Cambridge (CIE) A Level Physics

Your notes

Kirchhoff's Laws

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Your notes

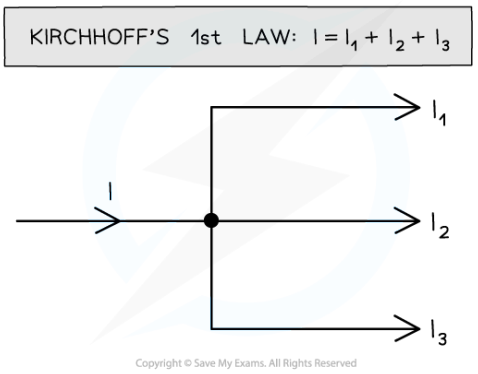
Kirchhoff's first law

- Kirchhoff's first law states that:

The sum of the currents entering a junction is always equal to the sum of the currents leaving the same junction

- This is a consequence of conservation of **charge** – current shouldn't decrease or increase in a circuit when it splits
- In a circuit:
  - A **junction** is a point where at least three circuit paths meet
  - A **branch** is a path connecting two junctions
- If a circuit splits into two branches, then the current before the circuit splits should be equal to the current after it has split
- The circuit below illustrates Kirchhoff's first law:

Kirchhoff's first law

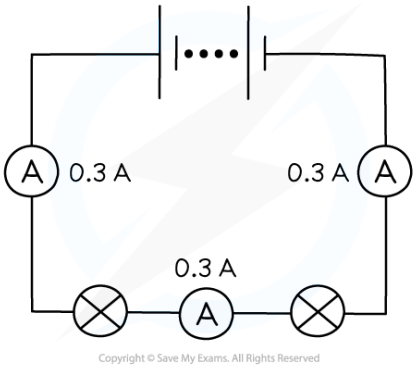


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The current I into the junction is equal to the sum of the currents out of the junction

- The charge is conserved on both sides of the junction
- In a **series** circuit, the current is the same at any point

Current in a series circuit

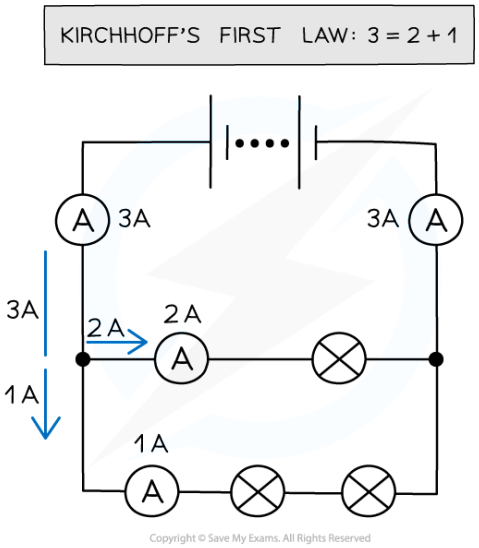


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The current is the same at all points in a series circuit

- In a **parallel** circuit, the current divides at the junctions and each branch has a different value. Kirchhoff's first law applies at each junction

Current in a parallel circuit



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The current divides at each junction in a parallel circuit

Examiner Tips and Tricks

Junctions only appear in parallel circuits, and as circuits become more complex, it can be confusing as to which currents are into the junction and which are out.

Drawing arrows on the diagram for the current flow (making sure it's from positive to negative) at each junction like in the worked example will help with this.

