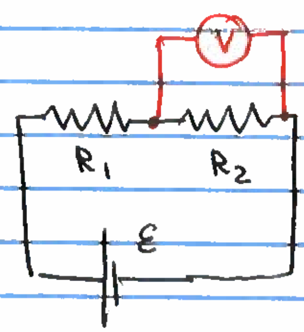
How to measure current and voltage

—(V)— Voltmeter: shows voltage drop across its contacts

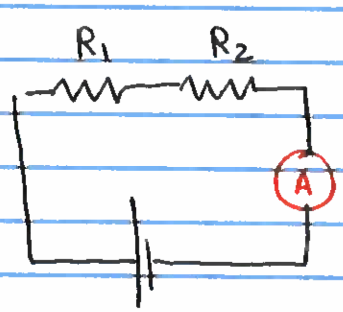
must be connected in parallel

—(A)— Amperemeter: shows current flowing through the device

must be connected in series



To measure the voltage drop across, say, R_2 it must be connected in parallel with R_2



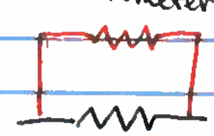
To measure the current through the circuit, the meter should be inserted into the loop

What makes a good voltmeter or ampermeter

Ideally, adding a measurement device should not change voltage / currents in the circuit

If the meter has internal resistance R_m

Voltmeter:



$$\frac{1}{R_{eq}} = \frac{1}{R_{test}} + \frac{1}{R_{meter}}$$

$$R_{eq} = R_{test} \frac{R_{meter}}{R_{test} + R_{meter}}$$

want to be closest to 1

$$\frac{R_{meter}}{R_{test} + R_{meter}} \longrightarrow 1 \quad \Rightarrow \quad R_{meter} \gg R_{test}$$

A good voltmeter has very <u>high</u> internal resistance, so that it diverts very little current from the main circuit

Ampere meter :

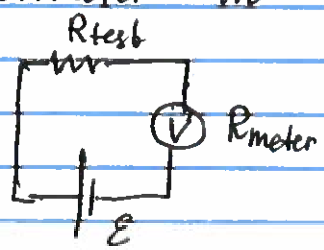
$$R_{eq} = R_{test} + R_{meter} = R_{test}\left(1 + \frac{R_{meter}}{R_{test}}\right)$$

$$1 + \frac{R_{meter}}{R_{test}} \longrightarrow 1 \quad \Rightarrow \quad R_{meter} \ll R_{test}$$

A good amperemeter has very <u>low</u> internal resistance, so that the voltage drop across it is negligible

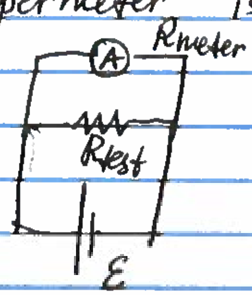
What happens if we plug them incorrectly?

Voltmeter in series



$$I = \frac{\mathcal{E}}{R_{test} + R_{meter}} \longrightarrow 0 \text{ if } R_{meter} \text{ is large}$$

Ampermeter is parallel



Current through the meter

$$I_{meter} = \frac{\mathcal{E}}{R_{meter}} \longrightarrow \infty$$

since R_{meter} is small

you fry your meter

Q: How does electric current works?

Common misconception: electrons are not moving w/o electric current.

Not true!

One can model electrons as an ideal free gas inside the metal (since total electric field from positive ions and negative electrons cancels out)

Average kinetic energy

$$\left\langle \frac{m_e v^2}{2} \right\rangle = \frac{3}{2} kT \Rightarrow \langle v \rangle_{RMS} = \sqrt{\frac{3kT}{m_e}}$$

For $T \sim 300k$

$$\langle v \rangle \sim \sqrt{\frac{3kT}{m_e}} \sim \sqrt{\frac{3 \cdot 1.38 \cdot 10^{-23} J/k \cdot 300k}{9 \cdot 10^{-31} kg}} \sim 10^5 \, m/s$$

Electric field adds a collective common motion in the direction of the electric field

$\longrightarrow E$ $\quad a = eE/m_e$

⊕

If L is the length of the conductor we expect $\langle v \rangle \sim \sqrt{aL} \propto \sqrt{E}$?!

No, because this is not a ballistic motion

Instead, electrons collide and change their speed after some average time τ

$$\langle v \rangle_{drift} \sim a \cdot \tau \sim eE/m_e \, \tau$$

in general $v_{drift} \sim 10^{-4}$ m/s for 10A current

What electron collide with?

Natural guess is with lattice, but it is actually imperfections.

Electrons are quantum particles, and they don't follow classical behavior. In fact in a perfect lattice there would be no collisions with the ions, since ~~electron~~ the probability of electrons to be ~~at~~ the location of ions is zero.