This week in the physics course

- **Lectures** will cover *Chapter 24 (Electric Current)* and start *Chapter 25 (Electric Circuits)*
- Please note: **lecture slides** and **scans of the textbook chapters** are available on Blackboard
- **Tutorial class** will practise problems from *Chapter 17 (Thermal Behaviour of Matter)*
- Physics help available in **MASH centre** (Chris Blake, Tues 10.30-12.30 and Wayne Rowlands Thurs 2.30-4.30)
- Don’t hesitate to get in touch with any questions – cblake@swin.edu.au

Chapter 22 summary

- Electric potential difference V is the work done when moving unit charge: $W = qV$

- The electric field is the gradient of the potential: $E = -\Delta V / \Delta x$

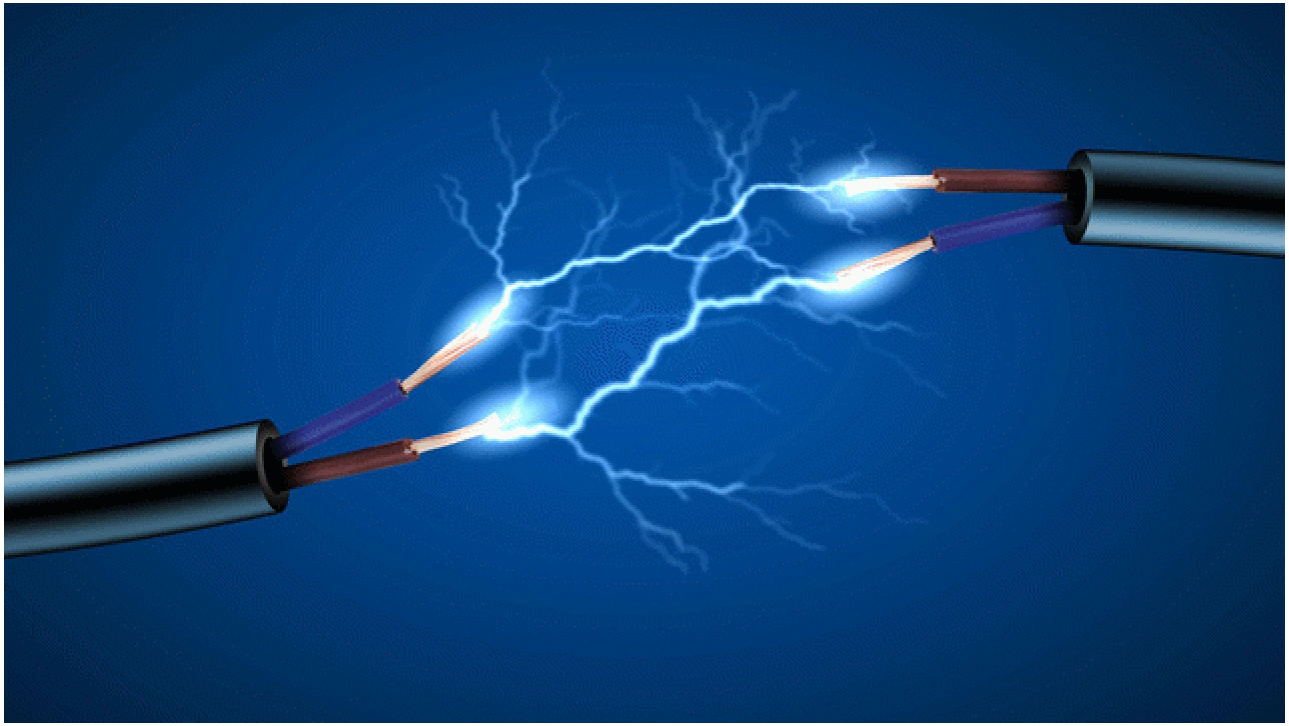
- Charges feel a force from high electric potential to low potential

Chapter 24 : Electric current

- How do we define current?
- Macroscopic and microscopic description of current
- Ohm's law and resistance
- Electrical power

Electric current

- A flow of charge is called an electric current



Electric current

- A flow of charge is called an electric current
- The current (symbol I) is the amount of charge Q [in Coulombs] flowing per unit time t [in seconds]