Your notes

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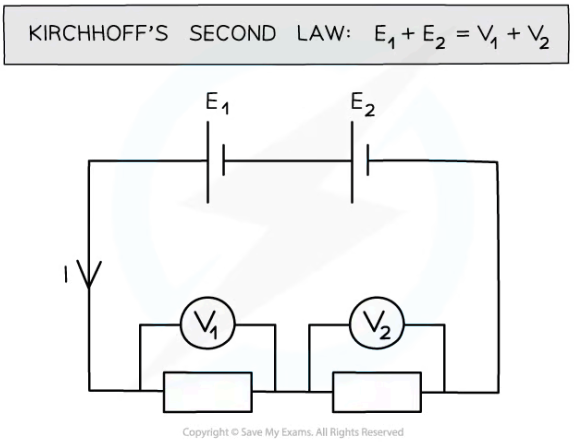
Kirchhoff's second law

- Kirchhoff's second law states that:

The total e.m.f in a closed circuit is equal to the sum of the potential differences across the components

- This is a consequence of conservation of **energy**
- The energy transferred **into** the circuit is equal to the energy transferred **out** of the circuit
- The circuit below illustrates Kirchhoff's second law:

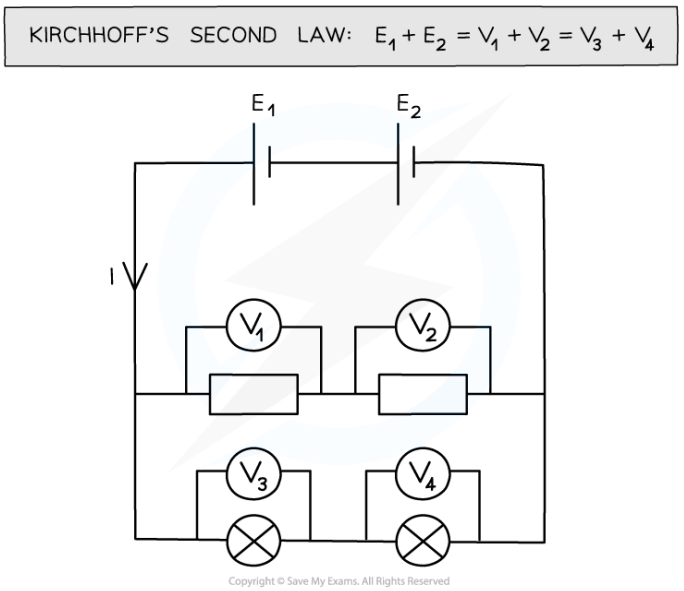
Kirchhoff's second law in a series circuit



The sum of the potential difference across the individual components is equal to the sum of the e.m.f supplied by the batteries

- In a **series** circuit, the potential difference is split across all components depending on their resistance
  - The sum of the potential difference across each component is equal to the total e.m.f of the power supply
- In a **parallel** circuit, the potential difference is the same across each closed loop
  - The sum of the potential difference **in each closed circuit loop** is equal to the total e.m.f of the power supply:

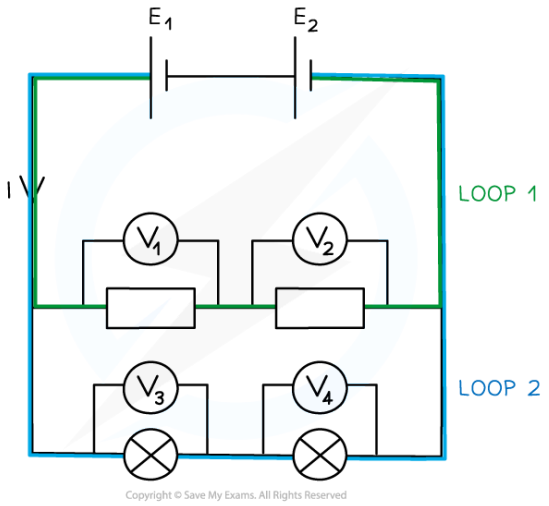
Kirchhoff's second law in a parallel circuit



The total potential difference across the components is the sum of the potential difference across each individual component

- A closed circuit loop acts as its own independent series circuit and each one separates at a junction. A parallel circuit is made up of two or more of these loops

Loops in a parallel circuit



Each circuit loop acts as a separate, independent series circuit

- This makes parallel circuits incredibly useful for home wiring systems
- A single power source supplies all lights and appliances with the same potential difference
- If one light breaks, current can still flow through the rest of the lights and appliances

