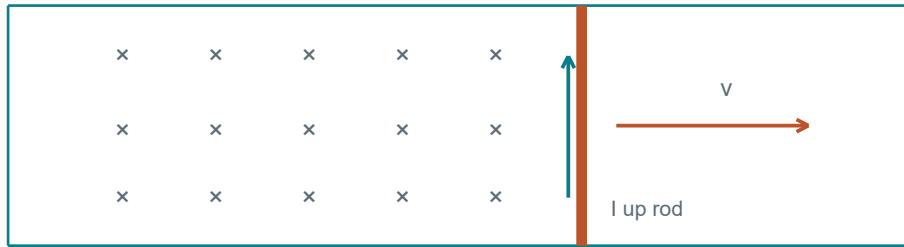
Motional emf and energy accounting

RELATIONSHIP AND CONDITIONS

Rod moving perpendicular to B and its length: $|\mathcal{E}| = BLv$

Closed circuit: $I = BLv/R$; $F_{\text{drag}} = BIL = B^2L^2v/R$

At constant speed: $P_{\text{external}} = Fv = I^2R$.



B into page; induced current counterclockwise

A rod moving right through a field into the page separates charge and drives current upward in the rod. Its magnetic force is leftward, opposing the imposed motion.

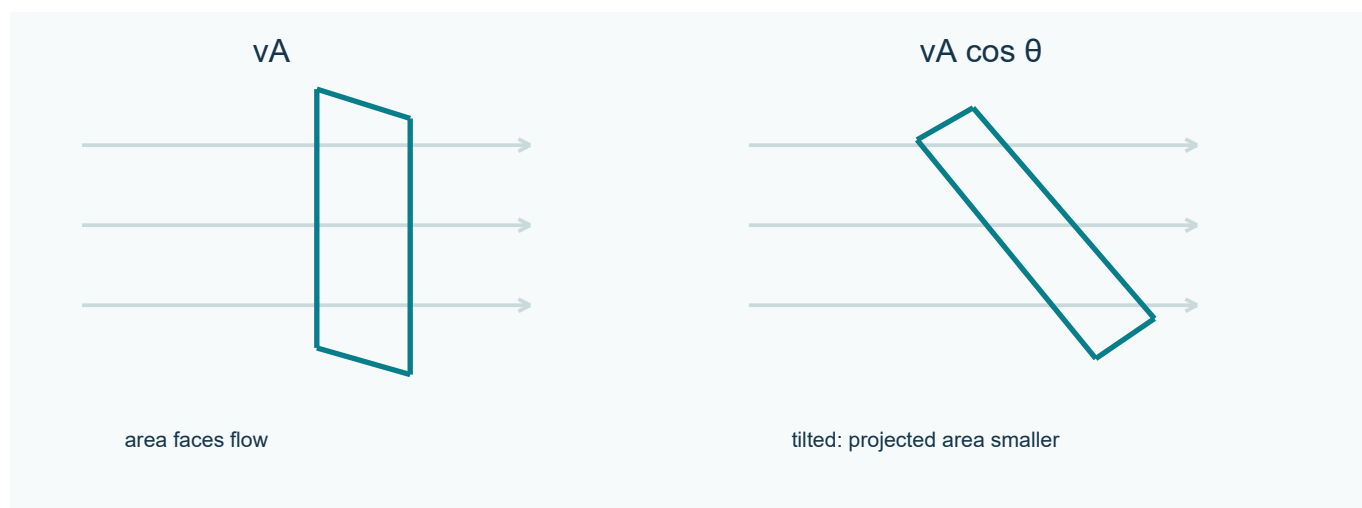
Worked example

Let $B = 0.40 \text{ T}$, $L = 0.25 \text{ m}$, $v = 3.0 \text{ m/s}$ and total $R = 2.0 \Omega$. Emf = **0.30 V**; $I = \mathbf{0.15 \text{ A}}$; drag = **0.015 N**; external power = **0.045 W**. Check: $I^2R = (0.15)^2(2) = 0.045 \text{ W}$.

For an isolated moving rod, charges redistribute until the electric force balances magnetic deflection along the rod. A voltage develops but no sustained circuit current flows without a return path. In the closed circuit, the external pulling agent supplies the energy dissipated as heat. This does not contradict the fact that the magnetic force on an individual charge does no work.

The simple BLv expression assumes mutually perpendicular rod length, motion and field and a uniform field over the rod. For a rotating loop use changing flux; do not insert an arbitrary perimeter into BLv . With nonuniform fields, reason about the changing area and field contribution carefully.