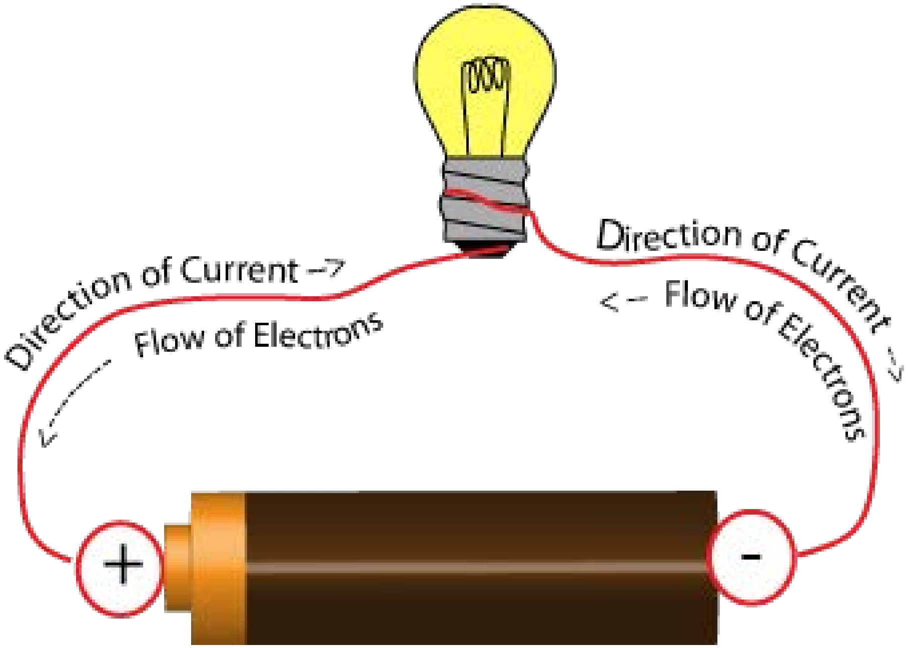
$$\boxed{I = \frac{Q}{t}}$$

- The units of current are C/s or “Amperes” A

$$\boxed{1\,A = 1\,C/s}$$

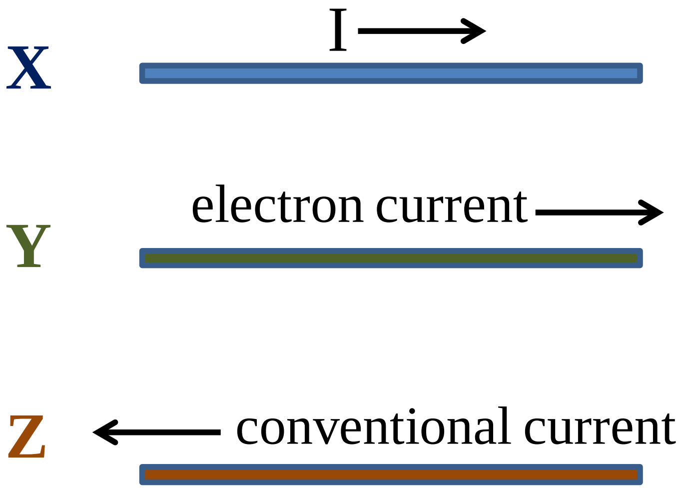
Electric current

- Current is in the direction that positive charge flows
- But in reality, current is transported by an opposite flow of negatively-charged electrons

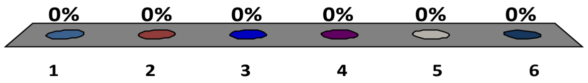


Sometimes described as "conventional current" (positive) or "electron current" (negative)

In which wire(s) are there electrons moving from right to left?

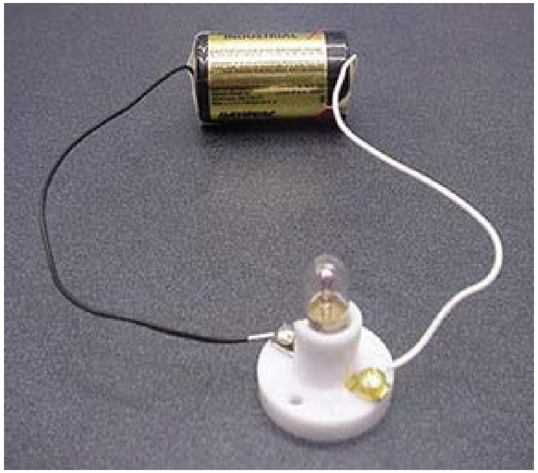


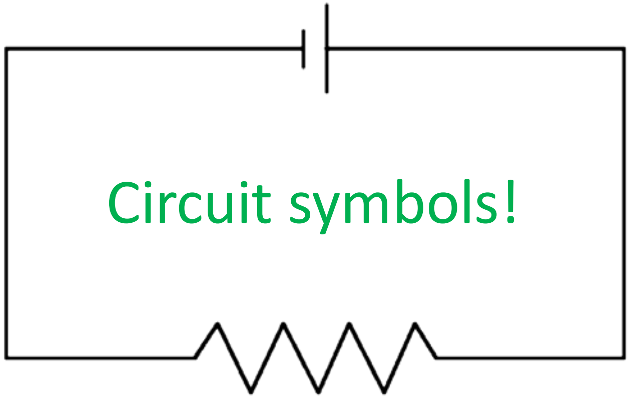
1. Z only
2. X only
3. Y only
4. X and Y
5. Y and Z
6. X, Y and Z



Electric current

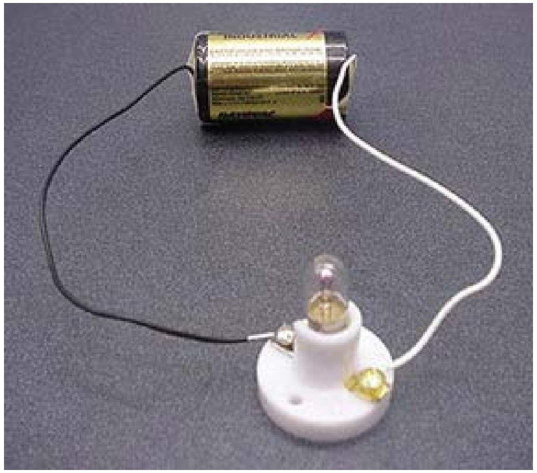
- How do we create an electric current?
- Create an electric potential difference between two points
- Connect those points to allow charge to flow
- Dissipate the energy (e.g. into light, heat)



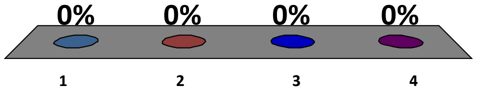


Circuit symbols!

Only one terminal of the battery is connected to the light bulb. What happens?

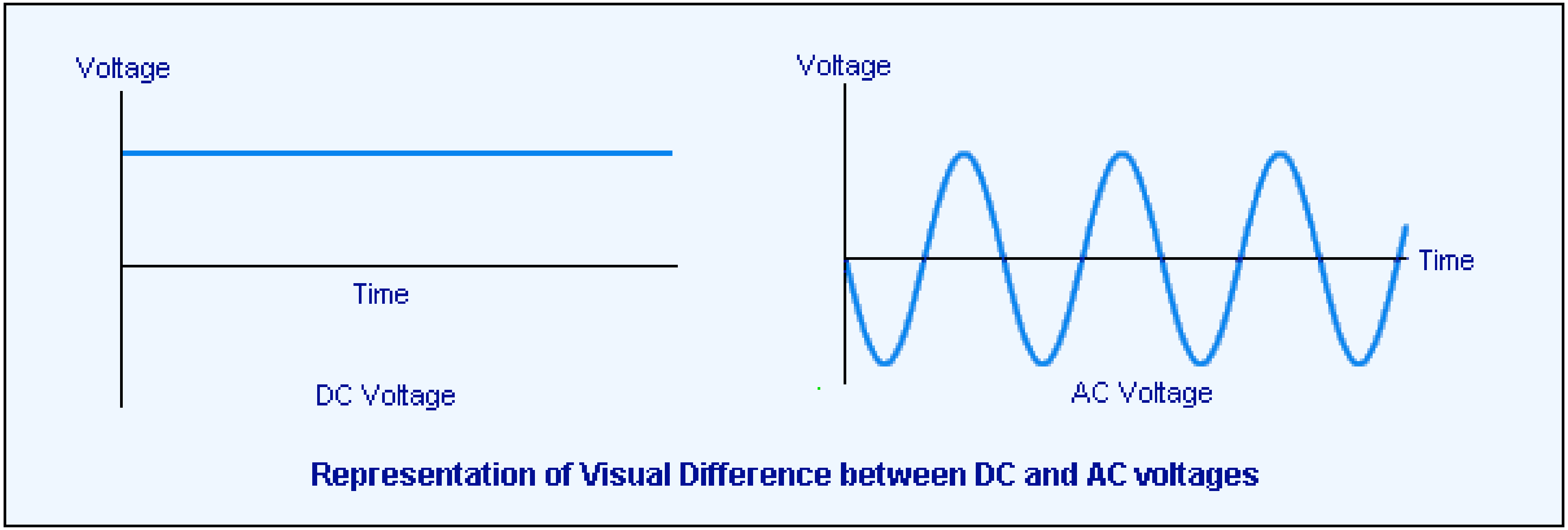


1. **No current flows**
2. **A very small current flows**
3. **A current flows for only a short time**
4. **Current flows at half the rate it flowed with two wires**