Your notes

Your notes

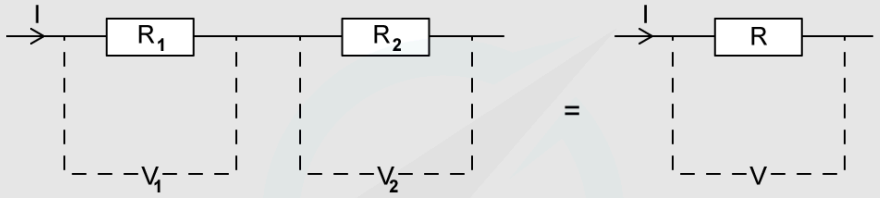
Deriving the equation for resistors in series

- In a **series** circuit, the **combined resistance** of two or more resistors is the **sum** of the **individual resistances**
- In a series circuit:
  - The **current** is the **same** through all resistors
  - The **potential difference** is **shared** between all the resistors
- The equation for combined resistors in series is derived using Kirchhoff's laws:

Derivation for resistors in series

CONSIDER TWO RESISTORS R_1 AND R_2 CONNECTED IN SERIES.
A SINGLE RESISTOR R IS EQUIVALENT TO THEM.

FROM KIRCHHOFF'S FIRST LAW: THE CURRENT I THROUGH EACH RESISTOR IS THE SAME SINCE THEY'RE CONNECTED IN SERIES (NO JUNCTIONS)



FROM KIRCHHOFF'S SECOND LAW: THE TOTAL p.d OF BOTH RESISTORS IN A CLOSED CIRCUIT LOOP MUST EQUAL THE SUM OF THE p.ds (THE p.d ACROSS THE SINGLE RESISTOR)

$$V = V_1 + V_2$$

FROM OHM'S LAW, POTENTIAL DIFFERENCE IS GIVEN BY THE PRODUCT OF CURRENT AND RESISTANCE

$$IR = IR_1 + IR_2$$

SINCE CURRENT I IS THE SAME FOR ALL RESISTORS, DIVIDING BY I

$$R = R_1 + R_2$$

THIS EQUATION CAN BE EXTENDED SO THE EQUIVALENT RESISTOR R OF SEVERAL RESISTORS CONNECTED IN SERIES IS GIVEN BY

$$R = R_1 + R_2 + R_3 + R_4 \ldots$$

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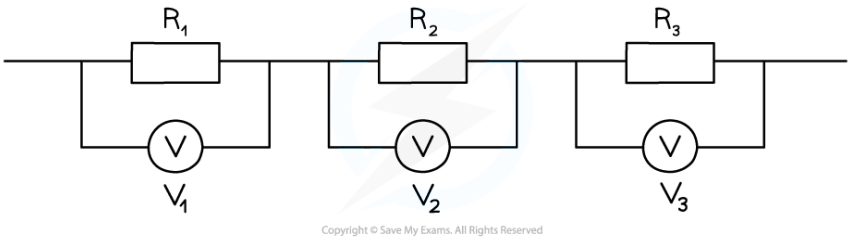
Resistors in series

Your notes

- When two or more components are connected in series:

  The combined resistance of the components is equal to the sum of the individual resistances

Resistors in series



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Resistors connected in series each have their own separate potential difference

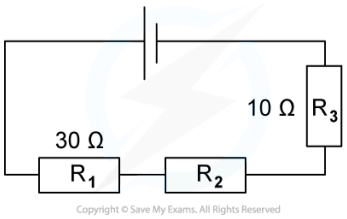
- The equation for the combined resistance, R of resistors in series is:

$$R = R_1 + R_2 + ...$$

Worked Example

The combined resistance R in the following series circuit is 60 Ω.

What is the resistance value of R_2?



