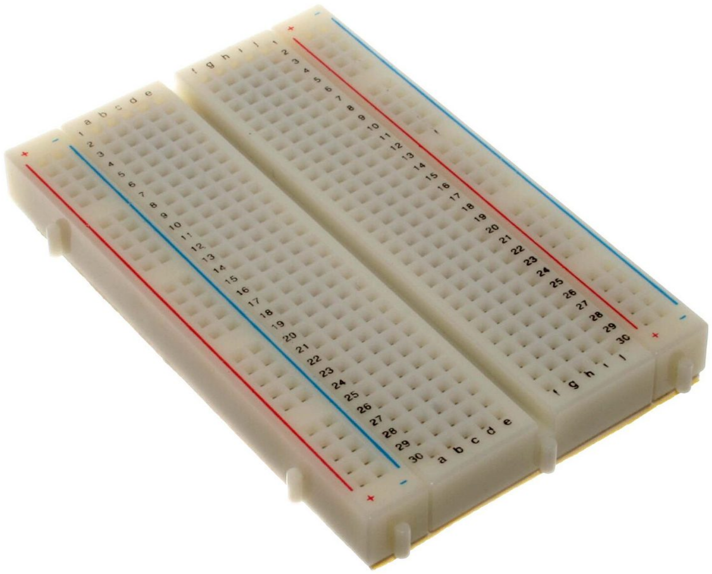
D.C. circuits

A-Level Physics

Practical circuits



A breadboard lets you build and test practical circuits without soldering.

Image: oomlout, CC BY-SA 2.0 (commons.wikimedia.org)

e.m.f. and p.d.

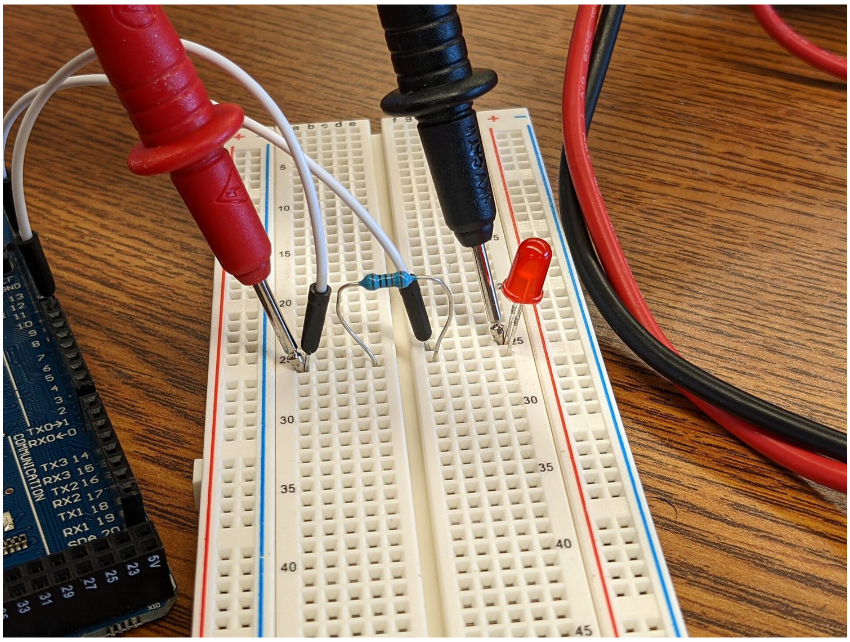
The **electromotive force** 电动势 (e.m.f.) ε of a source is the **energy** 能量 given to each unit of charge by the source as it drives the charge around a full circuit. Unit: volt.

The **potential difference** 电势差 (p.d.) across a component is the energy changed from electrical to other forms by each unit of charge as it passes through that component.

Both are in volts; they differ in energy direction:

- e.m.f. —energy put **into** the circuit by the source (chemical $\rightarrow$ electrical in a battery, mechanical $\rightarrow$ electrical in a generator).
- p.d. —energy taken **out** of the electrical form (electrical $\rightarrow$ thermal in a resistor, $\rightarrow$ light in a lamp, $\rightarrow$ kinetic in a motor).

