Introduction to d.c. Electrical Circuits

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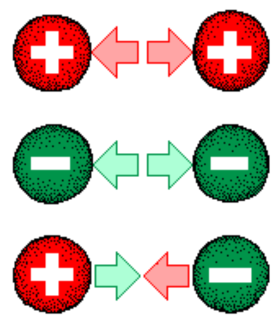
Overview

- Electrical charge and current
- Electric potential and Resistance
- Water/electricity analogies
- Ohms Law
- Resistors in series and parallel
- Variable resistors
- Measuring current and voltage

Electrical Charge

- Charge is a property of matter that causes a charged particle of matter to experience a force when it is near another charged particle
- There are two types of charge: positive and negative
  - Like charges repel
  - Unlike charges attract



- Charge is *quantized*: it comes in multiples of units of an elementary charge of 1.602×10^{-19} *Coulombs* (Coulombs is the unit of charge)
- 1.602×10^{-19} Coulombs is the charge on an electron

Electrical Current

- Current is defined as the *rate of flow* of charge
- It is measured in Amperes, almost always abbreviated to amps.

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

- 1 amp is the current that flows when a number of electrons equal to 1 coulomb of charge flows through a given point in 1 second

- Example: $12.5\text{x}10^{18}$ electrons flow past a given point in a wire during a 4 second period. What is the current?

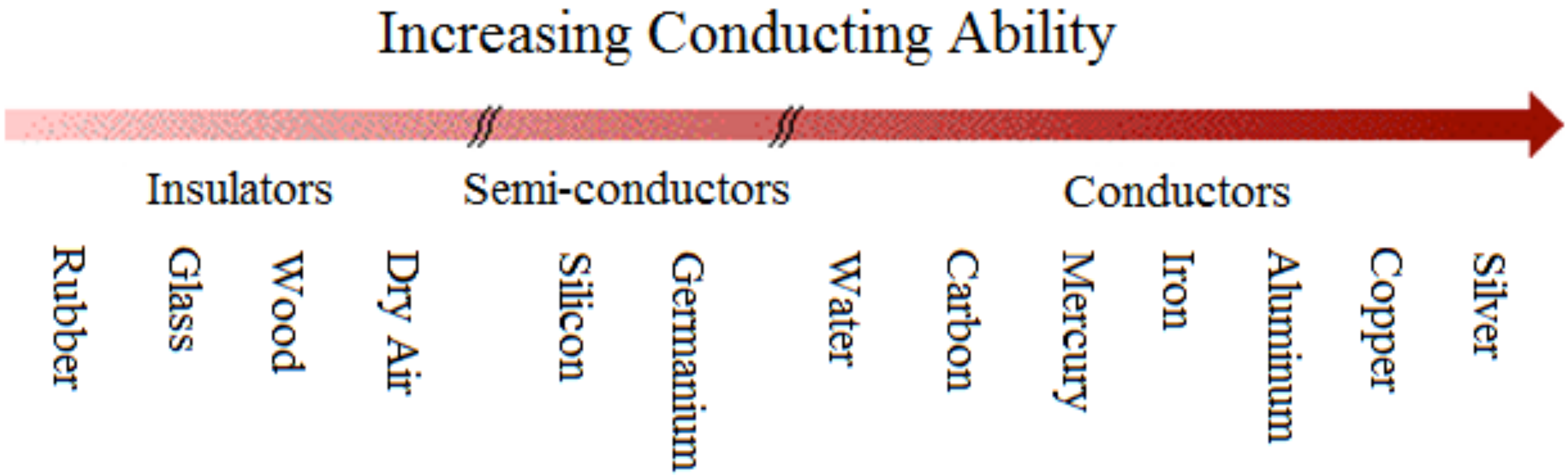
Find the total charge:

$$Q = 12.5 \times 10^{18} \times 1.602 \times 10^{-19} = 2.0 \text{ Coulombs}$$

Hence the current: $I = \frac{Q}{t} = \frac{2}{4} = 0.5\ A$

Conductors and Insulators

- Electrical conduction depends on the atomic properties of a substance
- In metals, the electrons in the outer electron shell are loosely bound to the nucleus and so are free to conduct.
- In an insulator, the electrons are tightly bound and so very little conduction is possible

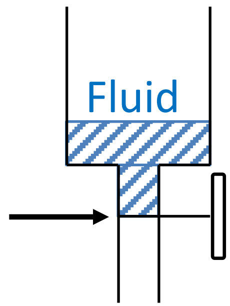


Note that there are different degrees of conductivity

Electric Potential (Voltage) and Resistance

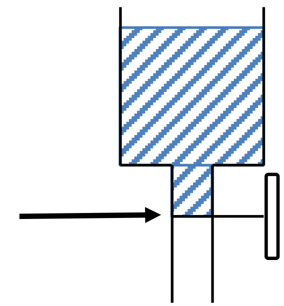
- If current is like *flow* in a water system, voltage is like *pressure*