Magnetic flux begins with the original water-flow analogy



A tilted opening presents a smaller effective area to the stream. Replace flow speed with B to build the magnetic-flux analogy.

Imagine uniform water moving at speed v through an area A . In time Δt , water travels a distance $v\Delta t$. If the opening faces the flow, the volume crossing it is $A(v\Delta t)$, so the volume flow rate is vA . Tilting the opening reduces its projected area to $A \cos \theta$, with θ measured from the normal.

RELATIONSHIP AND CONDITIONS

Water volume flow rate: $\Delta V_{\text{water}} / \Delta t = vA \cos \theta$

Magnetic flux: $\Phi_B = BA \cos \theta$

The analogy explains the projection and the angle. Magnetic flux is not a volume of magnetic material moving through the surface. It is a signed measure of the field through a chosen area. For a flat open loop, choose either normal and keep that choice consistent.

Orientation relative to the chosen normal	Flux
B parallel to the normal	$+BA$
B parallel to the plane	0
B opposite the normal	$-BA$
Flip from $+BA$ to $-BA$	$\Delta\Phi = -2BA$, not zero

ANGLE CHECK

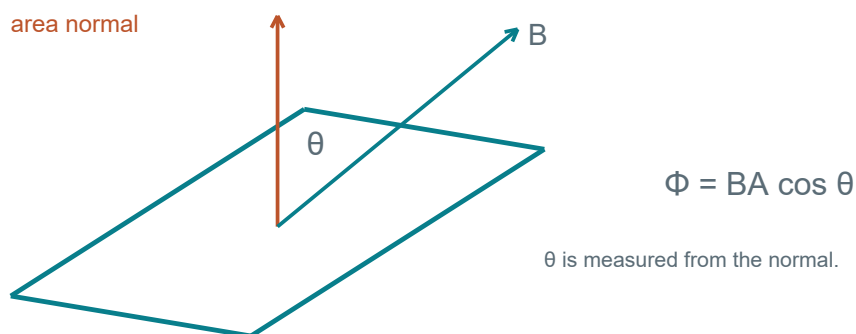
If α is given between the field and the plane, $\Phi = BA \sin \alpha$ with the appropriate sign. The cosine formula uses the angle from the normal.

Magnetic flux and Faraday's law

RELATIONSHIP AND CONDITIONS

Uniform field through a flat area: $\Phi_B = BA \cos \theta$

Average induced emf: $\varepsilon_{\text{avg}} = -N\Delta\Phi_B/\Delta t$; $1 \text{ Wb} = 1 \text{ T}\cdot\text{m}^2 = 1 \text{ V}\cdot\text{s}$.



The relevant angle is between B and the surface normal. If an angle is given relative to the plane, use its complement.

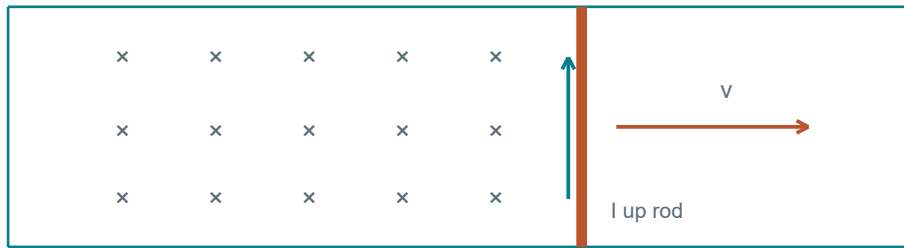
A loop can have magnetic flux without an induced emf. Induction requires a change in flux: B can change, the loop area can change, or the orientation can change. A loop moving entirely within a uniform steady field without changing shape or orientation has constant flux and no net loop emf. Emf can exist in an open conducting path, while a sustained circuit current requires a closed conducting path.

Worked example

A 50-turn coil has area 0.010 m^2 with its normal parallel to B . The field increases uniformly from 0.10 T to 0.30 T in 0.20 s . $|\varepsilon| = 50(0.010)(0.20)/0.20 = \mathbf{0.50 \text{ V}}$. If total resistance is 5.0Ω , the induced-current magnitude is $\mathbf{0.10 \text{ A}}$.

On a flux-versus-time graph, emf is proportional to the negative slope. A horizontal segment gives zero emf. A steep straight segment gives a larger constant emf; a slope reversal reverses polarity. The minus sign expresses Lenz's law when area orientation and positive circulation are defined consistently.