In the lab you often build a circuit on a **breadboard** 面包板 (a board with rows of holes that connect components without soldering) and measure currents and p.d.s with a **multimeter** 万用表.



A real circuit on a breadboard, being measured with a multimeter

Internal resistance

A real source has some **internal resistance** 内阻 r —usually the resistance of the **electrolyte** 电解质 in a **cell** 电池, or the wire windings in a generator. When current I flows, an internal p.d. of Ir is "lost" inside the source, so the **terminal p.d.** 端电压 across the outside circuit is

$$V_{\text{terminal}} = \varepsilon - Ir.$$

So:

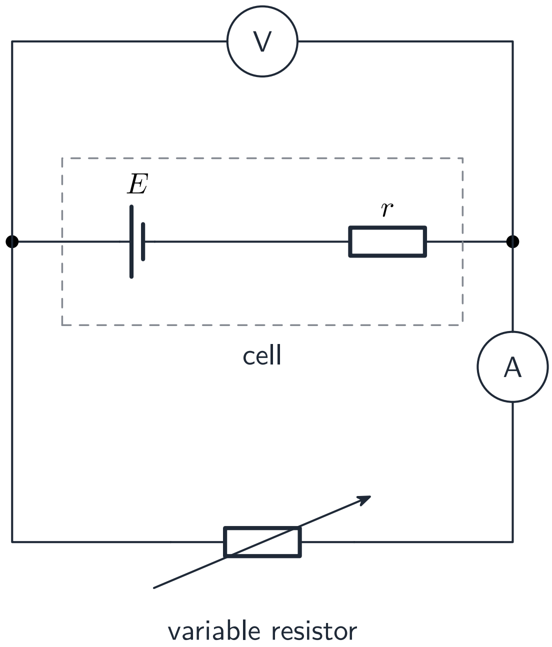
- **no current** (**open circuit** 开路, $I = 0$): the terminal p.d. equals the e.m.f.
- **larger current**: the terminal p.d. falls.
- **short circuit** 短路 ($R_{\text{external}} \to 0$): $I = \varepsilon/r$, a large current, with all the energy turned to heat inside the source.

To measure r, change the outside resistance and plot V_{terminal} against I: the line has y-intercept ε and gradient $-r$.

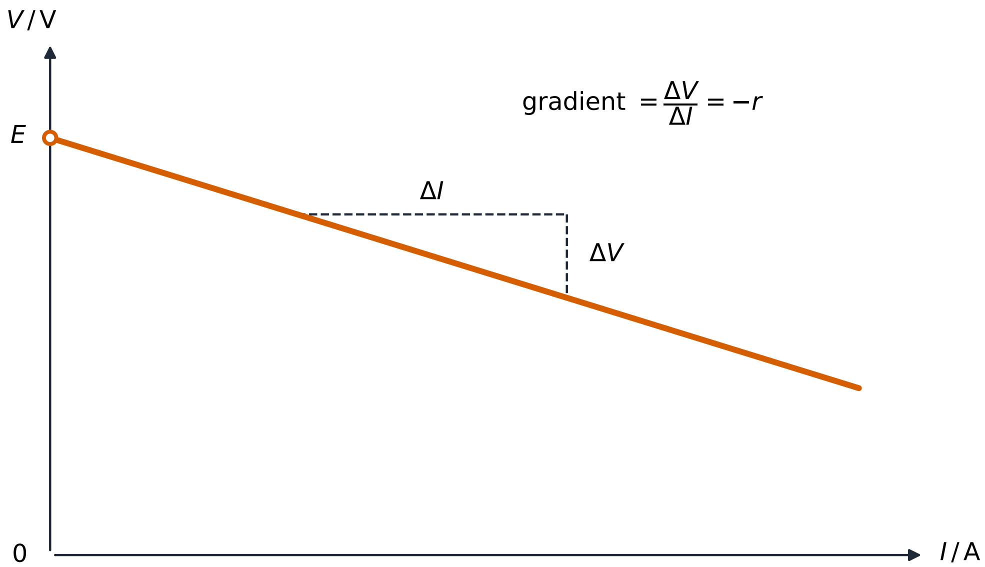
Worked example. A cell of e.m.f. 1.5 V and internal resistance 0.50 Ω is connected to a 2.5 Ω resistor. Find the current and the terminal p.d.