Low pressure:
slow flow when
valve opened



Low voltage

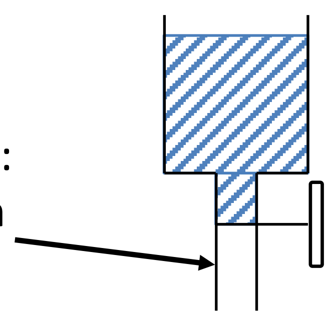
Higher pressure:
higher flow when
valve opened



Higher voltage

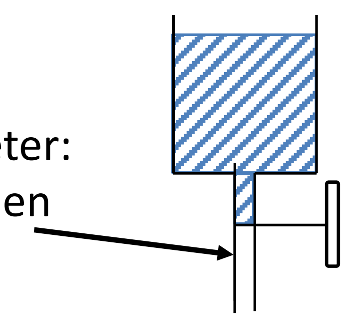
- Resistance is like pipe diameter in a water system:
  the smaller the diameter, the higher the resistance

Large diameter:
high flow when
valve opened



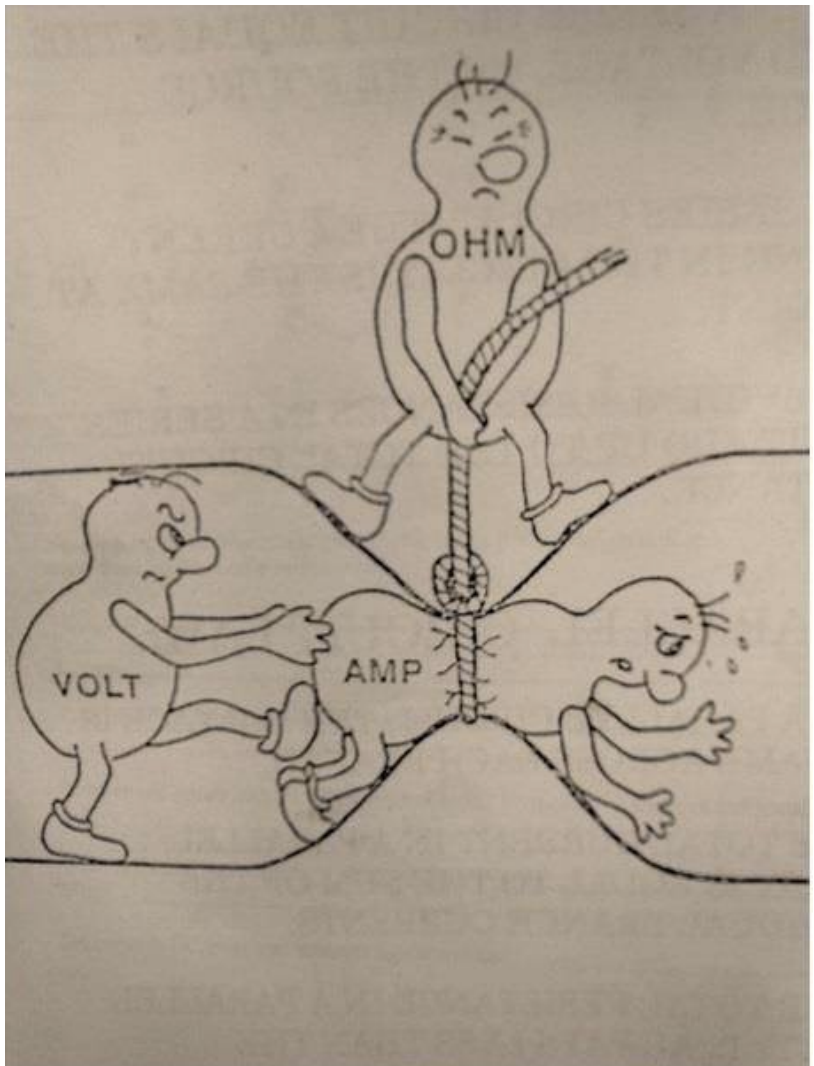
Low resistance

Smaller diameter:
lower flow when
valve opened

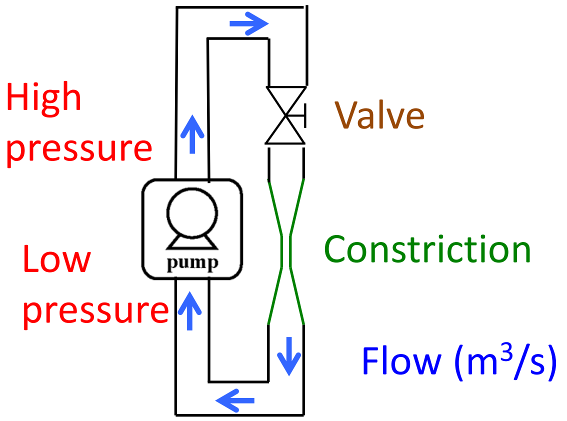


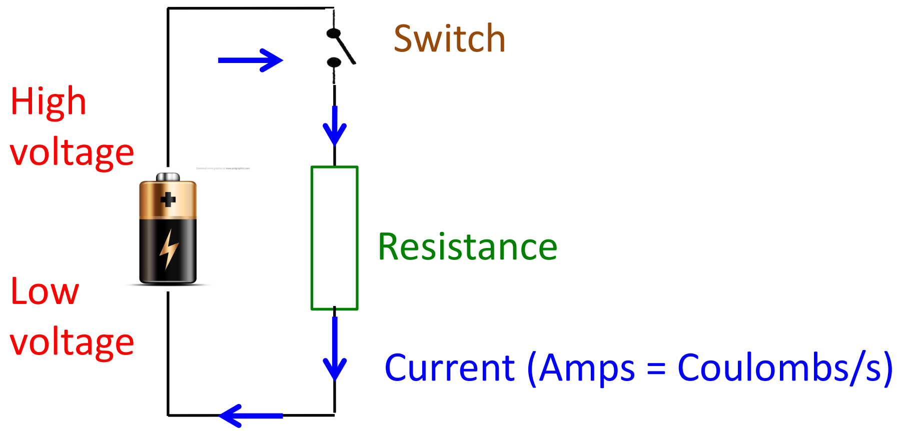
Higher resistance

How to Think about Voltage, Current and Resistance



Water Circuit / Electrical Circuit Analogies



