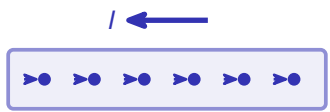
Electricity

AS Physics ▪ Topic 9

A-Level Physics



What we will cover

1. Current and charge 9.1
2. P.d. and power 9.2
3. Resistance and Ohm's law 9.3
4. Resistivity and sensors 9.3.1
5. Recap

1 Current and charge

Sheet 9.1 – what you need to know

You must be able to:

- describe a current as a flow of charge carriers
- say whether a charge is possible: charge is quantised
- use $Q = It$, and count the electrons that carry a charge
- use $I = Anvq$ to find a drift speed, in thick and thin wires

What the exam asks

"Determine an expression, in terms of some or all of the symbols e, L, N, R and V, for the current in the wire." **[1]**

"State and explain whether the average drift speed of the free electrons in wire Y is greater than, the same as, or less than that in wire X." **[3]**

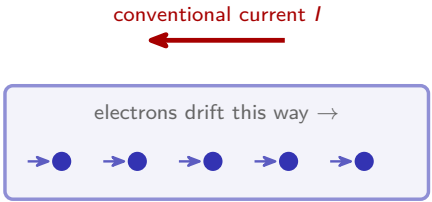
Practise on exercise sheet 9.1, then try the real exam questions on past-paper sheet 9.1.

Electric current

Current 电流 is a flow of **charge carriers** 载流子.

- metal: conduction **electrons** 电子
- electrolyte: positive & negative **ions** 离子

> Conventional current flows the way positive charge would – opposite to the electrons in a wire.



Charge and current

Charge is **quantised** 量子化: every free charge is a whole-number multiple of the **elementary charge** 基本电荷 $e = 1.60 \times 10^{-19}\,\mathrm{C}$, measured in **coulombs** 库仑. **Current** 电流 is the rate of flow of charge past a point:

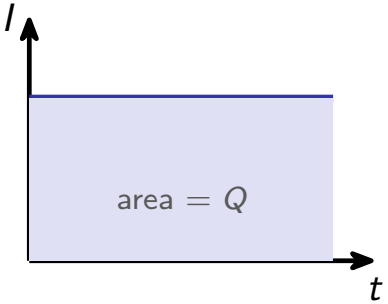
$$I = \frac{Q}{t}, \qquad Q = It$$

$0.50\,\mathrm{A}$ for 2.0 min

$$Q = It = (0.50\,\mathrm{A})(120\,\mathrm{s}) = 60\,\mathrm{C}$$

$$N = \frac{Q}{e} = \frac{60\,\mathrm{C}}{1.60 \times 10^{-19}\,\mathrm{C}} \approx 3.8 \times 10^{20}$$

electrons



Is this charge possible?

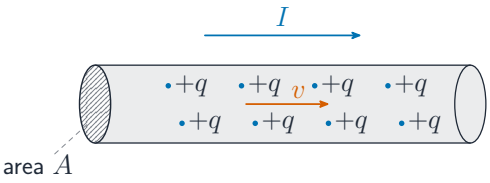
Charge is quantised: any free charge is a whole number of elementary charges, $Q = Ne$ with $e = 1.60 \times 10^{-19}\,\mathrm{C}$.

Divide by e and look for a whole number

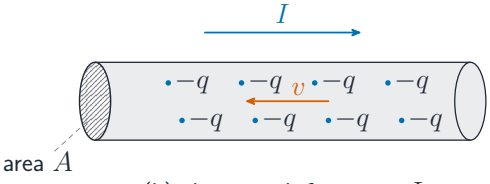
$$N = \frac{Q}{e} = \frac{4.8 \times 10^{-19}\,\mathrm{C}}{1.60 \times 10^{-19}\,\mathrm{C}} = 3\text{: possible}$$

$$N = \frac{Q}{e} = \frac{4.0 \times 10^{-19}\,\mathrm{C}}{1.60 \times 10^{-19}\,\mathrm{C}} = 2.5\text{: impossible}$$

Drift velocity



(a) positive carriers drift with I



(b) electrons drift against I

$$I = A\,n\,v\,q$$

A is the **cross-sectional area** 横截面积, n the **number density** 数密度 of carriers, q their charge and v the **drift velocity** 漂移速度.