The e.m.f. drives the current through both resistances: $I = \dfrac{\varepsilon}{R + r} = \dfrac{1.5}{2.5 + 0.50} = 0.50$ A. Then

$$V_{\text{terminal}} = \varepsilon - Ir = 1.5 - 0.50 \times 0.50 = 1.25 \text{ V}.$$



Circuit for measuring the e.m.f. and internal resistance of a cell



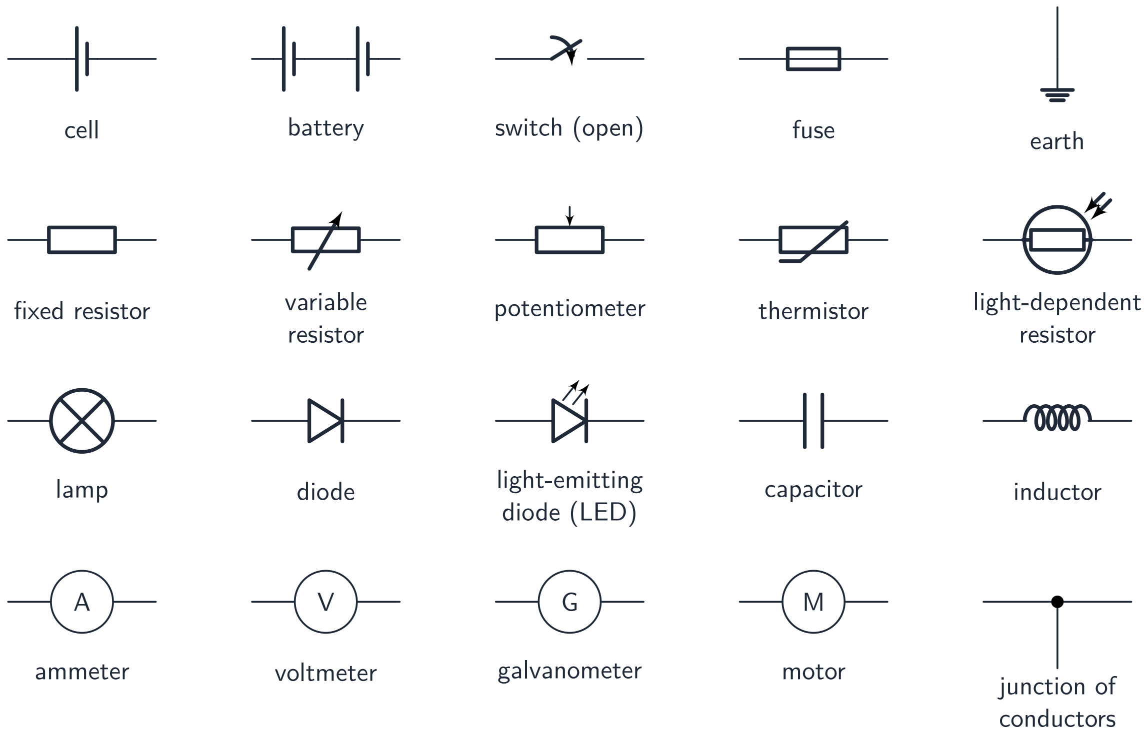
Terminal p.d. against current —the intercept is the e.m.f. and the gradient is minus the internal resistance

The **power** 功率 given to the outside load is $P_{\text{ext}} = (\varepsilon - Ir)I$; the power lost inside is $P_{\text{int}} = I^2r$; the total power from the source is εI.