The moving rod revisited through changing flux



B into page; induced current counterclockwise

The swept area in time Δt is $L v \Delta t$. This connects the earlier force-balance derivation to Faraday's law.

RELATIONSHIP AND CONDITIONS

$$|\Delta\Phi| = B\Delta A = BLv\Delta t$$

$$|\epsilon| = |\Delta\Phi|/\Delta t = BLv$$

The earlier argument used charge separation in the rod: $|q|E = |q|vB$ and $\Delta V = EL$. The new argument uses changing magnetic flux. Both predict the same emf in the stated perpendicular geometry. This is the point of introducing motional emf before the general flux law.

PAUSE AND EXPLAIN

A loop slides through a uniform field while remaining completely inside it. Each moving segment may experience magnetic forces on charges, but the net emf around the rigid loop is zero because its total flux stays fixed.

If the rod moves twice as fast in the same closed circuit, emf and current double, magnetic drag doubles, and resistor power quadruples. The external pulling agent must supply that larger power.

Lenz's law: oppose the change

The induced current produces a magnetic field that opposes the change in magnetic flux responsible for it. It does not always oppose the original magnetic field. If the original out-of-page flux is decreasing, the induced field points out of the page to oppose that decrease.

External flux through loop	Induced field	Current viewed on page
Out of page, increasing	Into page	Clockwise
Out of page, decreasing	Out of page	Counterclockwise
Into page, increasing	Out of page	Counterclockwise
Into page, decreasing	Into page	Clockwise

Four decisions, in order

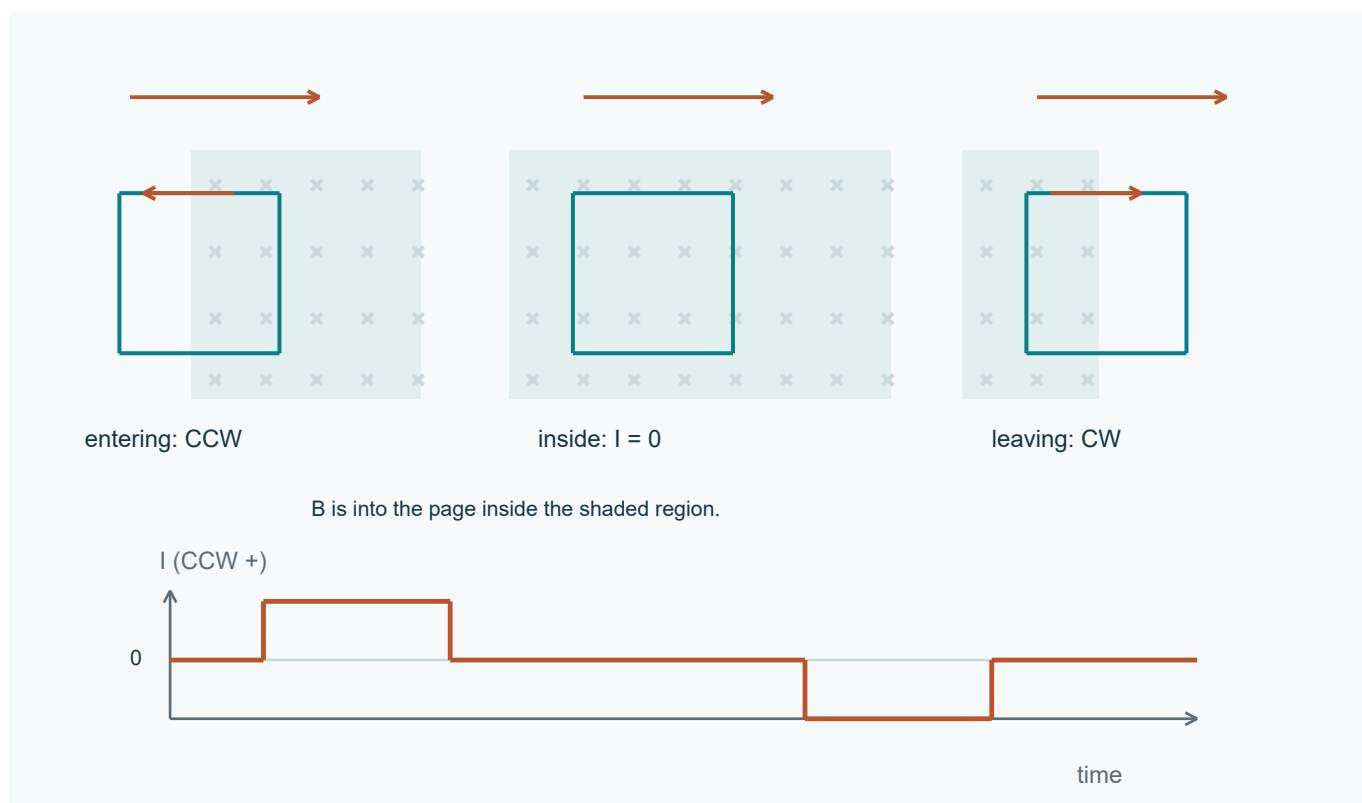
1. Determine the external flux direction.
2. Determine whether its magnitude is increasing or decreasing.
3. Choose an induced field opposing that change.
4. Curl the right-hand fingers to find the conventional current producing that induced field.