Same I in a thinner wire $\Rightarrow$ faster drift.

Copper, $A = 10^{-6}\,\mathrm{m}^2$**,** $I = 5.0\,\mathrm{A}$

$v \approx 3.7 \times 10^{-4}\,\mathrm{m\,s^{-1}}$ – under $1\,\mathrm{mm}$ per second

A drift speed

Copper: $A = 1.0 \times 10^{-6}\,\mathrm{m}^2$, $I = 5.0\,\mathrm{A}$, $n = 8.5 \times 10^{28}\,\mathrm{m}^{-3}$

rearrange $I = Anvq$: $v = \dfrac{I}{Anq}$

$$v = \frac{I}{Anq} = \frac{5.0\,\mathrm{A}}{(1.0 \times 10^{-6}\,\mathrm{m}^2)(8.5 \times 10^{28}\,\mathrm{m}^{-3})(1.60 \times 10^{-19}\,\mathrm{C})} = 3.7 \times 10^{-4}\,\mathrm{m\,s}^{-1}$$

Half the diameter gives a quarter of the area, so the same current drifts four times faster in the thin part: $v \propto \dfrac{1}{A}$.

2 P.d. and power

Sheet 9.2 – what you need to know

You must be able to:

- define potential difference and the volt, and use $V = \dfrac{W}{Q}$
- use $P = VI$, $P = I^2R$ and $P = \dfrac{V^2}{R}$, whichever fits the data
- find the energy transferred, $W = Pt = VIt$
- compare the power in components in series and in parallel

What the exam asks

"Define electric potential difference across a component." **[1]**

"State and explain which resistor dissipates more power." **[3]**

Practise on exercise sheet 9.2, then try the real exam questions on past-paper sheet 9.2.

Potential difference and e.m.f.

Voltage 电压 is energy transferred per unit charge, measured in **volts** 伏特:

$$V = \frac{W}{Q}, \qquad [V] = \mathrm{V} = \mathrm{J\,C^{-1}}.$$

e.m.f. 电动势

energy given to the charge by the source

p.d.

energy given up to a component

Electrical power

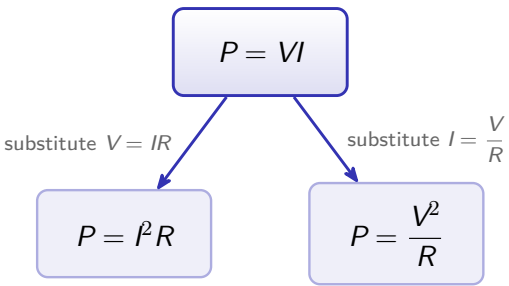
$$P = VI = I^2R = \frac{V^2}{R}$$

Pick the form for the quantities you know.

Kettle "$2.4\,\mathrm{kW}$, $240\,\mathrm{V}$"

$$I = \frac{P}{V} = \frac{2400\,\mathrm{W}}{240\,\mathrm{V}} = 10\,\mathrm{A}$$

$$R = \frac{V^2}{P} = \frac{(240\,\mathrm{V})^2}{2400\,\mathrm{W}} = 24\,\Omega$$



Which resistor takes more power?

In parallel across $12\,\mathrm{V}$: the same p.d.

$$P_{10} = \frac{V^2}{R} = \frac{(12\,\mathrm{V})^2}{10\,\Omega} = 14.4\,\mathrm{W}$$

$$P_{20} = \frac{V^2}{R} = \frac{(12\,\mathrm{V})^2}{20\,\Omega} = 7.2\,\mathrm{W}$$

Same V: the smaller resistance takes more.

In series at $0.40\,\mathrm{A}$: the same current

$$P_{10} = I^2 R = (0.40\,\mathrm{A})^2(10\,\Omega) = 1.6\,\mathrm{W}$$

$$P_{20} = I^2 R = (0.40\,\mathrm{A})^2(20\,\Omega) = 3.2\,\mathrm{W}$$

Same I: the larger resistance takes more.