Electric current

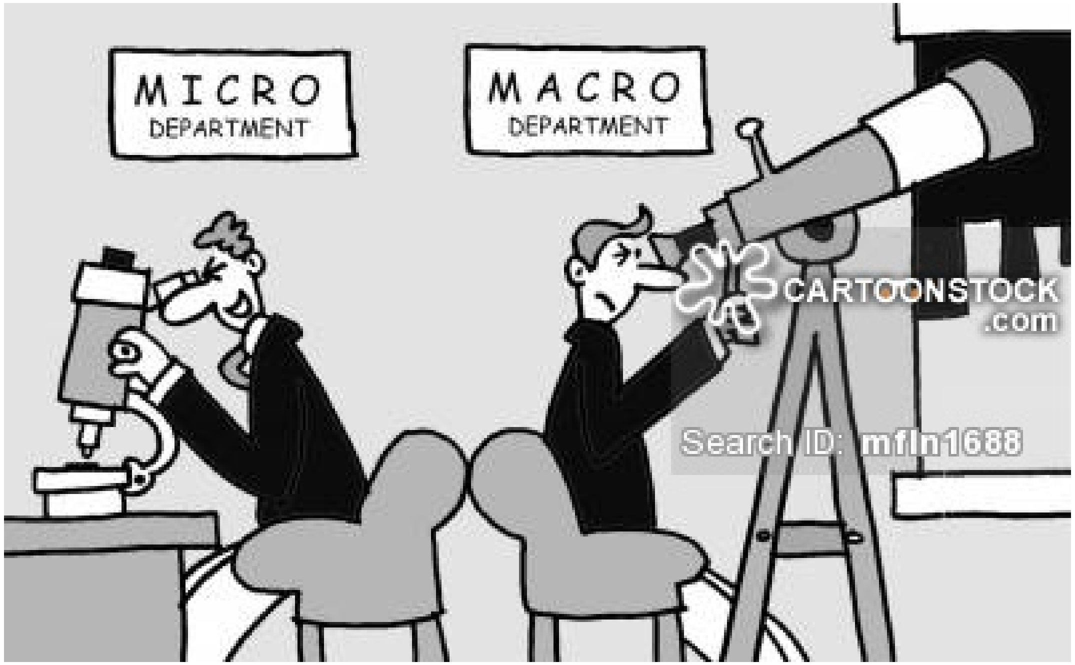
- Electrical power may be supplied as either a direct current or an alternating current



- We will only cover direct current in this topic

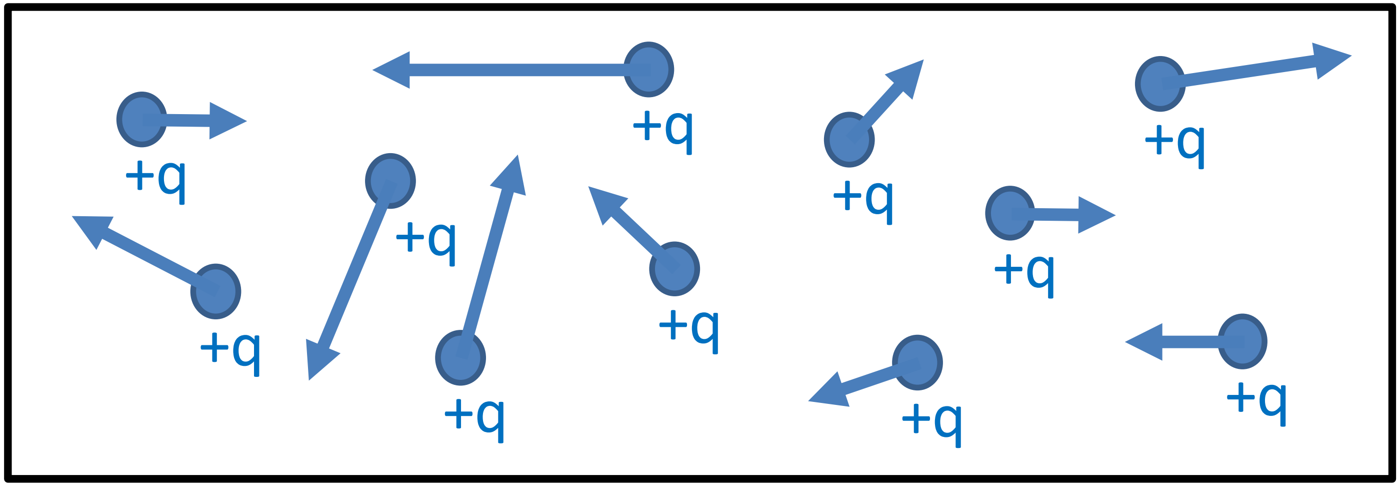
Macroscopic vs. Microscopic

- In physics and chemistry we try and relate the overall macroscopic properties of a system to its microscopic nature



