

Unit 11: Electric Circuits

Unit 11 covers what happens when charge is set in motion. It starts with current and resistance, builds through Ohm's law and electric power, compares series and parallel arrangements, applies Kirchhoff's rules to multi-loop circuits, explains how meters connect to circuits, and finishes with RC circuits and real batteries.

AP Physics 2

Electric Circuits

About 15 minutes to read

How to use this guide

Read it in order the first time because the ideas stack. Current is defined first, then resistance describes what opposes it, Ohm's law relates the two, power follows from both, and series and parallel circuits are where all of it gets applied. Kirchhoff's rules are the general tool for circuits that are not simple series or parallel. Exam questions almost always give you a circuit diagram and ask what happens to current, voltage, or power when something changes.

After the first read, use the trap boxes and the comparison tables to review the distinctions that exam questions test 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. Electric Circuits is 15 to 18 percent of the AP Physics 2 exam, which makes it one of the heaviest units on the test. The series and parallel rules and Kirchhoff's rules also show up inside other units whenever a circuit diagram appears, so time spent here pays off elsewhere too.

11.1 Electric Current: Charge on the Move

Electric current is the rate at which charge flows past a point, $I = \Delta Q / \Delta t$. The unit is the ampere: one ampere is one coulomb per second. If a wire carries 2.0 A for 30 s, the charge that passes is $Q = I\Delta t = (2.0)(30) = 60 \text{ C}$.

Conventional current is defined as the direction positive charge would flow, from the positive terminal toward the negative terminal outside the battery. In a metal wire the actual moving charges are electrons, which drift the opposite way, from negative toward positive. Every circuit diagram, every current arrow, and every calculation on the exam uses conventional current, so draw and think in that direction even though you know the electrons go the other way.

The **drift velocity** of the electrons themselves is surprisingly slow, on the order of millimeters per second. The reason a light turns on instantly when you flip a switch is that the electric field signal travels through the wire near the speed of light and pushes every electron at once. The electrons barely move, but they all start moving together.

Trap. Current is not used up by resistors. Charge is conserved, so the current entering a resistor equals the current leaving it. A resistor takes energy from the current, not charge from it. If 2.0 A enters a bulb, 2.0 A leaves the bulb.

11.2 Resistance and Resistivity

Resistance measures how strongly a conductor opposes current, in ohms (Ω). The resistance of a wire depends on the material and its shape: $R = \rho L / A$, where ρ is the **resistivity** of the material, L is the length, and A is the cross-sectional area. Longer wires resist more, and thicker wires resist less.

Work it out for a copper wire ($\rho = 1.7 \times 10^{-8} \Omega \cdot \text{m}$) of length 2.0 m and radius 0.50 mm. The area is $A = \pi r^2 = \pi(5.0 \times 10^{-4})^2 \approx 7.85 \times 10^{-7} \text{ m}^2$, so $R = (1.7 \times 10^{-8})(2.0) / (7.85 \times 10^{-7}) \approx 0.043 \Omega$. Now watch what happens to that same wire. Doubling the length doubles the resistance to about 0.087 Ω . Doubling the radius makes the area four times larger, so the resistance falls to one quarter, about 0.011 Ω .

Trap. Resistance depends on the square of the radius because area goes as r^2 . Doubling the radius quarters the resistance, it does not halve it. Any question that changes a wire's diameter is testing whether you remembered the square.

11.3 Ohm's Law: Ohmic and Non-Ohmic Devices

Ohm's law states that for many conductors, the current is directly proportional to the voltage across them: $V = IR$, where V is the voltage across that resistor, I is the current through it, and R is its resistance. A device whose resistance stays constant as voltage changes is **ohmic**; its current-versus-voltage graph is a straight line through the origin.

Not everything obeys Ohm's law. An incandescent bulb filament is **non-ohmic** because its resistance rises as the filament heats up, so doubling the voltage does not double the current. A diode is non-ohmic because it conducts freely in one direction and blocks current in the other. When a question asks you to apply $V = IR$, it is assuming ohmic behavior unless it tells you otherwise.