Two words the definitions turn on

E.m.f.	The **electromotive force** 电动势 (e.m.f.) of a source is the energy given per unit charge by the source; potential difference is the energy *delivered* per unit charge to a component.
Potential divider	Put a thermistor or LDR in a **potential divider** 分压器 and the output voltage changes with temperature or light – the standard sensing circuit.
In parallel	Two resistors in **parallel** 并联 across the same **voltage** 电压: the *smaller* resistance takes more power, since $P = V^2/R$.

E.m.f. and p.d. share a unit and a symbol but not a meaning. Say "per unit charge" in both definitions, and name which way the energy goes.

3 Resistance and Ohm's law

Sheet 9.3 – what you need to know

You must be able to:

- define resistance and the ohm, and use $V = IR$
- state Ohm's law, and use $R = \dfrac{V}{I}$ even when it does not hold
- sketch and explain the I–V graphs of a metal, a filament lamp and a diode
- explain why a filament's resistance rises with the current

What the exam asks

"Define resistance." **[1]**

"State and explain how the resistance of the lamp changes." **[1]**

"State and explain the effect, if any, on the resistance of a filament wire in a lamp as the current in the wire decreases." **[1]**

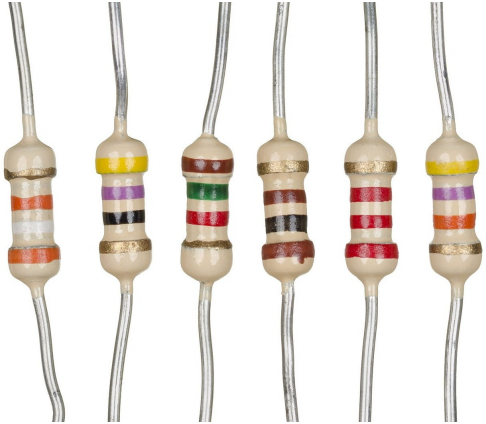
Practise on exercise sheet 9.3, then try the real exam questions on past-paper sheet 9.3.

Resistance and Ohm's law

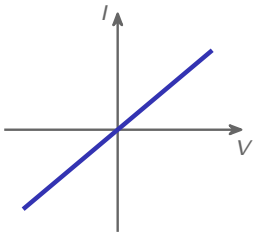
$$R = \frac{V}{I}, \qquad [R] = \Omega = \mathrm{V\,A^{-1}}.$$

> Ohm's law: $I \propto V$ *at constant temperature* – then R is constant (a straight I–V line).

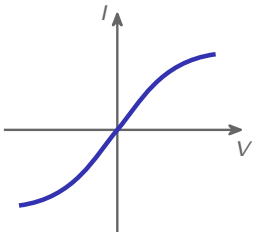
$R = V/I$ defines R for *any* component; only ohmic ones keep it constant. A metal's resistivity rises with temperature – more **lattice vibration** 晶格振动 **scatters** 散射 the electrons. An **insulator** 绝缘体 sits near $10^{15}\,\Omega\,\mathrm{m}$.



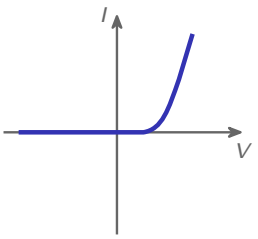
I–V characteristics



metal: straight



lamp: R rises

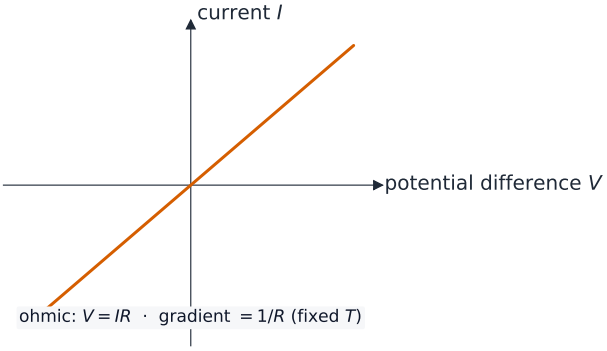


diode: switch-on

A hotter **filament lamp** 灯丝灯泡 has more resistance; a **diode** 二极管 conducts only above $\sim 0.7\,\mathrm{V}$.