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A. 100 Ω

B. 30 Ω

C. 20 Ω

D. 40 Ω

Answer: C

Step 1: State the equation for the combined resistance for resistors in series

$$R = R_1 + R_2 + ... = R_1 + R_2 + R_3$$

Step 2: Rearrange for resistance R_2

$$R_2 = R - (R_1 + R_3)$$

Step 3: Substitute the values

$$R_2 = 60 - (30 + 10) = 20\,\Omega$$



Your notes

Your notes

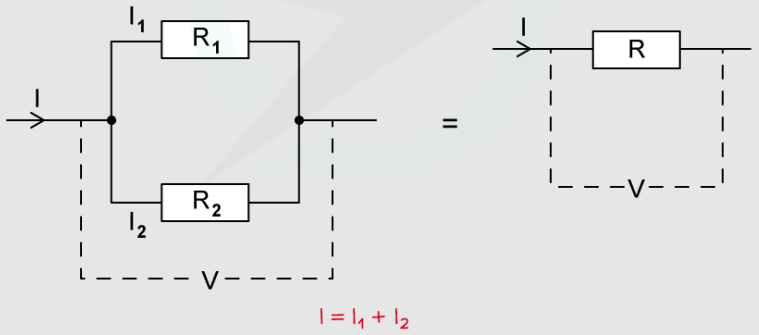
Deriving the equation for resistors in parallel

- In a **parallel** circuit, the **reciprocal** of the **combined resistance** of two or more resistors is the **sum** of the **reciprocal** of the **individual resistances**
- In a parallel circuit:
  - The **current** is **split** at the junction (and therefore between resistors)
  - The **potential difference** is the **same** through all resistors
- The equation for combined resistors in parallel is derived using Kirchhoff's laws:

Derivation for resistors in parallel

CONSIDER TWO RESISTORS R_1 AND R_2 CONNECTED IN PARALLEL. A SINGLE RESISTOR R IS EQUIVALENT TO THEM.

FROM KIRCHHOFF'S FIRST LAW: THE CURRENT THROUGH EACH RESISTOR WILL BE DIFFERENT DUE TO THE CURRENT SPLITTING AT THE JUNCTION. THE CURRENT THROUGH THE EQUIVALENT RESISTOR R WILL BE THE TOTAL CURRENT I



$I = I_1 + I_2$

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FROM KIRCHHOFF'S SECOND LAW, THE P.D ACROSS EACH RESISTOR IN DIFFERENT BRANCHES IS THE SAME.
THE RESISTOR R WILL HAVE THAT SAME p.d ACROSS IT TOO

$$V = V_1 = V_2$$

REARRANGING OHM'S LAW V = IR FOR CURRENT I

$$I = \frac{V}{R}$$

$$\frac{V}{R} = \frac{V}{R_1} + \frac{V}{R_2}$$

SINCE POTENTIAL DIFFERENCE V IS THE SAME FOR ALL RESISTORS, DIVIDING BY V

$$\frac{I}{R} = \frac{I}{R_1} + \frac{I}{R_2}$$

THIS EQUATION CAN BE EXTENDED SO THE EQUIVALENT RESISTOR R OF SEVERAL RESISTORS CONNECTED IN PARALLEL IS GIVEN BY

$$\frac{I}{R} = \frac{I}{R_1} + \frac{I}{R_2} + \frac{I}{R_3} \cdots$$

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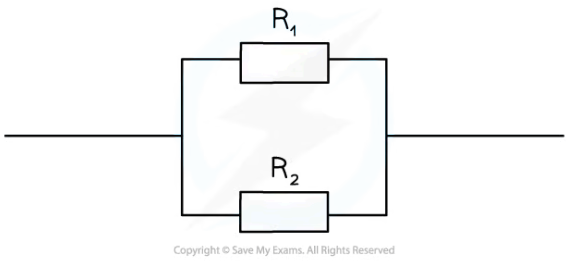
Your notes

Resistors in parallel

- When two or components are connected in parallel:

  The reciprocal of the combined resistance is the sum of the reciprocals of the individual resistances