Microscopic nature of current

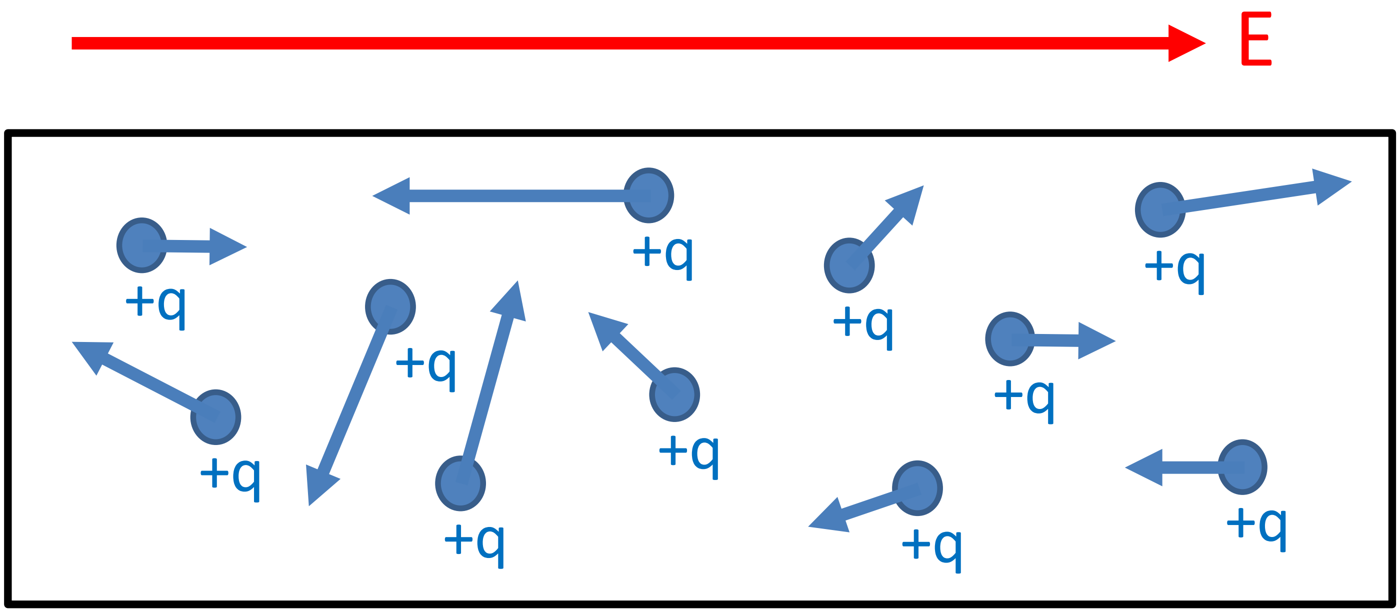
- What really happens when a battery is connected?
- (1) As we saw in the "temperature" topic, particles are in constant thermal motion



Microscopic nature of current

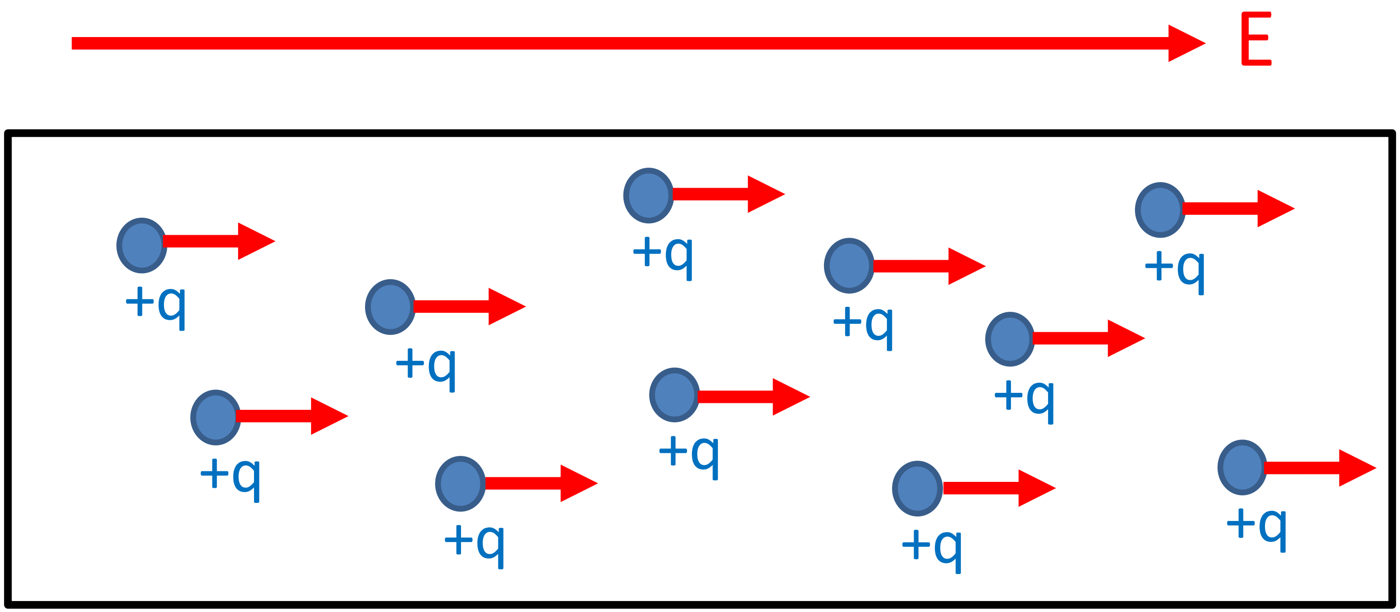
- What really happens when a battery is connected?