An entering and leaving loop

A loop moves right into a region of B into the page. During entry, inward flux increases: current is **counterclockwise**. When fully inside a uniform region, flux is constant: **zero induced current**. During exit, inward flux decreases: current is **clockwise**. Induced magnetic forces oppose the motion during entry and exit.

The opposition to change is required by energy conservation. If induced forces amplified the motion without an external energy supply, a passive system could produce ever-increasing mechanical and electrical energy. In a generator, an external agent must do work against the electromagnetic reaction.

Entering, inside and leaving: the original current graph



A rectangular loop moves right at constant speed through a finite region of field into the page. Take counterclockwise current as positive. The current graph below takes counterclockwise as positive and assumes constant speed and a field region wider than the loop.

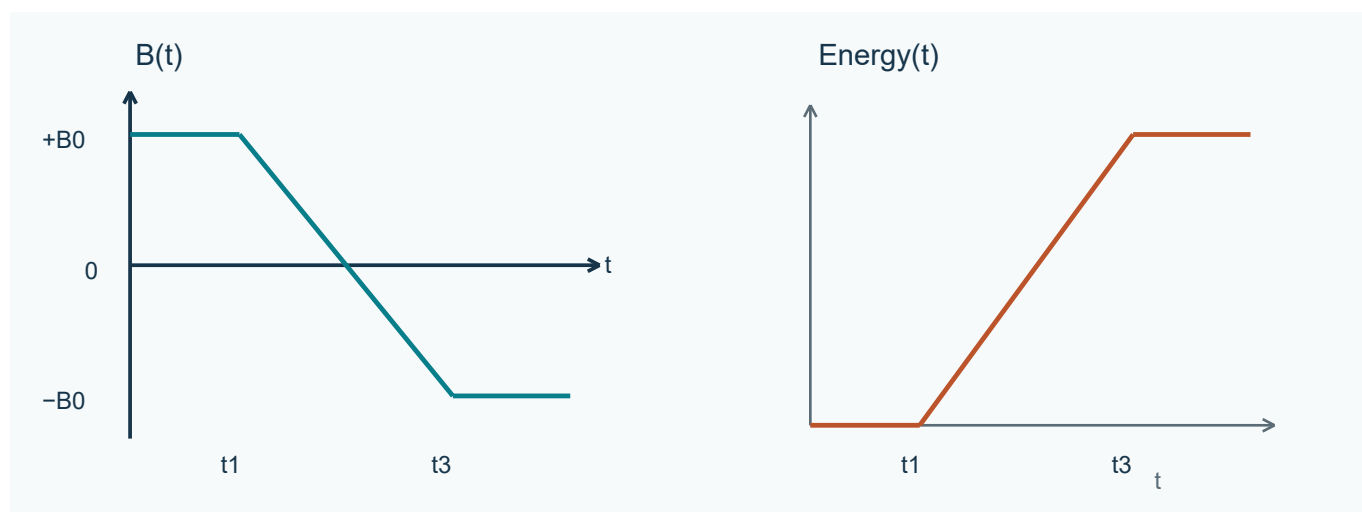
Stage	Inward flux magnitude	Induced current
Entering	Increases at constant rate	Positive constant: counterclockwise
Fully inside	Constant	Zero
Leaving	Decreases at constant rate	Negative constant: clockwise

For sharp boundaries, constant v and B , identical entry/exit geometry and constant loop resistance, the two current pulses have equal magnitude and opposite sign. Their duration is the loop width along the motion divided by v . Reversing the direction of travel reverses the order of the pulse signs.

SOURCE GRAPH CHECK

The handwritten sketch communicates opposite pulses. Under the ideal equal-speed geometry, draw them equally high in magnitude. A different height requires a stated difference in speed, field, geometry or resistance.