Trap. The V in $V = IR$ is the voltage across that one resistor, not necessarily the battery voltage. In a circuit with several resistors, each resistor gets only part of the battery voltage. Applying $V_{\text{battery}} = IR_{\text{one resistor}}$ is one of the most common errors in this unit. Always match the voltage, current, and resistance to the same piece of the circuit.

11.4 Electric Power

Electric power is the rate at which electrical energy is converted to another form, such as heat or light: $P = IV$. Substituting $V = IR$ gives two more forms, $P = I^2R$ and $P = V^2/R$. All three are the same equation rearranged, and the unit is the watt: one watt is one joule per second.

Take a bulb with resistance $24\ \Omega$ connected across a 12 V battery. The current is $I = V/R = 12/24 = 0.50\text{ A}$. Now compute the power three ways to see the agreement: $P = IV = (0.50)(12) = 6.0\text{ W}$; $P = I^2R = (0.50)^2(24) = (0.25)(24) = 6.0\text{ W}$; $P = V^2/R = 144/24 = 6.0\text{ W}$. All three give the same 6.0 W , as they must.

Trap. Pick the power formula that uses what you actually know about that resistor. If you know the voltage across the resistor, use V^2/R . If you know the current through it, use I^2R . The classic mistake is using the battery voltage in V^2/R for a resistor that sits in a series string, where it only gets part of that voltage. The V in the formula must be the drop across the resistor whose power you want.

11.5 Series Circuits: One Path for Current

In a **series** circuit the resistors are connected end to end, so there is only one path and the same current flows through every resistor. The battery voltage is split among the resistors, with the larger resistor taking the larger share, and the voltages add up to the battery voltage. The equivalent resistance is the simple sum: $R_{\text{eq}} = R_1 + R_2 + \dots$

Work it out with a 12 V battery and two resistors, 4 Ω and 8 Ω , in series. The equivalent resistance is $R_{\text{eq}} = 4 + 8 = 12 \Omega$, so the current everywhere is $I = V/R_{\text{eq}} = 12/12 = 1.0 \text{ A}$. The voltage drops are $V_1 = IR_1 = (1.0)(4) = 4.0 \text{ V}$ and $V_2 = IR_2 = (1.0)(8) = 8.0 \text{ V}$, and they add to $4.0 + 8.0 = 12 \text{ V}$, the full battery voltage. The powers are $P_1 = I^2 R_1 = (1.0)^2(4) = 4.0 \text{ W}$ and $P_2 = (1.0)^2(8) = 8.0 \text{ W}$, and the total 12 W matches the power from the battery, $P = IV = (12)(1.0) = 12 \text{ W}$.

Trap. In series, the current is the same everywhere, but the voltage is not. Each resistor drops only its share. Also note what the numbers show: in series, the larger resistor dissipates more power, because $P = I^2 R$ with I fixed. That flips in parallel, which is the next section.

11.6 Parallel Circuits: One Voltage for All

In a **parallel** circuit the resistors sit side by side across the same two points, so every resistor feels the full battery voltage. The current splits, with the smaller resistor taking the larger share, and the branch currents add up to the total current from the battery. The equivalent resistance follows the reciprocal rule: $1/R_{\text{eq}} = 1/R_1 + 1/R_2 + \dots$ For two resistors this simplifies to $R_{\text{eq}} = (R_1 R_2) / (R_1 + R_2)$, the product over the sum.

Use the same components as before: a 12 V battery with 4 Ω and 8 Ω in parallel. The equivalent resistance is $R_{\text{eq}} = (4 \times 8) / (4 + 8) = 32/12 \approx 2.67 \Omega$. Each branch gets the full 12 V, so $I_1 = 12/4 = 3.0 \text{ A}$ and $I_2 = 12/8 = 1.5 \text{ A}$, and the total is $3.0 + 1.5 = 4.5 \text{ A}$. Check it against the equivalent resistance: $I = V/R_{\text{eq}} = 12/2.67 \approx 4.5 \text{ A}$, which agrees. The powers are $P_1 = V^2/R_1 = 144/4 = 36 \text{ W}$ and $P_2 = 144/8 = 18 \text{ W}$, and the total 54 W matches $P = IV = (12)(4.5) = 54 \text{ W}$.