- (2) The battery supplies a potential difference hence electric field



Microscopic nature of current

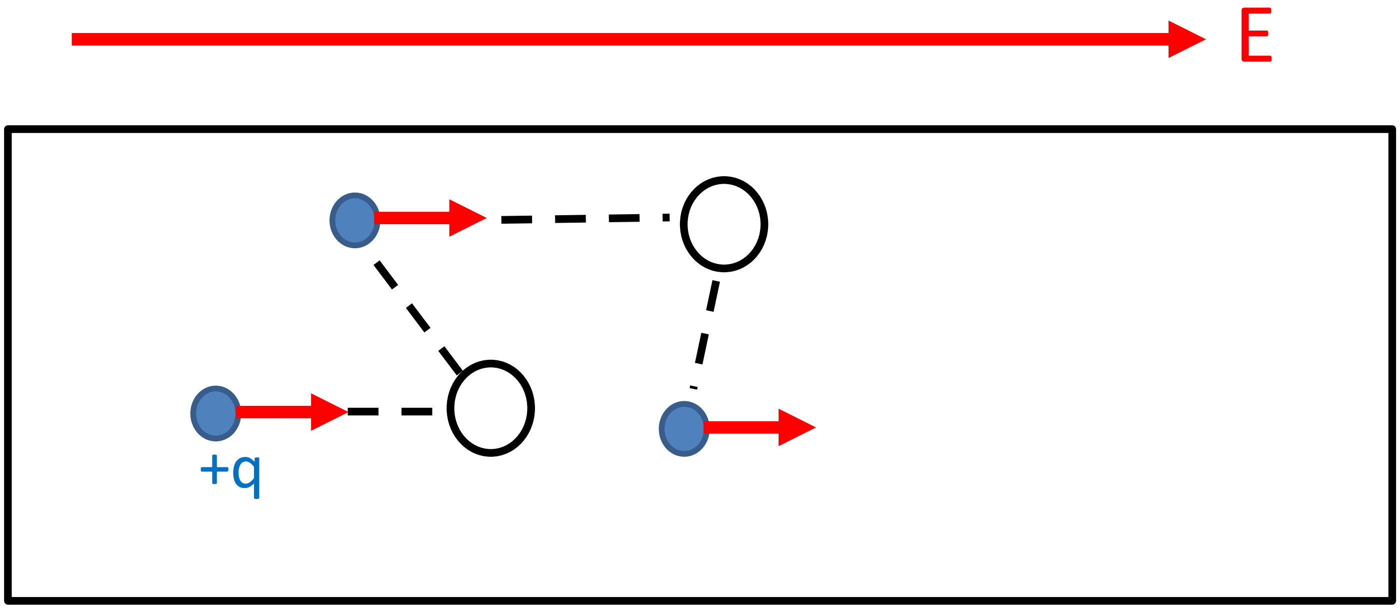
- What really happens when a battery is connected?
- (3) The charges feel a force from the electric field and start to accelerate



Microscopic nature of current

- What really happens when a battery is connected?

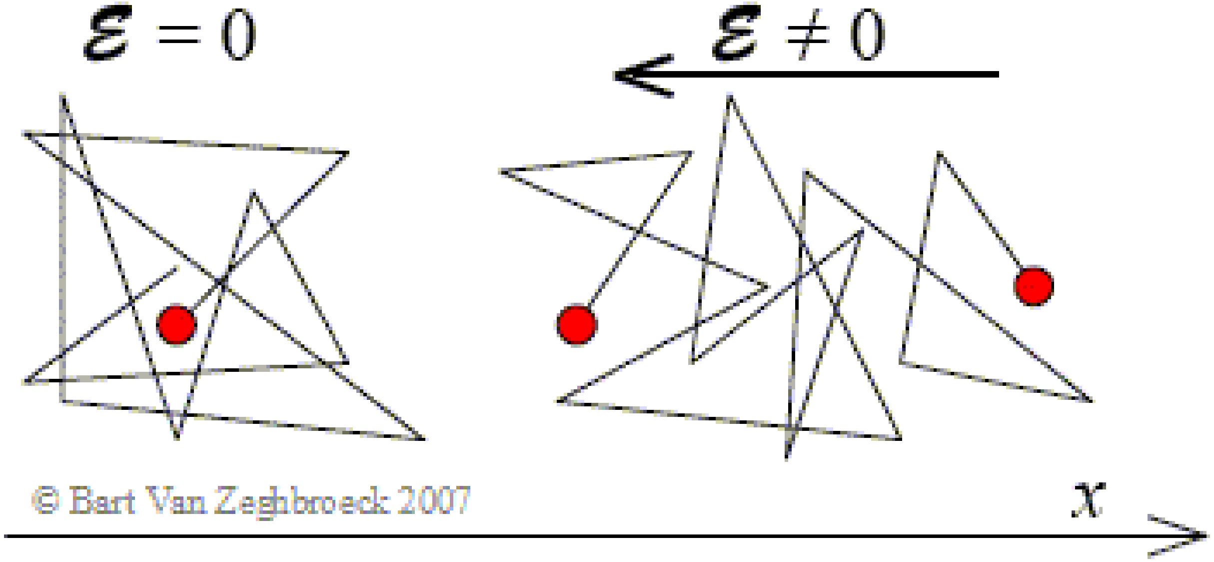
- (4) The charges undergo collisions with the other particles in the material which slows their motion



Microscopic nature of current

- What really happens when a battery is connected?

- (5) These collisions produce a resistance to motion which results in an equilibrium drift velocity

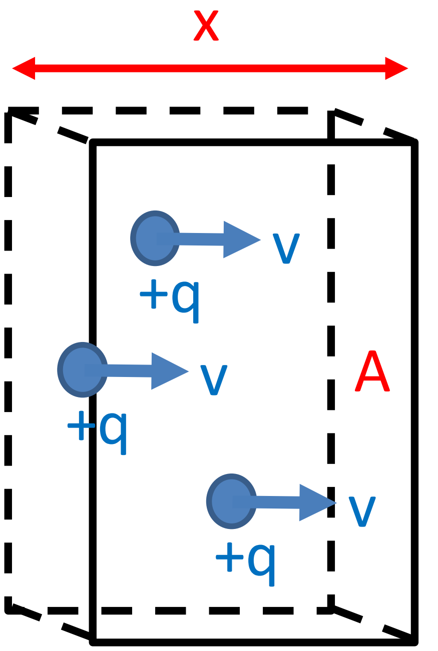


Microscopic nature of current

- What really happens when a battery is connected?
- (5) These collisions produce a resistance to motion which results in an equilibrium drift velocity

Microscopic nature of current

- How much current is produced by drift velocity v?

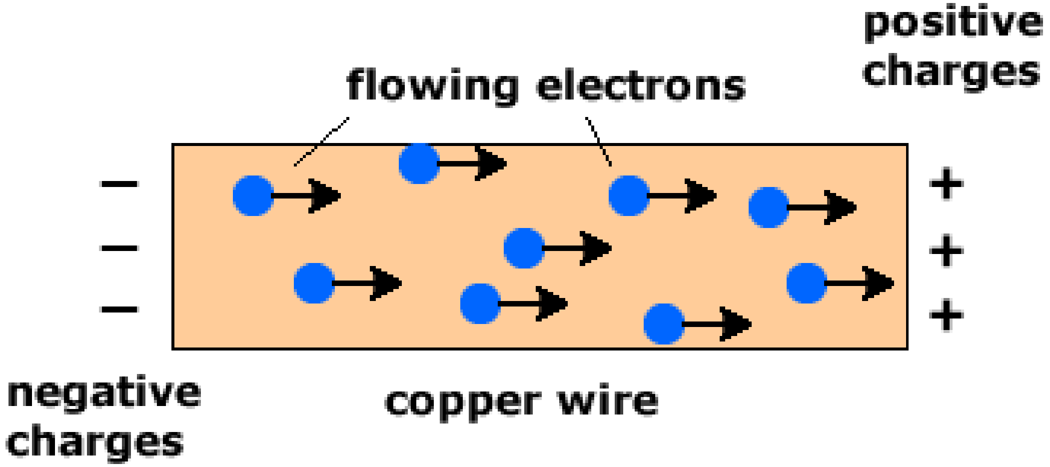


Number density of charges = n

- How much charge Q flows through the area A in time t?
- It's contained with a length x where x = v t , which means a volume V = A x = A v t
- So, charge Q = q n V = q n A v t
- Current $I = \frac{Q}{t} = q\,n\,A\,v$