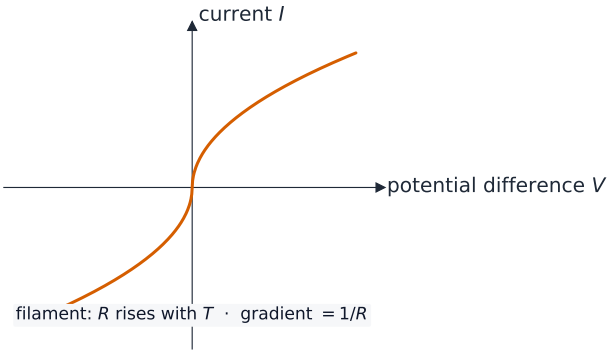
Characteristic 1 – a metal wire

Straight through the origin: R is constant, so the wire obeys Ohm's law (provided its temperature does not change).



Characteristic 2 – a filament lamp

The curve bends over: as the current heats the filament its resistance rises, so equal steps in V buy less and less current.



A filament lamp's resistance

A lamp takes $0.50\,\mathrm{A}$ at $6.0\,\mathrm{V}$ and $0.20\,\mathrm{A}$ at $1.0\,\mathrm{V}$.

> Use $R = \dfrac{V}{I}$ at the point, never the gradient of the I–V graph.

The definition at each point

at $6.0\,\mathrm{V}$: $R = \dfrac{V}{I} = \dfrac{6.0\,\mathrm{V}}{0.50\,\mathrm{A}} = 12\,\Omega$

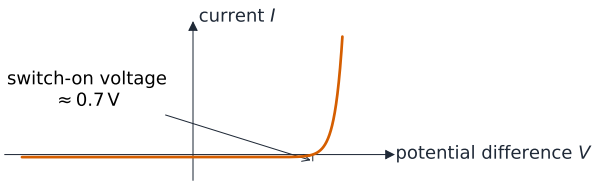
at $1.0\,\mathrm{V}$: $R = \dfrac{V}{I} = \dfrac{1.0\,\mathrm{V}}{0.20\,\mathrm{A}} = 5.0\,\Omega$

a smaller current, a cooler filament, a lower resistance

Characteristic 3 – a diode

A **semiconductor diode** 半导体二极管 conducts one way only, and only above about $0.6\,\mathrm{V}$.

> In reverse the current is negligible until breakdown – which is why a diode can turn a.c. into d.c.



Si diode: conducts above ≈ 0.7 V · reverse blocks

4 Resistivity and sensors

Sheet 9.3.1 – what you need to know

You must be able to:

- use $R = \dfrac{\rho L}{A}$, with the area from the diameter
- find the resistance of a stretched wire, and of a block between different faces
- find a resistivity from the gradient of a resistance–length graph
- state how an NTC thermistor and an LDR respond to heat and light

What the exam asks

"State and explain which resistor is made of wire with the larger cross-sectional area." **[2]**

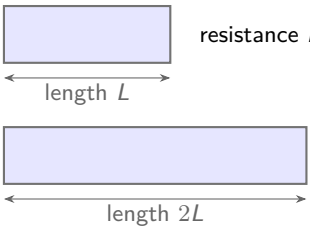
"State the effect of this change on the resistance of the lightning rod." **[1]**

"State and explain how the resistance of wire Q compares with the resistance of wire P." **[4]**

Practise on exercise sheet 9.3.1, then try the real exam questions on past-paper sheet 9.3.1.

Resistivity

same area A – twice the length gives twice R



$R \propto L$

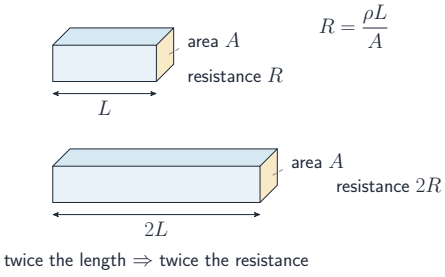
$$R = \frac{\rho L}{A}$$

ρ is the **resistivity** 电阻率 (a material property, $\Omega\,\mathrm{m}$).