Resistors in parallel



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Resistors connected in parallel have the same voltage

- The equation for the combined resistance, R of resistors in parallel is:

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \ldots$$

- This means the combined resistance decreases and is less than the resistance of any of the individual components

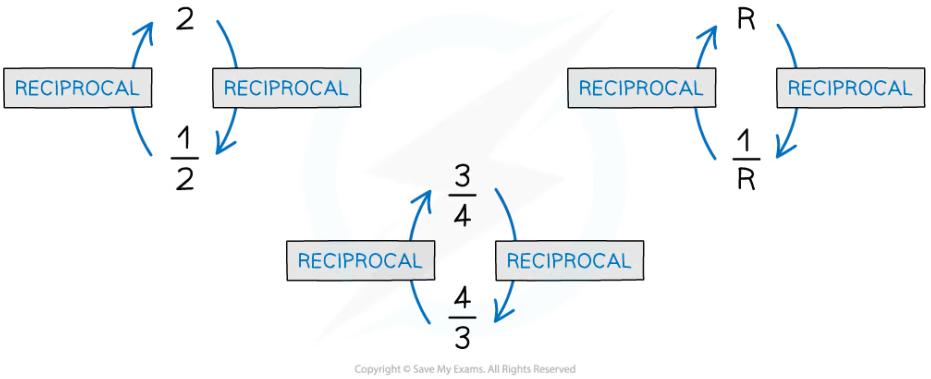
- For example, If two resistors of equal resistance are connected in parallel, then the combined resistance will halve

Your notes

Maths tip

- The reciprocal of a value is $\frac{1}{value}$
- For example, the reciprocal of a whole number such as 2 equals $\frac{1}{2}$
  - The reciprocal of $\frac{1}{2}$ is 2
- If the number is already a fraction, the numerator and denominator are 'flipped' round

Reciprocals



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The reciprocal of a number is 1 ÷ number

- In the case for the resistance R, this becomes $\frac{1}{R}$. To get the value of R from $\frac{1}{R}$, you must calculate $\frac{1}{your\ answer}$
- You can also use the reciprocal button on your calculator (labelled either x^{-1} or $\frac{1}{x}$, depending on your calculator

Worked Example

The circuit below shows 3 resistors connected in parallel.

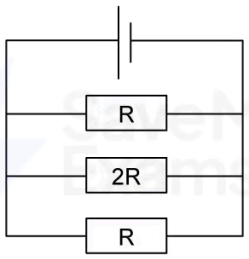
Which value gives the combined resistance of all the resistors in this circuit?

A. $\frac{5R}{2}$

B. $\frac{2}{5R}$

C. $\frac{5}{2R}$

D. $\frac{2R}{5}$



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Answer: D

Step 1: Resistors in parallel equation

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + ... = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

Step 2: Substitute in the values given from the equation

$$\frac{1}{R_T} = \frac{1}{R} + \frac{1}{2R} + \frac{1}{R} = \left(1 + \frac{1}{2} + 1\right)\frac{1}{R} = \frac{5}{2R}$$

Step 3: Calculate the total resistance

$$\frac{1}{R_T} = \frac{5}{2R}$$

$$R_T = \frac{2R}{5}$$

Examiner Tips and Tricks

The most common mistake is to leave the answer as $1/R_T$. Remember to calculate $\frac{1}{answer}$ to get the value of R_T.

Your notes

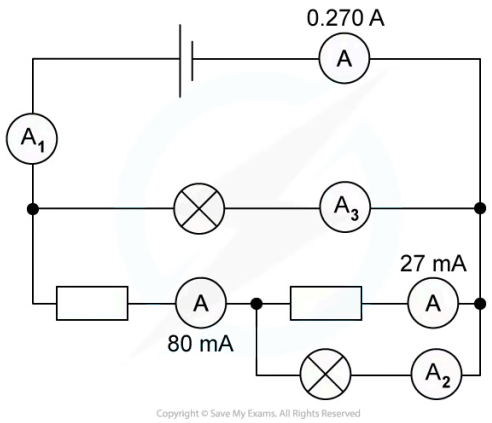
Your notes

Solving problems with Kirchhoff's laws

- Kirchhoff's laws can be used to solve simple circuit problems

Worked Example

For the circuit below, state the readings of ammeters A_1, A_2 and A_3.