Microscopic nature of current

<u>Exercise:</u> A 5-A current flows in a copper wire with cross-sectional area 1 mm^2, carried by electrons with number density 1.1 x 10^{29} m^{-3}. What is the electron drift speed?



$$\boxed{I = q\,n\,A\,v}$$

$$I = 5\,A$$
$$q = 1.6 \times 10^{-19}\,C$$
$$n = 1.1 \times 10^{29}\,m^{-3}$$
$$A = 1\,mm^2 = 10^{-6}\,m^2$$

$$v = \frac{I}{q\,n\,A} = \frac{5}{(1.6 \times 10^{-19}) \times (1.1 \times 10^{29}) \times (10^{-6})} = 0.28\,mm/s$$

Isn’t this incredibly slow? Yes – but the electric field itself is established at the speed of light.

Microscopic nature of current

- The current density (symbol J) is the current flowing per unit area ("concentration of current")

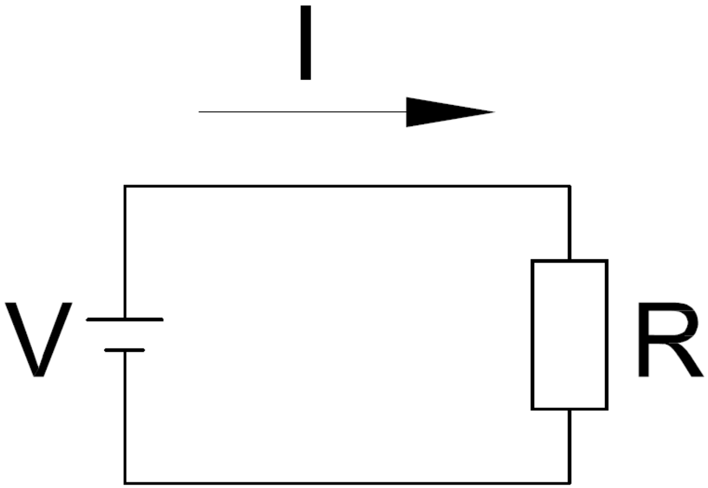
$$\boxed{J = \frac{I}{A} = nqv}$$

- The units of J are A/m^2

- Used in a microscopic description of current

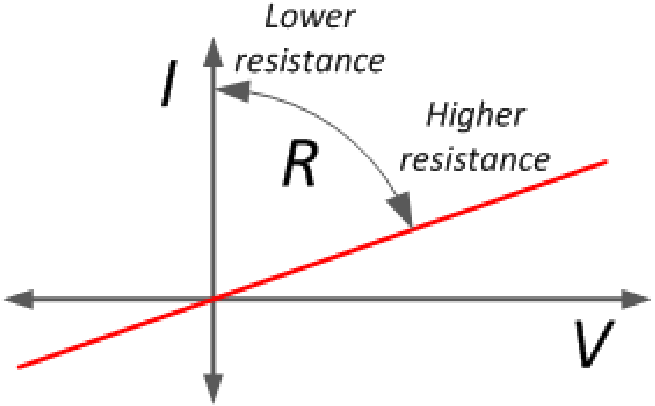
Ohm's Law : macroscopic version

- Ohm's law describes the resistance of a material to the flow of current (or its inverse – conductance)



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

$$\boxed{V = IR}$$



- The greater the resistance, the less current can flow for a given potential difference

- Resistance is measured in units of Ohms (symbol: Ω)

Ohm’s Law : electrical shock

- Current of “only” 100 mA can be fatal to humans

- Luckily, resistance between points on human skin $= 10^5\ \Omega$
- So, fatal voltage = V = I R = 0.1 x 10^5 = 10,000 V
- If skin is wet, resistance is reduced. Be careful!

Ohm’s Law : microscopic version

- The current density J flowing for a given electric field E depends on the resistivity ρ of the material (or its inverse – conductivity $\sigma = 1/\rho$)

$$\boxed{J = \frac{E}{\rho} = \sigma\, E}$$

High resistivity ρ
means low current!

Ohm’s Law : “lie detection”

- Sweat increases the conductance of the skin, which will change the current flowing for fixed voltage

“machines do detect deception better than chance, but with significant error rates”

Ohm's Law : microscopic version

Exercise: A 1.8-mm diameter copper wire carries 15 A to a household appliance. What is the electric field in the wire? The resistivity of copper is $1.68 \times 10^{-8} \Omega\, m$.

Ohm's Law : $J = E/\rho$

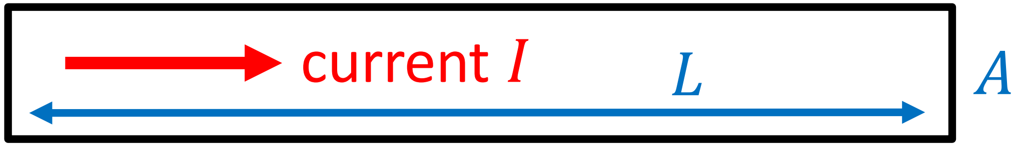
Resistivity of copper : $\rho = 1.68 \times 10^{-8}\ \Omega\, m$

Current density $J = \frac{I}{A} = \frac{I}{\pi\, r^2} = \frac{15}{\pi\, (0.9 \times 10^{-3})^2} = 5.9 \times 10^6\ A\, m^{-2}$

Electric field : $E = J\, \rho = (5.9 \times 10^6) \times (1.68 \times 10^{-8}) = 0.099\, V/m$

Ohm’s Law : microscopic version

Exercise: A copper wire 0.5 cm in diameter and 70 cm long connects your car’s battery to the starter motor. What’s the wire’s resistance? The resistivity of copper is $1.68 \times 10^{-8} \Omega\, m$.