Circuit symbols

You must recognise and draw the standard symbols in the syllabus: cell, battery, switch, resistor, variable resistor, **ammeter** 电流表, **voltmeter** 电压表, lamp, **diode** (and **LED** 发光二极管), **capacitor** 电容器, inductor, thermistor, light-dependent resistor, **fuse** 保

险丝, earth, junction. An ideal ammeter has zero **resistance** 电阻 and goes in **series** 串联. An ideal voltmeter has infinite resistance and goes in **parallel** 并联.



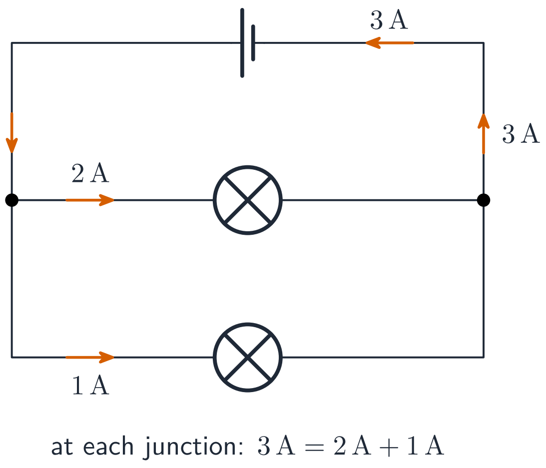
The standard circuit symbols you need to recognise and draw

Kirchhoff's laws

First law (junction rule)

At any **junction** 节点, **the total current flowing in equals the total current flowing out**. This follows from **conservation of charge** 电荷守恒—charge cannot build up at a point in a steady circuit, so charge in per second equals charge out per second.

For a junction with three wires: $I_1 = I_2 + I_3$ if currents 2 and 3 flow out and current 1 flows in.



Current divides at a junction in a parallel circuit (3 A in equals 2 A plus 1 A)

Second law (loop rule)

Around **any closed loop** 回路, **the total e.m.f. equals the total p.d. across the components in that loop**. This follows from **conservation of energy** 能量守恒: as a unit of charge goes once round a loop, the energy it gains from sources equals the energy it gives up to components.

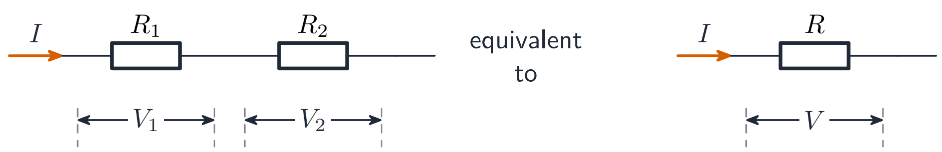
Pick a direction round the loop. Take an e.m.f. as positive when the loop direction goes from − to + of the source, and a p.d. as positive when the loop direction is the conventional current direction through the resistor.

Combining resistors

Resistors in series carry the same current; the total p.d. is the sum:

$$\varepsilon = IR_1 + IR_2 + \ldots = I(R_1 + R_2 + \ldots),$$

so $R_{\text{series}} = R_1 + R_2 + \ldots$.

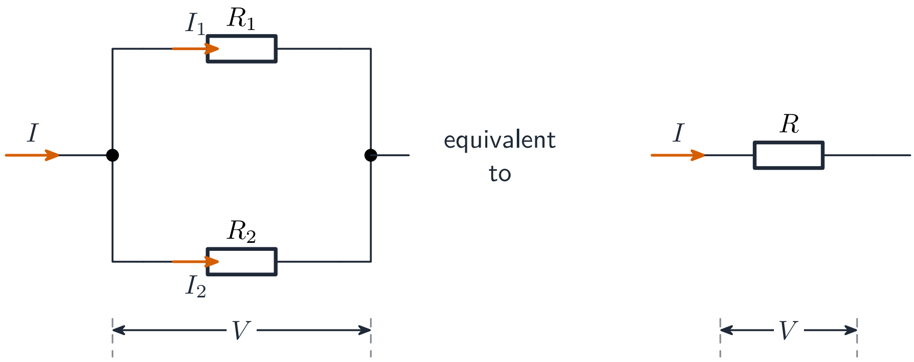


Two resistors in series and their single equivalent resistor

Resistors in parallel have the same p.d.; the total current is the sum:

$$I = \frac{V}{R_1} + \frac{V}{R_2} + \ldots = V\left(\frac{1}{R_1} + \frac{1}{R_2} + \ldots\right),$$

so $\dfrac{1}{R_{\text{parallel}}} = \dfrac{1}{R_1} + \dfrac{1}{R_2} + \dots$.



