Electricity

A-Level Physics

Electric current

An **electric current** 电流 is a flow of **charge carriers** 载流子. In a metal the carriers are negative conduction **electrons** 电子; in an **electrolyte** 电解质 they are positive and negative **ions** 离子; in a **semiconductor** 半导体 they may be electrons or "**holes**" 空穴. The **conventional current** 常规电流 direction is the way **positive** charge would flow — opposite to the real flow of electrons in a wire.

Charge

Charge is **quantised** 量子化: the smallest free unit of charge is the **elementary charge** 基本电荷

$$e = 1.60 \times 10^{-19}\ \text{C}.$$

Every free charge in this syllabus is a whole-number multiple of e. The unit of charge is the **coulomb** 库仑, C.

Current as the rate of flow of charge

If charge Q passes a point in time t, the current is

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

Unit of current: ampere, A ($=$ C s^{-1}). For a changing current, the charge that has flowed in a time is the **area under** an I–t graph.

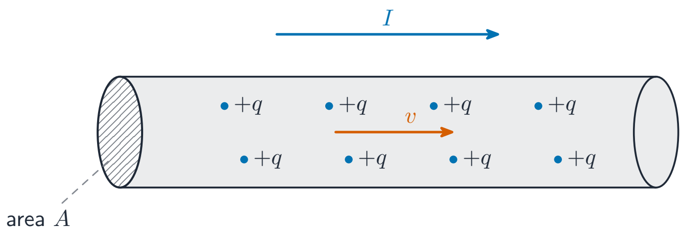
Worked example. A current of 0.50 A flows for 2.0 minutes. Find the charge that passes, and how many electrons this represents. ($e = 1.60 \times 10^{-19}$ C.)

$$Q = It = 0.50 \times 120 = 60\ \text{C}, \qquad N = \frac{Q}{e} = \frac{60}{1.60 \times 10^{-19}} \approx 3.8 \times 10^{20}.$$

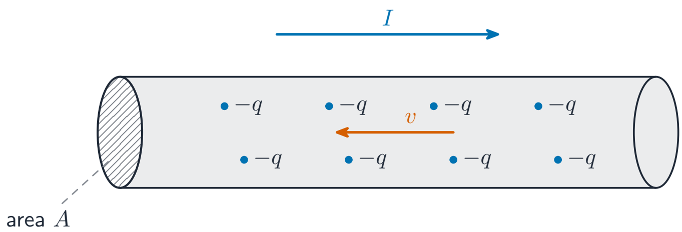
Drift velocity equation

For a uniform conductor of cross-section area A, with n charge carriers per unit volume (the **number density** 数密度), each carrying charge q, moving with average **drift velocity** 漂移速度 v:

$$I = Anvq.$$



(a) positive carriers drift with I



(b) electrons drift against I

Charge carriers drifting inside a conductor: positive carriers drift with I, electrons against it

Worked example. A copper wire of cross-sectional area 1.0×10^{-6} m^2 carries a current of 5.0 A. Copper has $n = 8.5 \times 10^{28}$ free electrons per m^3. Find the drift velocity. ($e = 1.60 \times 10^{-19}$ C.)

Rearranging $I = Anvq$ gives $v = \dfrac{I}{Anq}$:

$$v = \frac{5.0}{(1.0 \times 10^{-6})(8.5 \times 10^{28})(1.60 \times 10^{-19})} \approx 3.7 \times 10^{-4} \text{ m s}^{-1}.$$

The electrons drift very slowly — less than a millimetre per second.

Use this to compare currents:

- a thinner wire (smaller A) at the same I needs a faster drift v.

- a semiconductor has far fewer free carriers than a metal (smaller n), so for the same I the drift velocity is much larger.
- in **series** 串联 components, I is the same everywhere, so if A stays the same but the material changes, nv changes the other way.

Potential difference

The **potential difference** 电势差 (p.d.) across a component is the **energy** 能量 transferred per unit charge as that charge passes through it:

$$V = \frac{W}{Q}.$$

Unit: **volt** 伏特, V (= J C^{-1}).

If 1 J of electrical energy changes into other forms (thermal, light, kinetic, ...) when 1 C of charge passes through a component, the p.d. across it is 1 V.