Trap. The parallel formula gives a result smaller than the smallest branch resistor, never larger. If your computed R_{eq} for parallel resistors comes out bigger than any single branch, you added the reciprocals wrong or forgot to take the reciprocal at the end. Compare with the series example above: the same two resistors give 12 Ω in series but only 2.67 Ω in parallel, which is why the parallel circuit draws far more power from the same battery.

11.7 Series vs Parallel: Side by Side

PROPERTY	SERIES	PARALLEL
Current	The same through every resistor.	Splits among branches; branch currents add to the total.
Voltage	Splits among resistors; drops add to the battery voltage.	The same across every resistor, equal to the battery voltage.
Equivalent resistance	$R_{eq} = R_1 + R_2 + \dots$ Always larger than any one resistor.	$1/R_{eq} = 1/R_1 + 1/R_2 + \dots$ Always smaller than any one resistor.
If one resistor is removed	The circuit breaks. Everything goes out, like one string of old holiday lights.	The other branches keep working. Each branch is independent.
Which resistor uses more power	The larger resistor, since $P = I^2R$ with the same I .	The smaller resistor, since $P = V^2/R$ with the same V .

Read the numbers from the two worked examples together. The same $4\ \Omega$ and $8\ \Omega$ resistors across the same $12\ \text{V}$ battery draw $1.0\ \text{A}$ and $12\ \text{W}$ in series, but $4.5\ \text{A}$ and $54\ \text{W}$ in parallel. Parallel arrangements always draw more current from a given battery because the equivalent resistance is smaller. That is also why household outlets are wired in parallel: every appliance gets the full wall voltage, and switching one off does not interrupt the others.

11.8 Kirchhoff's Rules

Some circuits are neither simple series nor simple parallel, and for those you need **Kirchhoff's rules**, which are just conservation of charge and conservation of energy written for circuits.

The **junction rule** says that the total current entering a junction equals the total current leaving it. It is conservation of charge: charge cannot pile up at a point, so whatever flows in must flow out. The **loop rule** says that the sum of the voltage changes around any closed loop is zero. It is conservation of energy: a charge that travels around a loop and returns to its starting point must end with the same energy it began with, so every voltage rise from a battery is exactly canceled by voltage drops across resistors.

Here is a two-loop circuit worked with clean numbers. A 12 V battery drives current I_1 through a $2\ \Omega$ resistor, and a 9 V battery drives current I_2 through another $2\ \Omega$ resistor, and the two loops share a middle $2\ \Omega$ resistor carrying current I_3 . Label the currents so the junction rule at the shared node reads $I_1 + I_2 = I_3$. Going around the left loop gives $12 - 2I_1 - 2I_3 = 0$, so $I_1 + I_3 = 6$. Going around the right loop gives $9 - 2I_2 - 2I_3 = 0$, so $I_2 + I_3 = 4.5$. Substituting the junction equation into the sum of the two loop equations gives $I_3 = 3.5\text{ A}$, and then $I_1 = 2.5\text{ A}$ and $I_2 = 1.0\text{ A}$. The junction rule checks: $2.5 + 1.0 = 3.5$.

Now check energy, which is the point of the loop rule. The batteries supply $P = (12)(2.5) + (9)(1.0) = 30 + 9 = 39\text{ W}$. The resistors dissipate $P = 2(I_1^2 + I_2^2 + I_3^2) = 2(6.25 + 1.0 + 12.25) = 2(19.5) = 39\text{ W}$. Supply equals dissipation, exactly as conservation of energy requires.