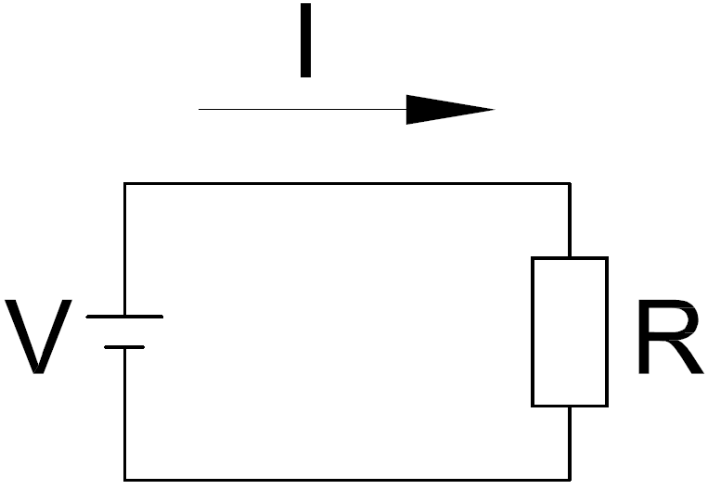
$$I = V/R \qquad J = I/A$$
$$J = E/\rho \qquad E = V/L$$

$$R = \frac{V}{I} = \frac{E\,L}{J\,A} = \frac{\rho\,L}{A} = \frac{1.68 \times 10^{-8} \times 0.7}{\pi \times (0.0025)^2} = 6 \times 10^{-4}\ \Omega$$

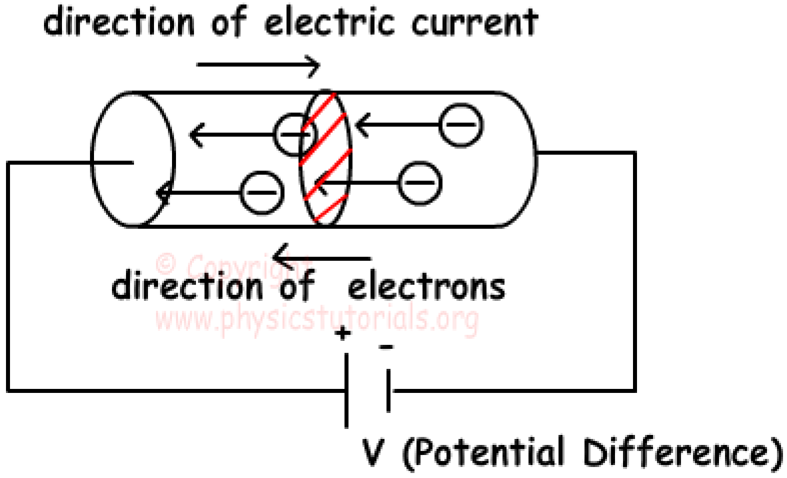
Exercise: If the starter motor draws a current of 170 A, what’s the potential difference across the wire?

$$V = I\,R = 170 \times (6 \times 10^{-4}) = 0.1\ V$$

Macroscopic vs. Microscopic



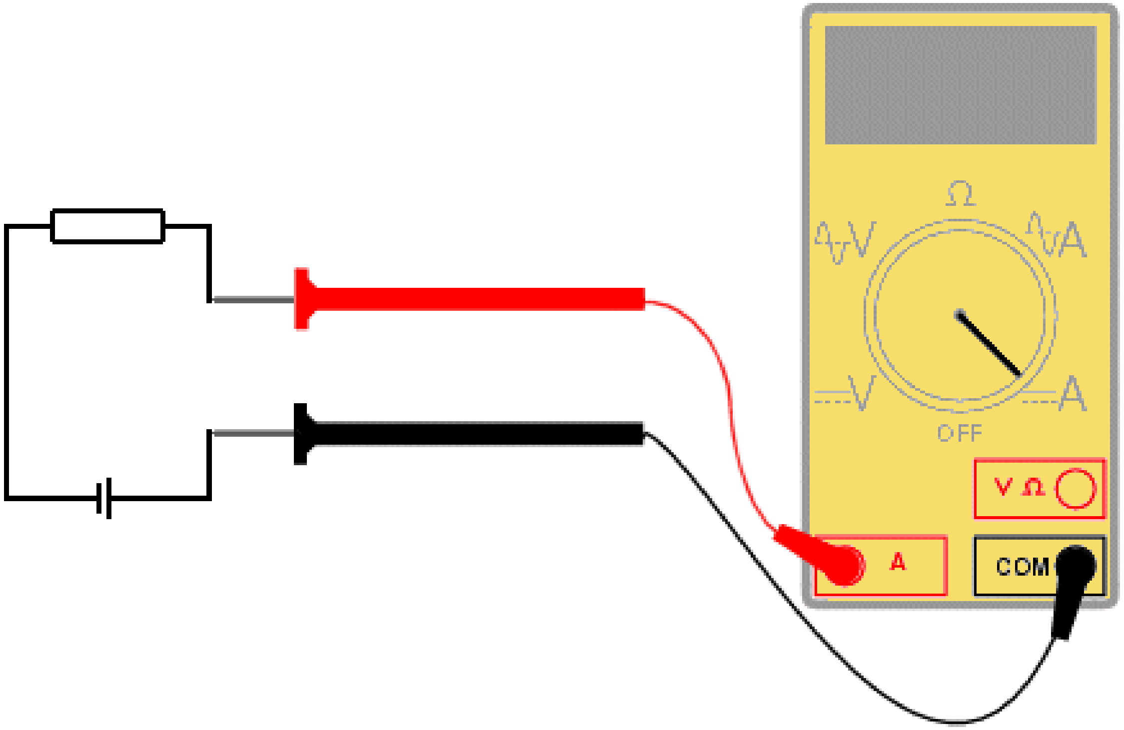
- Current I driven by potential difference V
- Experiences resistance R
- Ohm's law $I = V/R$