The **electromotive force** 电动势 (e.m.f.) of a source is the energy given **per unit charge by the source**. The formula is the same as for p.d.; the difference is direction: e.m.f. is energy given **to** the charge by the source; p.d. is energy given **up** by the charge to the component.

Electrical power

High-voltage power lines carry electrical energy across the country.

Combining $V = W/Q$ and $I = Q/t$:

$$P = \frac{W}{t} = VI.$$

Using Ohm's law $V = IR$:

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

Pick the form with the quantities you know. Examples:

- two heaters of equal resistance — the one with the larger current gives more **power** 功率 ($P = I^2R$).
- two resistors in **parallel** 并联 across the same **voltage** 电压 — the one with smaller R gives more power ($P = V^2/R$).
- a kettle marked "2.4 kW, 240 V" draws $I = P/V = 10$ A and has resistance $R = V^2/P = 24\ \Omega$.

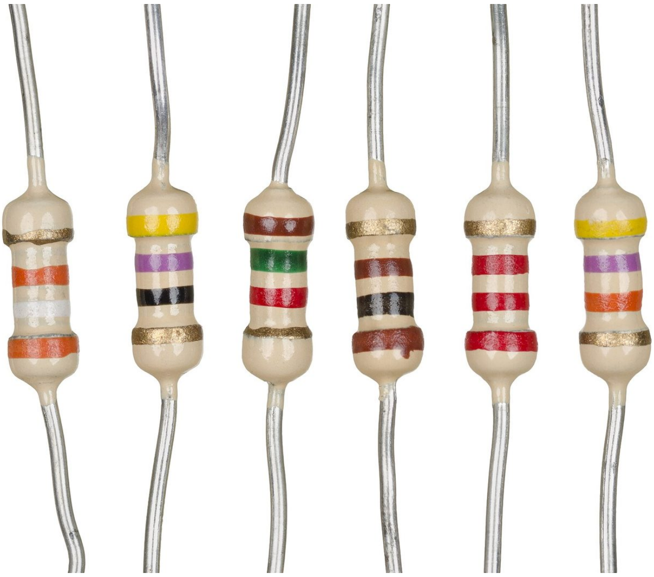
Energy transferred in time t is $E = Pt$.

Resistance and Ohm's law

The **resistance** 电阻 R of a component is

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

Unit: **ohm** 欧姆, Ω ($=$ V A^{-1}). Resistance depends on the conditions (such as temperature) when it is measured.



Real fixed resistors — the coloured bands code the resistance in ohms

Ohm's law

A conductor obeys **Ohm's law** 欧姆定律 when the current through it is **proportional to the p.d.** across it, as long as the conditions (especially temperature) stay constant. For such a conductor R is constant and the I–V graph is a straight line through the origin.

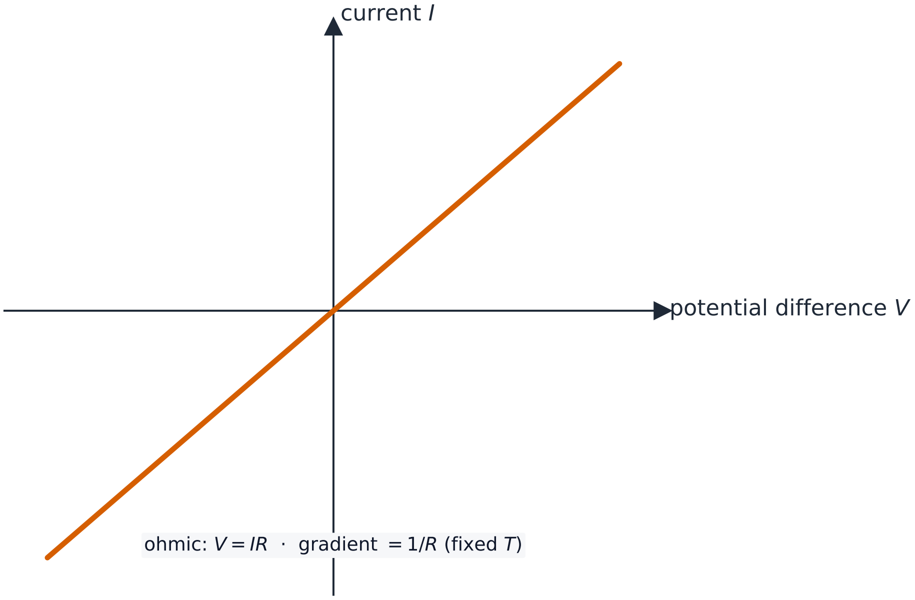
Ohm's law is an experimental result, not a definition. The definition $R = V/I$ works for **any** component; only ohmic ones have constant R.