Trap. Set up sign conventions before you write any loop equation and stick to them. When you traverse a resistor in the direction of its labeled current, the voltage change is $-IR$. When you traverse a battery from its negative terminal to its positive terminal, the change is $+ \mathcal{E}$; going the other way it is $- \mathcal{E}$. A negative current at the end is not a mistake, it just means the current actually flows opposite to the arrow you drew.

11.9 Meters: Ammeters and Voltmeters

An **ammeter** measures current, so it must be placed **in series** with the component whose current you want, and it must have **very low resistance**, ideally zero. A good ammeter lets the existing current pass through unchanged, the way a toll counter should not slow down the traffic it counts.

A **voltmeter** measures voltage, so it must be placed **in parallel** across the component whose voltage you want, and it must have **very high resistance**, ideally infinite. A good voltmeter draws almost no current, so it does not change the circuit it is measuring.

METER	CONNECTION	RESISTANCE	WHY
Ammeter	In series	Very low	It must carry the current it measures without adding resistance.
Voltmeter	In parallel	Very high	It must draw almost no current so the circuit is undisturbed.

Trap. Swapping the placements breaks the circuit or the measurement. An ammeter placed in parallel across a component gives current a near-zero-resistance shortcut, which can blow a fuse or the meter. A voltmeter placed in series blocks the current it was meant to let through, since its huge resistance chokes the whole branch. Match each meter to its row of the table.

11.10 Real Batteries: Internal Resistance

A real battery is not a perfect voltage source. It behaves like an ideal source of EMF $\mathcal{E}$ in series with a small **internal resistance** r . When the battery delivers current I , part of its EMF is dropped across its own internal resistance, so the **terminal voltage** available to the circuit is $V = \mathcal{E} - Ir$, which is always less than $\mathcal{E}$ while current flows.

For example, a 9.0 V battery with $1.0\ \Omega$ of internal resistance delivering 2.0 A has a terminal voltage of $V = 9.0 - (2.0)(1.0) = 7.0$ V. The missing 2.0 V is dropped inside the battery and appears as heat there. This is why a battery's voltage sags when you draw a large current from it, and why a nearly dead battery can still read full voltage on a meter but collapse under load.

11.11 RC Circuits: Charging and Discharging

An **RC circuit** has a resistor and a capacitor in series. The behavior is all about time: the capacitor charges or discharges gradually, not instantly.

When an uncharged capacitor is connected to a battery through a resistor, the charging current starts large and decays as charge builds up on the plates. The capacitor voltage rises toward the battery voltage, quickly at first and then more and more slowly, approaching it asymptotically. When a charged capacitor is disconnected from the battery and connected across a resistor instead, it discharges: the current and the capacitor voltage both decay toward zero, quickly at first and then slowly.

The **time constant** $\tau = RC$ sets the pace. After one time constant, a charging capacitor has reached about 63% of its final charge, and a discharging capacitor has fallen to about 37% of its starting charge. After roughly five time constants the process is essentially complete. For example, with $R = 10 \text{ k}\Omega$ and $C = 220 \text{ }\mu\text{F}$, the time constant is $\tau = RC = (1.0 \times 10^4)(2.2 \times 10^{-4}) = 2.2 \text{ s}$. Connected to a 9 V battery, the capacitor voltage after 2.2 s is about $0.63 \times 9 \approx 5.7 \text{ V}$, and after about 11 s (five time constants) it is essentially the full 9 V.

Physically, τ is the time the circuit needs to respond. A larger resistance slows the flow of charge onto the plates, and a larger capacitance needs more charge to reach a given voltage, so either one stretches the time out. One more fact that exam questions use: in steady state with a DC source, a fully charged capacitor carries no current, so it acts like an open switch and the resistor branch through it draws nothing.

Trap. Do not mix up the 63% and 37% figures. Charging climbs to 63% of full in one τ , because 63% of the charging is done. Discharging falls to 37% of full in one τ , because 37% of the charge remains. Also, τ is a time, not a rate: a bigger τ means a slower circuit, not a faster one.