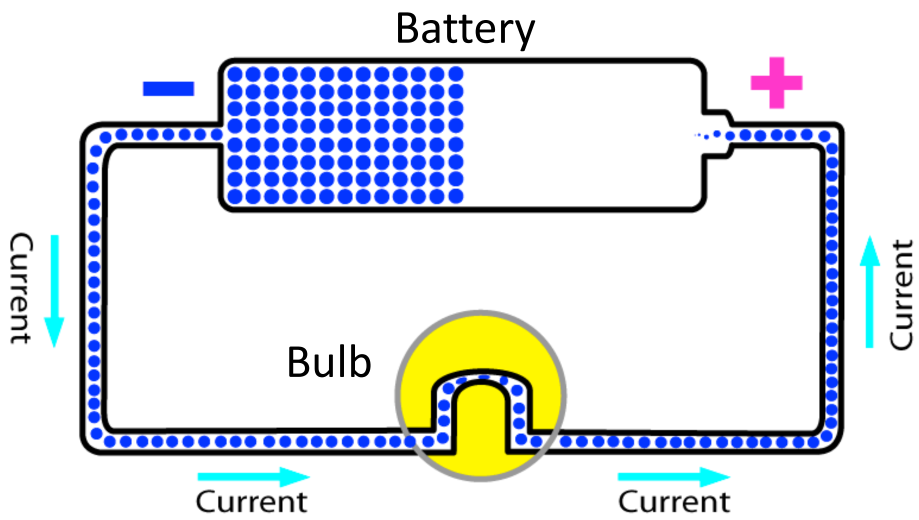


Water Circuit	Units	Electrical Circuit	Units
Pump	-	Battery (poor analogy!)	-
Constriction	-	Resistor	-
Valve	-	Switch	
Pressure	Pascals	Voltage	Volts
Flow	m^3/s	Current	Coulombs/s = Amps

- In these circuits, water (current) flows in a single direction from high pressure (voltage) to low pressure (voltage).
- Hence this is known as a *direct current* (d.c.) circuit

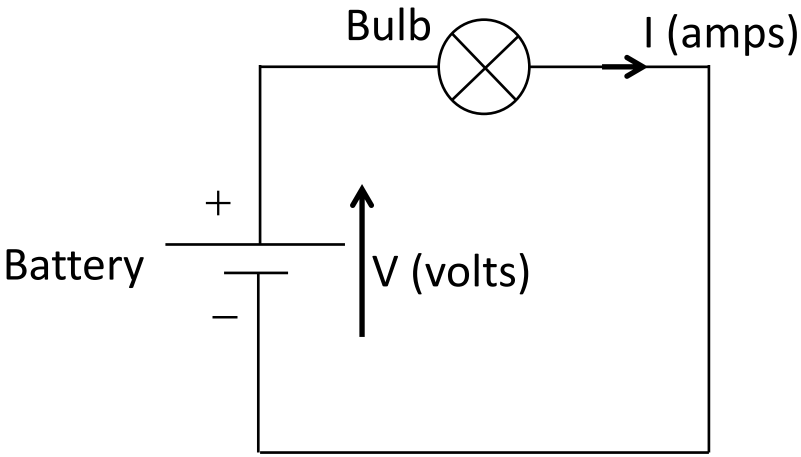
- Beware: the analogy between water and electrical circuits is simplistic and does not help to explain matters such as:
  —a.c. (alternating current) circuits
  —electromagnetic fields
  —semiconductors etc. etc.