The original energy graph: its slope is power



A constant slope of $B(t)$ produces constant emf, constant power and a straight rising cumulative-energy graph.

RELATIONSHIP AND CONDITIONS

$$|\mathcal{E}| = A|\Delta B/\Delta t|; P = \mathcal{E}^2/R$$

For a linear sweep from $+B_0$ to $-B_0$ over Δt :

$$E_{\text{dissipated}} = 4A^2B_0^2/(R\Delta t)$$

Before and after the sweep, B is constant: emf and power vanish, and accumulated energy is flat. During the sweep, a constant field slope gives a constant energy-graph slope. Passing through $B = 0$ does not stop the heating: dB/dt remains nonzero.

Change	Effect on emf	Effect on power / energy slope
Increase R , same $B(t)$	Unchanged	Decreases as $1/R$
Double all B values, same times	Doubles	Quadruples
Same field change in half the time	Doubles	Quadruples; total energy doubles

A PRODUCTIVE ERROR CHECK

An energy expression proportional to R would predict more energy for a larger resistance at the same induced emf. Use $P = \mathcal{E}^2/R$, dimensions, and the graph slope to reject that expression.

Experiments and graph interpretation

A | Field of a straight wire

Use a low-voltage current supply, a long straight wire, a magnetic-field sensor and a distance scale. Hold current fixed and measure the appropriate B component at several perpendicular distances. Measure the ambient-field baseline with current off and subtract it. Plot B against $1/r$: slope should be $\mu_0 I/(2\pi)$. Reverse current to help separate the wire contribution from a background field.

Keep the sensor orientation fixed, measure distance to the wire's center and use r small compared with the wire length. A position offset causes curvature in the intended linear plot. Nearby return wires and metal objects can add fields; reposition them or include their effects in the model.

B | Compare induced pulses

Move the same magnet through the same coil at different controlled speeds and record induced voltage versus time. A faster passage gives larger peak magnitude and a shorter pulse. Reversing motion reverses the relevant pulse polarity. Keep coil orientation, magnet trajectory and starting/ending positions the same.

Area versus height

For equal endpoints, the signed area under $\epsilon(t)$ is $-\Delta\Phi$. Faster motion changes pulse shape and peak magnitude, but the signed area for the same flux change is unchanged. A full passage beginning and ending far away has approximately zero net signed area, though both individual pulses can be nonzero.

To test the energy model, compare the mechanical resistance felt during a magnet's motion with an open versus closed coil circuit. Closing the circuit permits induced current and a stronger electromagnetic opposition. A voltage sensor alone can still detect emf in an effectively open circuit.

Student practice

1. An electron moves right through a magnetic field out of the page. Give the force direction and state whether its speed changes under magnetic force alone.
2. Extension: A $+2.0\ \mu\text{C}$ charge moves at $3.0 \times 10^4\ \text{m/s}$ at 30° to a $0.40\ \text{T}$ field. Find the force magnitude.
3. A proton moves at $1.0 \times 10^6\ \text{m/s}$ perpendicular to a $0.10\ \text{T}$ field. Find its orbit radius.
4. A long wire carries $6.0\ \text{A}$. Find B at $r = 0.030\ \text{m}$.
5. Two wires $0.050\ \text{m}$ apart carry $3.0\ \text{A}$ each in opposite directions. Find force per length and attraction/repulsion.

Review: induction and energy

6. A 20-turn coil of area 0.030 m^2 is perpendicular to $\mathbf{B}$. $\mathbf{B}$ falls from 0.50 T out of page to zero in 0.10 s . Find average emf magnitude and induced-current direction.
7. A 0.40 m rod moves at 2.0 m/s perpendicular to $\mathbf{B} = 0.25 \text{ T}$ in a 5.0Ω closed circuit. Find emf, current and mechanical power needed at constant speed.
8. A loop rotates from its normal parallel to $\mathbf{B}$ to its normal perpendicular to $\mathbf{B}$. What happens to its flux? Why is the angle convention important?
9. A velocity selector has $E = 3.0 \times 10^4 \text{ V/m}$ and $B = 0.20 \text{ T}$. Find the undeflected speed.
10. A coil is moved rigidly within a uniform, time-independent field. It stays fully in the field and does not rotate. Is motion alone sufficient to induce net emf?