I–V characteristics

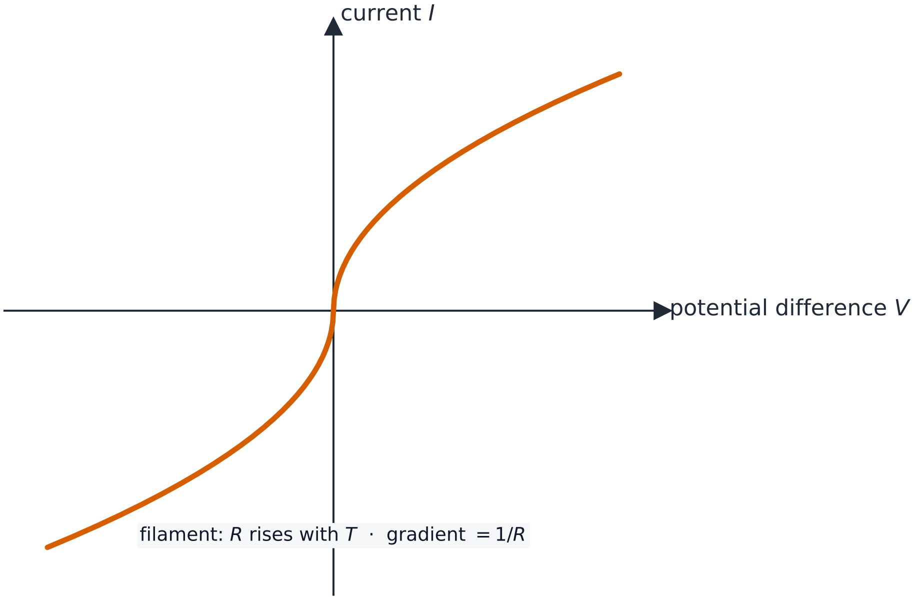
You should be able to sketch these:

- **metal wire at constant temperature** — a straight line through the origin (constant R). Reversing the p.d. drives the current the other way, giving a straight line in both directions.

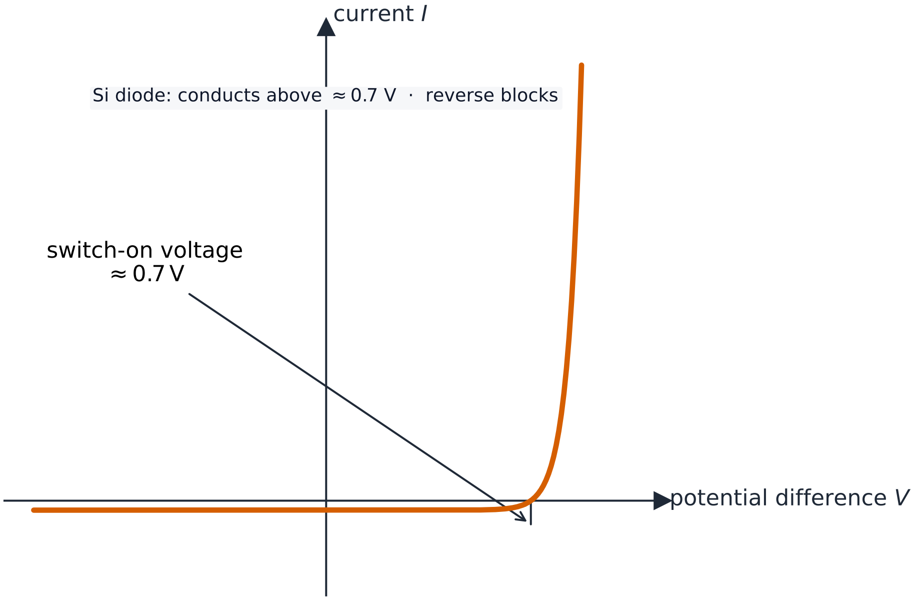
- **filament lamp** 灯丝灯泡 — through the origin, steep at first, then flatter as V (and I) grow. Reason: more current heats the filament, so its resistance rises and the gradient $1/R$ falls.
- **semiconductor diode** 二极管 — almost no current for negative V or small positive V. Above a "switch-on" voltage (about 0.7 V for silicon), the current rises sharply.