Two resistors in parallel and their single equivalent resistor

Two equal resistors R in parallel give $R/2$; N equal ones give R/N. A parallel combination is **always smaller** than any of its resistors; a series combination is always larger.

Worked example. A 4.0 Ω resistor and a 12 Ω resistor are connected in parallel. Find their combined resistance.

$$\frac{1}{R} = \frac{1}{4.0} + \frac{1}{12} = \frac{3}{12} + \frac{1}{12} = \frac{4}{12} = \frac{1}{3} \quad \Rightarrow \quad R = 3.0\ \Omega.$$

Solving a circuit

1. **Label** every current with a symbol and a chosen direction.
2. **Use Kirchhoff's first law** 基尔霍夫第一定律 at each junction to link the currents.
3. **Use Kirchhoff's second law** 基尔霍夫第二定律 around each loop to get equations in the p.d.s.
4. **Use** $V = IR$ for each resistor.
5. Solve the equations together.

For symmetric resistor networks, use the symmetry to spot branches with equal currents —the branch with the most current gives the most power ($P = I^2R$).

Potential dividers

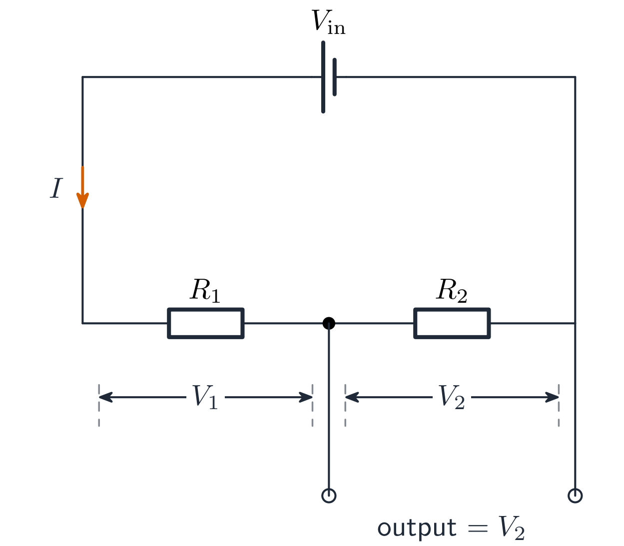
A **potential divider** 分压器 is two (or more) resistors in series across a source. The p.d. across each resistor is in **direct proportion** to its resistance:

$$V_1 = V_{\text{in}} \cdot \frac{R_1}{R_1 + R_2}, \qquad V_2 = V_{\text{in}} \cdot \frac{R_2}{R_1 + R_2}.$$

The output (tapped between R_1 and R_2) can be set to any **voltage** 电压 between 0 and V_{in} by choosing the resistances. A **rheostat** 变阻器 (a slider on a uniform-resistance wire) gives a smoothly variable divider.

Worked example. A 6.0 V supply is connected across a 2.0 kΩ resistor in series with a 4.0 kΩ resistor. Find the output voltage tapped across the 4.0 kΩ resistor.

$$V_2 = V_{in} \cdot \frac{R_2}{R_1 + R_2} = 6.0 \times \frac{4.0}{2.0 + 4.0} = 4.0 \text{ V}.$$