Practice solutions

1. For a positive charge $\mathbf{v} \times \mathbf{B}$ points down; for an electron it points **up**. Speed is unchanged by magnetic force alone.
2. $F = |q|vB \sin 30^\circ = \mathbf{0.012\text{ N}}$.
3. $r = mv/(eB) = \mathbf{0.104\text{ m}}$.
4. $B = (2 \times 10^{-7})(6)/0.030 = \mathbf{4.0 \times 10^{-5}\text{ T}}$.
5. $F/L = (2 \times 10^{-7})(9)/0.050 = \mathbf{3.6 \times 10^{-6}\text{ N/m}}$, repulsive.

Answers: induction and energy

6. $|\varepsilon| = 20(0.030)(0.50)/0.10 = \mathbf{3.0\ V}$. Outward flux decreases; induced field is outward, so current is **counterclockwise**.

7. $\varepsilon = BLv = \mathbf{0.20\ V}$; $I = \varepsilon/R = \mathbf{0.040\ A}$; $P = I^2R = \mathbf{0.0080\ W}$.

8. Flux changes from BA to **zero**. It uses the angle from the normal; angle from the plane would use sine instead.

9. $v = E/B = \mathbf{1.5 \times 10^5\ m/s}$, provided force directions oppose.

10. **No**. The flux is constant in the specified situation; the total emf around the rigid loop is zero.

Original notes and syllabus map

The source sequence determines the teaching order. Repeated examples are consolidated while distinct reasoning, diagrams and comparisons are retained.

Original source	Content retained
N06, pp.1-9 Magnetism 12.1-12.3.pdf	Poles → current fields → solenoid → wire/charge force → circular paths
N07, pp.1-4 Problem Solving - Magnetism 12.1-12.4 - 01.pdf	Magnetic-force and particle-motion practice
N08, pp.1-4 Problem Solving - Magnetism 12.1-12.4 - 02.pdf	Magnetic-force practice with annotations
N09, pp.1-11 Magnetism 12.3-12.4.pdf	Wire interactions, motional emf, water-flux analogy, Faraday and Lenz
N10, pp.2-9 Magnetism 12.1-12.4 + Electrostatics 10.1, 10.3-10.5, 10.7 + Circuits 11.4.pdf	Hand-rule review and field/emf/power/energy graph comparison
N34, pp.2-4 Magnetism 12.3-12.4 + Electrostatics 10.1 + Thermal 9.3.pdf	Induction review

Curriculum: supplied *AP Physics 2 Course and Exam Description*, 2026, Unit 12. Topic labels on each content page show where the syllabus connects to the original lesson. Extensions remain labeled.

Clarifications and independent references

Point checked	Treatment in this chapter
Hand rules	Separate the field-creation curl rule from the force rule.
Flux angle	Use the normal; a 180° flip changes signed flux by $2BA$ in magnitude.
Energy source	The pulling agent supplies resistor heating in the moving-rod example.
Lenz's law	Oppose the change in flux, not necessarily the existing field.
CED boundary	Numerical charge-force angles are 0° , 90° or 180° ; other numerical angles are labeled extensions.

Independent checks

[OpenStax: motional emf](#)

[OpenStax: Lenz's law](#)

[OpenStax: magnetic fields and nonintersecting field lines](#)

Constants and calculations use the values stated in each example. Historical practice provides context and reasoning patterns. New worked questions and corrected explanations are distinguished from an official answer key.

Master summary: source, force and induction

Idea	Magnitude / relationship	Direction or condition
Field around long wire	$B = \mu_0 I / (2\pi r)$	Right-hand curl; r perpendicular to wire
Force on moving charge	$F = q vB \sin \theta$	$q(\mathbf{v} \times \mathbf{B})$; no magnetic work on a point charge
Force on straight wire	$F = ILB \sin \theta$	$\mathbf{I} \times \mathbf{B}$; external field and immersed length
Circular path	$r = mv / (q B)$	Uniform B , v perpendicular, nonrelativistic
Parallel wires	$F/L = \mu_0 I_1 I_2 / (2\pi d)$	Same currents attract; opposite currents repel
Flux	$\Phi = BA \cos \theta$	θ from area normal; signed quantity
Faraday / Lenz	$\varepsilon_{\text{avg}} = -N\Delta\Phi/\Delta t$	Induced current opposes the flux change
Moving rod	$\varepsilon = BLv$; $P_{\text{external}} = I^2 R$	Perpendicular geometry; closed circuit for sustained I

Do not confuse	What to check
B with Φ or ε	B is local field; Φ includes area/orientation; ε requires flux change
Field strength with energy-graph slope	Slope of accumulated energy is $P = \varepsilon^2/R$
A sign convention with a physical change	Reversing a chosen normal changes signs but not measured effects