I–V characteristic of an ohmic conductor (metal wire at constant temperature)



I–V characteristic of a filament lamp



I–V characteristic of a semiconductor diode

Resistivity

For a uniform conductor of length L and cross-section area A,

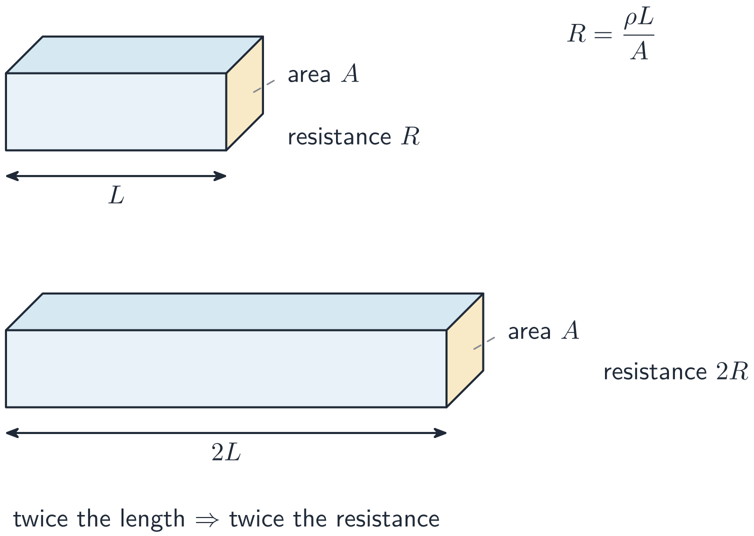
$$R = \frac{\rho L}{A}.$$

ρ is the **resistivity** 电阻率, a property of the material, with unit Ω m. Doubling the length doubles R; doubling the area halves it; halving the diameter quarters the area and so makes R four times bigger.

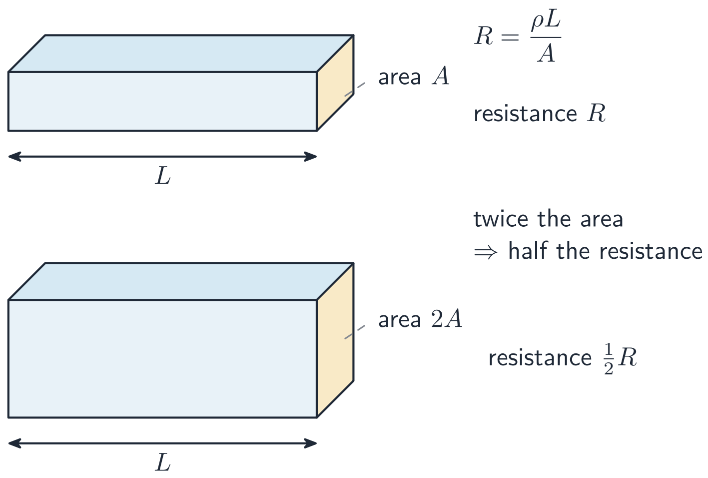
Worked example. A copper wire of length 2.0 m and cross-sectional area 1.7×10^{-7} m^2 has resistivity 1.7×10^{-8} Ω m. Find its resistance.

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

Typical values: copper at room temperature $\rho \sim 1.7 \times 10^{-8}$ Ω m; an **insulator** 绝缘体 $\rho \sim 10^{15}$ Ω m or more.