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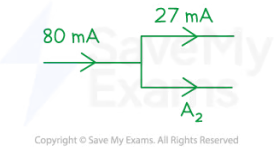
Answer:

Step 1: Calculate the current through ammeter A_1

- The 0.270 A and A_1 are connected in series
- The current entering the cell must equal the current out of it at A_1
- Therefore A_1 = 0.270 A

Step 2: Calculate the current through ammeter A_2

- From Kirchhoff's first law, the total current into a junction must equal the total current out of it



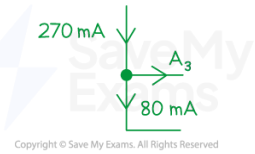
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$$80\ \text{mA} = 27\ \text{mA} + A_2$$

$$A_2 = 80 - 27 = 53\ \text{mA}$$

Step 3: Calculate the current through ammeter A_3

- Applying Kirchhoff's first law again gives:



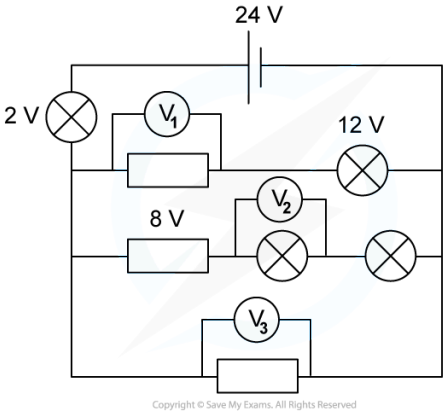
$$270\ \text{mA} = A_3 + 80\ \text{mA}$$

$$A_3 = 270 - 80 = 190\ \text{mA}$$

Worked Example

For the circuit below, state the readings of the voltmeters V_1, V_2 and V_3.

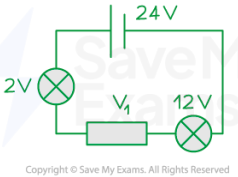
All the lamps and resistors have the same resistance.



Answer:

Step 1: Calculate the potential difference shown by voltmeter V_1

- Kirchhoff's second law states that the sum of the three components is equal to the e.m.f of the supply

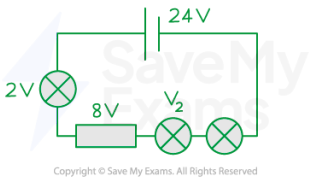


$$2\ \text{V} + V_1 + 12\ \text{V} = 24\ \text{V}$$

$$V_1 = 24 - 12 - 2 = 10\ \text{V}$$

Step 2: Calculate the potential difference shown by voltmeter V_2

- Applying Kirchhoff's second law to this loop
- Both lamps have the same resistance *R* and the same current *I* through them so they share the energy equally and have the same potential difference



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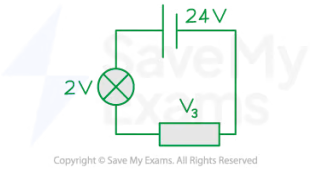
$$24\,\text{V} = 2\,\text{V} + 8\,\text{V} + (2\text{V}_2)$$

$$2\text{V}_2 = 24 - 2 - 8 = 14\,\text{V}$$

$$\text{V}_2 = \frac{14}{2} = 7\,\text{V}$$

Step 3: Calculate the potential difference shown by voltmeter V_3

- Applying Kirchhoff's second law to this loop



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$$24\ V = 2\,\text{V} + \text{V}_3$$

$$\text{V}_3 = 24 - 2 = 22\,\text{V}$$

Your notes