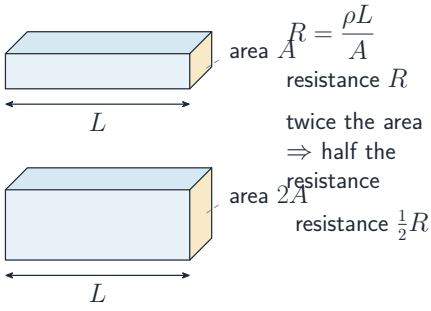
Copper: $L = 2.0\,\mathrm{m}$, $A = 1.7 \times 10^{-7}\,\mathrm{m}^2$

$$R = \frac{\rho L}{A} = \frac{(1.7 \times 10^{-8}\,\Omega\,\mathrm{m})(2.0\,\mathrm{m})}{1.7 \times 10^{-7}\,\mathrm{m}^2} = 0.20\,\Omega$$

What $R = \rho L/A$ is saying



Twice the length, twice the resistance.



Twice the area, half the resistance.

ρ is the **resistivity** 电阻率, a property of the material alone, in $\Omega\,\mathrm{m}$; R also depends on the shape.

A stretched wire

Stretching does not change the volume of metal, so AL stays the same: a longer wire is also thinner.

> Double the length: half the area, so four times the resistance.

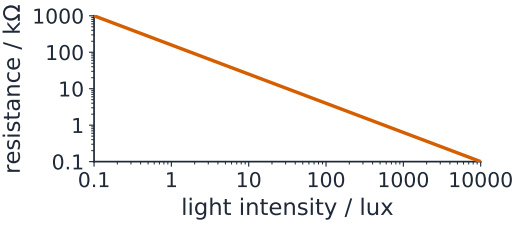
Stretched until its diameter is 90% of the old value

$A \propto d^2$: $\dfrac{A'}{A} = 0.90^2 = 0.81$

AL constant: $\dfrac{L'}{L} = \dfrac{1}{0.81} = 1.23$

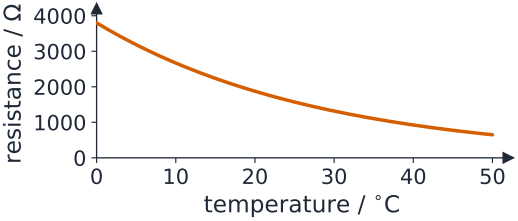
$R' = \dfrac{\rho L'}{A'} = \dfrac{\rho(1.23L)}{0.81A} = 1.5\,R$

Light-dependent resistor and thermistor



LDR: more light ⇒ lower R

LDR 光敏电阻*: R falls as light rises*



NTC: R falls as T rises

thermistor 热敏电阻*: R falls as temp. rises*

Both are semiconductors: light or heat frees more carriers, so R falls – the opposite of a metal.

5 Recap

Exam tips

- Use $I = Q/t$, $V = W/Q$ (energy per unit charge) and $P = VI = I^2R = V^2/R$.
- **Ohm's law ($V = IR$)** applies only to an ohmic conductor at constant temperature – a filament lamp is non-ohmic.
- Sketch and interpret the *I-V* **characteristics** of a resistor, filament lamp and diode.
- An **LDR's** resistance falls with light; a **thermistor's** falls as temperature rises.

Topic 9 – key takeaways

1 Current

$I = Q/t = Anvq$; conventional = positive flow

2 Power

$P = VI = I^2R = V^2/R$

3 Resistance

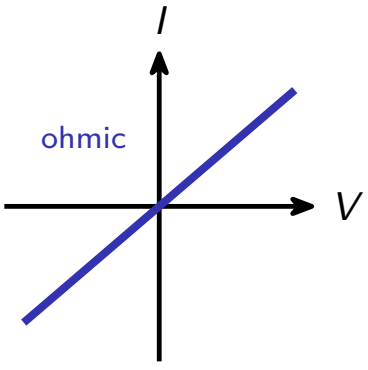
$R = V/I = \rho L/A$; Ohm's law if T constant

4 Sensors

LDR and thermistor: R falls with light / heat

Check yourself

1. Charge passing in $10\,\mathrm{s}$ at $2.0\,\mathrm{A}$?
2. Three forms of the power equation?
3. Why does a filament lamp's I–V line curve?
4. What happens to an LDR's R in the dark?



Answers **1.** $Q = It = 20\,\mathrm{C}$ **2.** VI, I^2R, V^2/R **3.** R rises as it heats **4.** rises (to MΩ)