A longer conductor has more resistance — doubling L doubles R

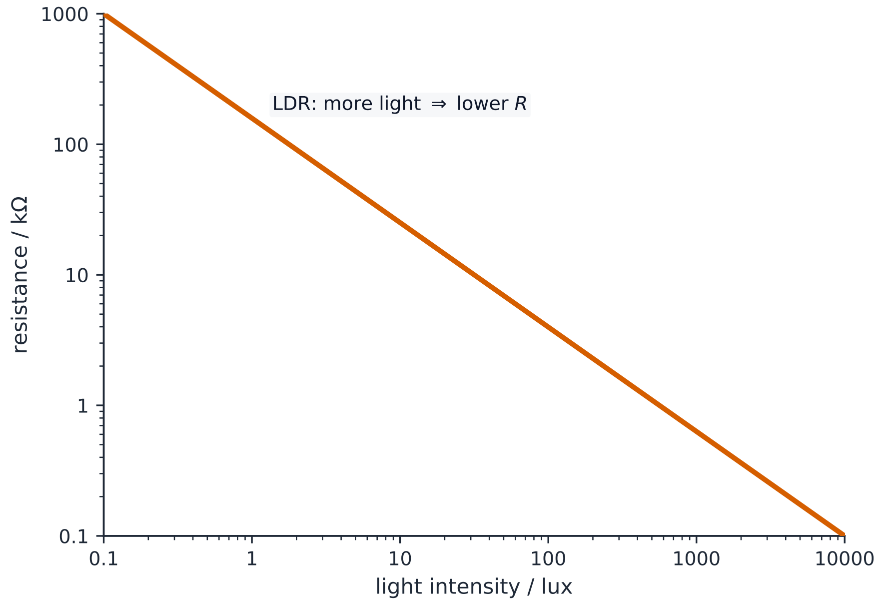


A wider conductor has less resistance — doubling A halves R

The resistivity of a metal **rises with temperature** (more **lattice vibration** 晶格振动 **scatters** 散射 the electrons), which is why the filament lamp's I–V line curves.

Light-dependent resistor (LDR)

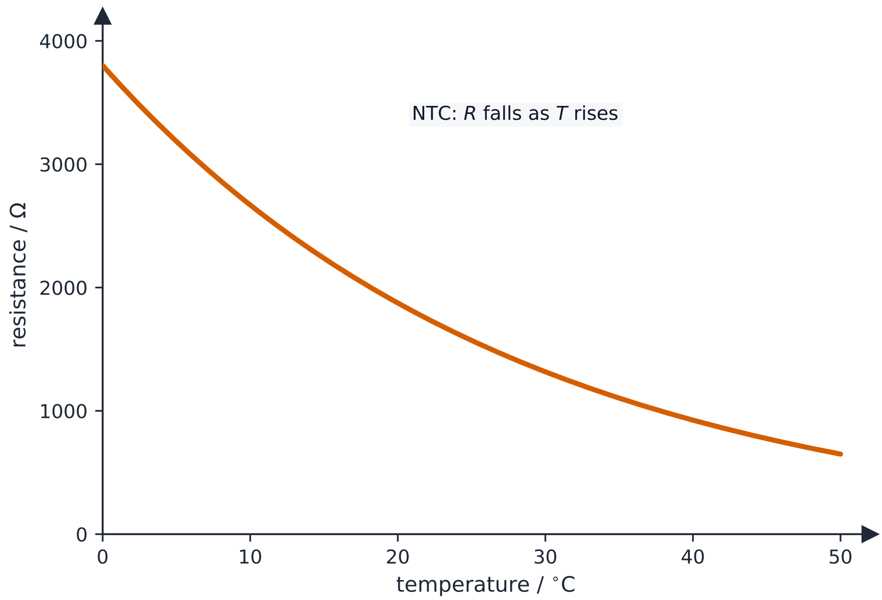
A **light-dependent resistor** 光敏电阻 (LDR) is a semiconductor whose **resistance falls as the light intensity rises**. In bright light R may be a few hundred Ω; in the dark it can be in the megaohms. LDRs are used in light-sensing circuits (street lamps, camera light meters). Here the **light intensity** 光强 controls the resistance.



Resistance of an LDR decreases as light intensity increases

Thermistor

In this syllabus a **thermistor** 热敏电阻 has a **negative temperature coefficient** 负温度系数: its **resistance falls as its temperature rises**. This is useful for sensing temperature — put it in a **potential divider** 分压器 and the output voltage changes with temperature.



Resistance of a thermistor falls as temperature rises

This is the opposite of a metal: in a semiconductor, more thermal energy frees more charge carriers, and this matters more than the extra scattering.

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.