Confusions That Cost Points

PAIR	HOW TO KEEP THEM STRAIGHT
Current vs voltage	Current is the flow of charge, measured in amperes. Voltage is the energy per charge driving it, measured in volts. Resistors do not use up current; they use up energy.
$V = IR$ for one resistor vs the whole circuit	The V , I , and R must all belong to the same piece of the circuit. Battery voltage pairs with equivalent resistance, never with one resistor in a string.
Series vs parallel equivalent resistance	Series adds directly and the result is bigger than any branch. Parallel adds reciprocals and the result is smaller than any branch. Sanity-check the size of your answer.
$P = I^2R$ vs $P = V^2/R$	Same current through the resistors means the bigger R wins, so use I^2R for series. Same voltage across them means the smaller R wins, so use V^2/R for parallel.
Ammeter vs voltmeter	Ammeter in series with low resistance, because it must carry the current. Voltmeter in parallel with high resistance, because it must not steal current.
Charging vs discharging in one τ	Charging reaches 63% of full. Discharging falls to 37% of full. Bigger τ means slower, not faster.
EMF vs terminal voltage	EMF is the battery's ideal voltage. Terminal voltage is what the circuit actually gets: $V = \mathcal{E} - Ir$, lower whenever current flows.

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. A wire carries a steady current of 2.0 A for 30 s. How much charge passes through a cross section of the wire in that time?

1. 60 C
2. 30 C
3. 15 C
4. 0.067 C

2. A copper wire has resistance R . The wire is replaced with one made of the same material but with twice the length and twice the radius. What is the resistance of the new wire?

1. $R/4$
2. $R/2$
3. $2R$
4. R

3. Two identical resistors are connected across the same battery, first in series and then in parallel. How does the total power dissipated in the parallel arrangement compare with the total power dissipated in the series arrangement?

1. The same
2. One quarter as large
3. Four times as large
4. Twice as large

4. A resistor has 6.0 V across it and dissipates 12 W. What is the current through the resistor?

1. 0.50 A
2. 72 A
3. 0.33 A
4. 2.0 A

5. At a junction in a circuit, a current of 3.0 A flows in. Two branches carry current out of the junction, and one branch carries 1.2 A. What current does the other branch carry?

1. 1.8 A
2. 4.2 A
3. 1.2 A
4. 3.0 A

6. To measure the current through a resistor, an ammeter must be connected ____ and must have ____ resistance.

1. in parallel / low
2. in series / low
3. in parallel / high
4. in series / high

7. An uncharged capacitor charges through a resistor. The time constant of the circuit is $\tau = RC = 2.0$ s. Approximately what fraction of its final charge does the capacitor hold after 2.0 s of charging?

1. 100%
2. 50%
3. 63%
4. 37%

8. A real battery has an EMF of 9.0 V and an internal resistance of $1.0\ \Omega$. While delivering 2.0 A to a circuit, what is the terminal voltage of the battery?