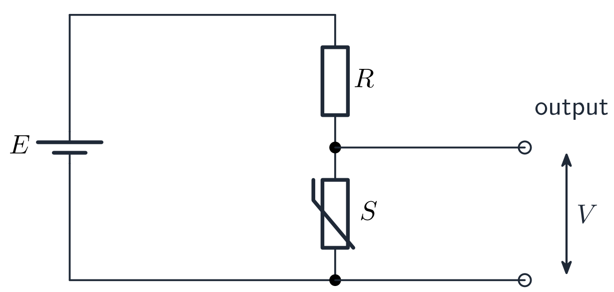
A potential divider —the p.d. splits between R1 and R2 in proportion to their resistances

Sensor circuits

Replace one fixed resistor with a **sensor** 传感器 whose resistance changes with a physical quantity:

- **thermistor** 热敏电阻 (NTC): R falls as temperature rises. In a divider, the output voltage changes with temperature in a fixed direction.
- **light-dependent resistor** 光敏电阻 (LDR): R falls as **light intensity** 光强 rises, giving a brightness-dependent output.

Connect the output to a **transistor** 晶体管 base or a **comparator** 比较器 to switch a load on or off when the temperature or light passes a **threshold** 阈值.



A thermistor in a potential divider gives an output voltage that changes with temperature

Potentiometer and the null method

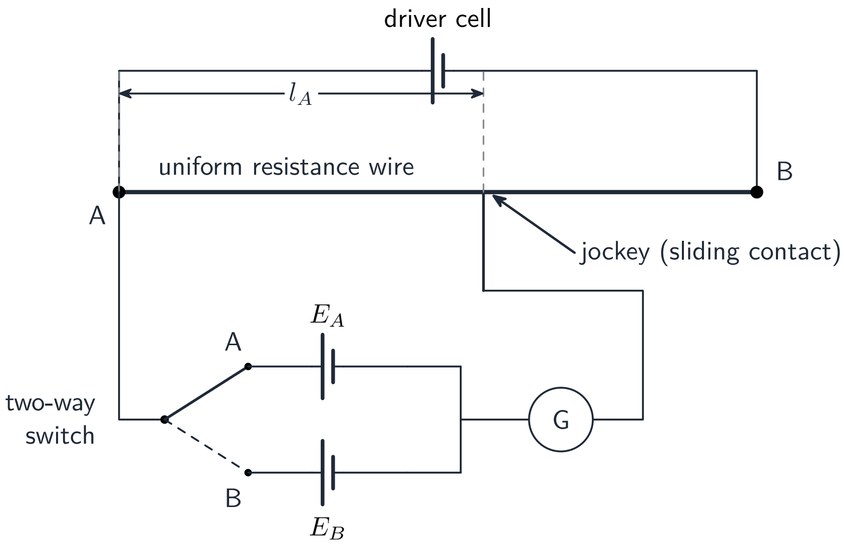
A **potentiometer** 电位差计 is a uniform resistance wire of length L_0 with a sliding contact (**jockey** 滑动触头). The resistance per unit length is uniform, so the p.d. from one end to the jockey is proportional to the length:

$$V_x = V_{\text{full}} \cdot \frac{x}{L_0}.$$

To **compare two e.m.f.s** (an unknown cell against a standard cell), connect each in turn with the jockey through a **galvanometer** 检流计. Slide the jockey until the galvanometer reads zero (a **null** —no current flows through the cell being measured, because the potentiometer's voltage there exactly opposes the cell's e.m.f.). The two balance lengths are in the ratio of the e.m.f.s:

$$\frac{\varepsilon_1}{\varepsilon_2} = \frac{l_1}{l_2}.$$

This is a **null method** 零点法: you find the balance (zero current) instead of measuring a current's value. Its advantage is that at balance the unknown cell gives no current, so its internal resistance does not affect the result.



A potentiometer comparing two cell e.m.f.s by the null method

Exam tips

- Apply **Kirchhoff's laws**: current into a junction = current out (charge conserved); $\sum$e.m.f. = $\sum$p.d. round a loop (energy conserved).
- Combine resistors: **series** $R = R_1 + R_2$; parallel $1/R = 1/R_1 + 1/R_2$.
- A **potential divider** splits voltage in the ratio of the resistances.
- Include **internal resistance**: e.m.f. $= I(R + r)$ —the "lost volts" are Ir.