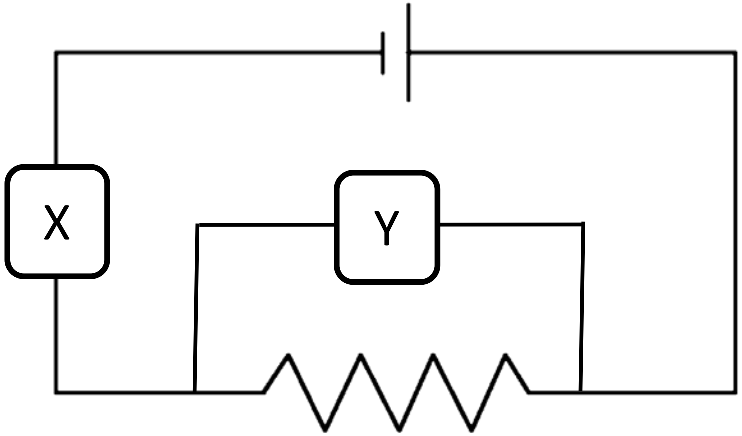
- Current density J driven by electric field E
- Experiences resistivity ρ
- Ohm's law $J = E/\rho$

Electric current

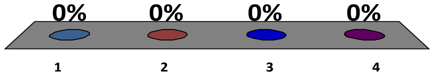
- Current can be measured using an ammeter



Two electrical measuring devices, X and Y, are placed in the circuit as shown to measure properties of the resistor. Which of the following descriptions is correct?



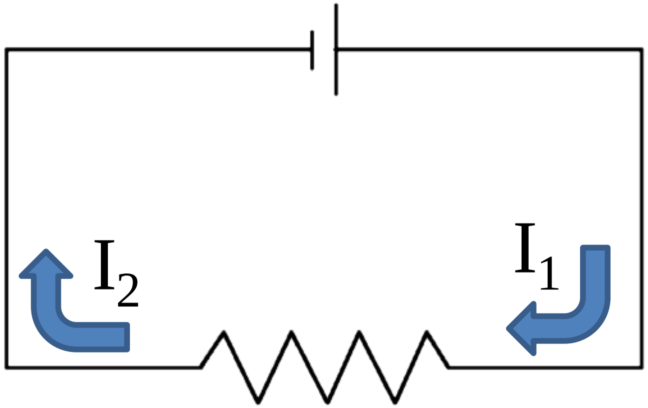
1. **X measures current, Y measures voltage**
2. **X measures voltage, Y measures current**
3. **X and Y measure current**
4. **X and Y measure voltage**



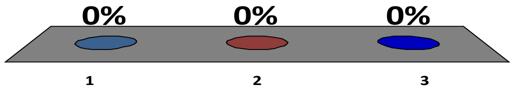
Current is measured at a location – *ammeters in series.*

Voltage (potential difference) between two locations – *voltmeters in parallel.*

How does the current entering the resistor, I_1, compare to the current leaving the resistor, I_2?



1. $I_1 < I_2$
2. $I_1 > I_2$
3. $I_1 = I_2$



CHARGE CONSERVATION: charge cannot be created or destroyed.

Energy is dissipated as current flows through a resistance, but charge is conserved, so current in = current out.

Electric power

- Power is the rate of use of energy : $Power = \frac{Energy}{Time}$

- How much power does an electric circuit consume?

- Moving charge Q across a potential difference V requires work : $W = Q\,V$ (from last chapter)

- Power = $\frac{Work}{Time} = \frac{Q\,V}{t}$ = I V (in terms of current I = Q/t)

- Using Ohm's law V = I R : Power = V I = I^2R = V^2/R

Electric power

- This power is dissipated as heat energy in the resistance – why electrical components get hot!

Electric power

- Power is measured in Watts (1 W = 1 J/s)
- Your "power bill" is probably measured in "kWh" or "kilo-Watt hours"
- This is really an "energy bill" …
- 1 kWh = 1000 J/s x 3600 s = 3.6 x 10^6 J = 3.6 MJ

Electric power

- Why do power lines operate at 100,000 V?

- P = V I : high power can be delivered using high V or high I
- Some power will be lost in heating the transmission wires
- $P = I^2R$: low current minimizes these transmission losses

Electric power

Exercise: What is the resistance of a 60 W 240V light bulb?

Power P = 60 W
Voltage V = 240 V

$$P = I\,V \quad \rightarrow \quad I = \frac{P}{V} = \frac{60}{240} = 0.25\;A$$

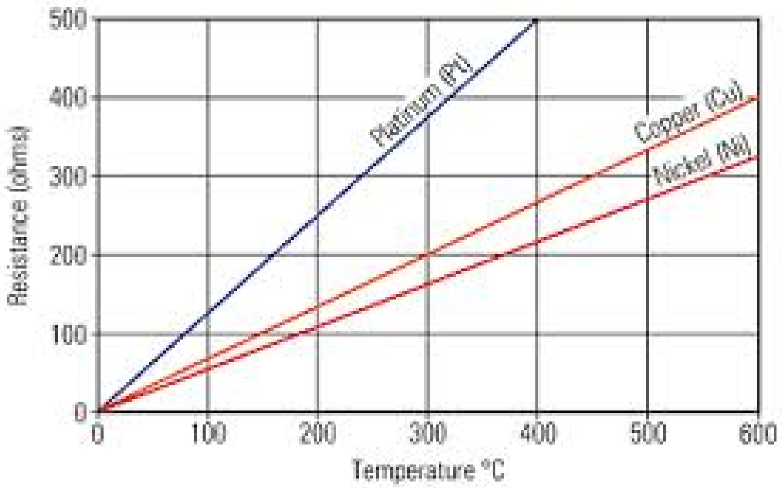
$$V = I\,R \quad \rightarrow \quad R = \frac{V}{I} = \frac{240}{0.25} = 960\;\Omega$$

Exercise: What would be the power output if the bulb was plugged into the US mains of 110 V?

$$P = I\,V = \frac{V^2}{R} = \frac{110^2}{960} = 12\;W$$

Thermal runaway and fuses

For most conductors, resistance is not completely constant, but increases with increasing temperature.



If part of a circuit starts to overheat, its resistance can increase, causing larger power dissipation, causing higher resistance etc.

A **fuse** protects a circuit from general damage by acting as the “weak point”; a thin wire that will physically fail (melt) if current exceeds a safe level.

“Circuit breakers” or “safety switches” either mechanical or electronic, are now able to offer faster and more reliable protection.

Chapter 24 summary

- Electric current is the rate of flow of charge measured in Amperes: $I = Q/t$
- Microscopically charges q have a drift velocity v such that $I = nAqv$ [A=area, n=number density]
- Ohm's law relates the current to a resistance R ($I = V/R$) or resistivity ρ ($J = E/\rho$)
- Electric current dissipates power P = V I