1. 9.0 V
2. 11 V
3. 4.5 V
4. 7.0 V

Answer Key

- 1. A.** From $I = \Delta Q/\Delta t$, the charge is $Q = I\Delta t = (2.0)(30) = 60$ C. B forgets the 2.0 A and reports just the time as if it were charge. C divides the current by 2 instead of multiplying. D divides current by time, computing $I/\Delta t$, which has no physical meaning here.
- 2. B.** From $R = \rho L/A$, doubling the length multiplies R by 2, and doubling the radius multiplies the area by 4, which divides R by 4. Together the factor is $2/4 = 1/2$, so the new resistance is $R/2$. C remembers only the length change and misses the area change. D assumes the two changes cancel, which would require the area to double rather than quadruple. A remembers only the radius change and misses the length change.
- 3. C.** Call each resistor R . In series, $R_{\text{eq}} = 2R$, so $P_{\text{series}} = V^2/(2R)$. In parallel, $R_{\text{eq}} = R/2$, so $P_{\text{parallel}} = V^2/(R/2) = 2V^2/R$, which is four times P_{series} . D only accounts for one of the two changes: it treats the equivalent resistance as halving once instead of comparing $2R$ against $R/2$. A assumes the arrangement does not matter, but the battery sees a different equivalent resistance in each case. B inverts the ratio, confusing which arrangement has the smaller equivalent resistance.
- 4. D.** From $P = IV$, the current is $I = P/V = 12/6.0 = 2.0$ A. A computes V/P instead of P/V . B multiplies P by V , which gives units of $\text{W}\cdot\text{V}$, not amperes. C divides P by V^2 , which is $1/R$, the conductance, not the current.
- 5. A.** The junction rule is conservation of charge: current in equals current out, so $3.0 = 1.2 + I$, giving $I = 1.8$ A. B adds the incoming and known outgoing currents instead of subtracting. C assumes the two branches must carry equal current, but the junction rule only constrains the sum. D reports the incoming current as if the second branch carried nothing.
- 6. B.** An ammeter measures current, so it must be in series with the resistor to carry the current being measured, and its resistance must be low so it does not change that current. C describes a voltmeter, not an ammeter. D gets the connection right but would add significant resistance in series, choking the very current being measured. A is the most dangerous error: a low-resistance ammeter in parallel gives the current a near-zero-resistance shortcut around the component.
- 7. C.** After one time constant, a charging capacitor reaches about 63% of its final charge. D is the discharging figure: after one τ , a discharging capacitor has fallen to 37% of its starting charge. A assumes the capacitor charges instantly, but the resistor limits how fast charge can arrive. B splits the difference with no physical basis; the 63% comes from $1 - 1/e$, not from a guess.
- 8. D.** The terminal voltage is $V = \mathcal{E} - Ir = 9.0 - (2.0)(1.0) = 7.0$ V. The internal resistance drops 2.0 V while current flows. A ignores the internal resistance entirely, which is only correct for an ideal battery or an open circuit. B adds the Ir drop instead of subtracting it. C halves the EMF, confusing internal resistance with something like a voltage divider that splits the EMF evenly.

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 Electric Circuits 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 Electric Circuits deck and let spaced review bring them back over the next few days.

- State $I = \Delta Q / \Delta t$ in words and compute the charge for 2.0 A over 30 s.
- Explain conventional current and why it points opposite to electron drift.
- Explain why a light turns on instantly even though drift velocity is tiny.
- Write $R = \rho L / A$ and predict the effect of doubling length and doubling radius.
- State Ohm's law and describe two non-ohmic devices and why each is non-ohmic.
- Explain why the V in $V = IR$ must belong to the same resistor as the I and R .
- Write all three power formulas and say when each one is the right choice.
- Work the 12 V, $4\ \Omega + 8\ \Omega$ series example from scratch: R_{eq} , I , both drops, both powers.
- Work the same components in parallel from scratch and check the total current two ways.
- State Kirchhoff's junction rule and loop rule, and name the conservation law behind each.
- Explain the sign convention for resistors and batteries when writing a loop equation.
- State where an ammeter and a voltmeter connect and what resistance each must have.
- Explain what happens if an ammeter is placed in parallel or a voltmeter in series.
- Describe charging and discharging in an RC circuit and state what $\tau = RC$ means.
- State the 63% and 37% rules and which one applies to charging versus discharging.
- Explain terminal voltage $V = \mathcal{E} - Ir$ and why a battery sags under load.

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 Electric Circuits 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

Electric current, Ampere, Conventional current, Drift velocity, Resistance, Resistivity, Ohm's law, Ohmic device, Non-ohmic device, Electric power, Watt, Series circuit, Parallel circuit, Equivalent resistance, Kirchhoff's junction rule, Kirchhoff's loop rule, Ammeter, Voltmeter, RC circuit, Time constant, Internal resistance, EMF, Terminal voltage.

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