A first circuit

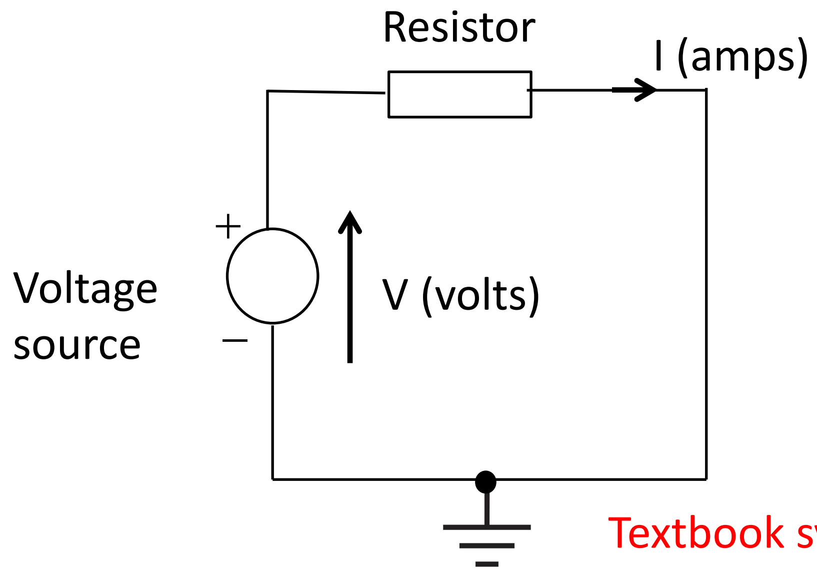


- A battery is a device that converts chemical energy into electrical energy
  - A battery has two terminals and by chemically separating positive and negative charges, produces a *potential difference* or *voltage* across these terminals, as shown
- When the two plates of the battery are connected via a resistive component, a *current* flows (flow of electrons)
- The flow of charge causes energy to be released in the resistive element as heat (and, in a light bulb, also as light)

Schematic Circuit Diagrams



Informal symbols



Textbook symbols

- *Schematic diagrams* of the circuit on the last slide
  - Left: from a technician's manual
  - Right: from a textbook
- The connecting wires are assumed to have zero resistance
  - Hence any two points on an uninterrupted line are at the same potential (voltage)
- Wires that cross are not connected unless they share a blob ●
- By convention, current flows from positive to negative voltage in the circuit
- The ground symbol can be used to designate a potential of zero volts 

Resistors and Ohm's Law

- In the last circuit, the bulb behaves as a *resistor*
- As the name implies, a resistor offers "resistance" to the flow of current in the circuit
- There is a simple relationship between the voltage across the resisitor and the current flowing through it:

Ohm's Law:

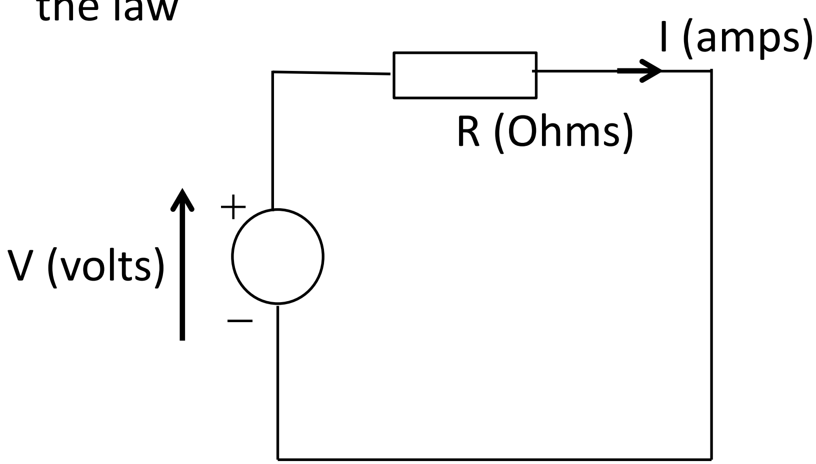
$$I = \frac{V}{R}$$

Current *through* terminals of resistor (amps, A)

Voltage *across* terminals of resistor (volts, V)

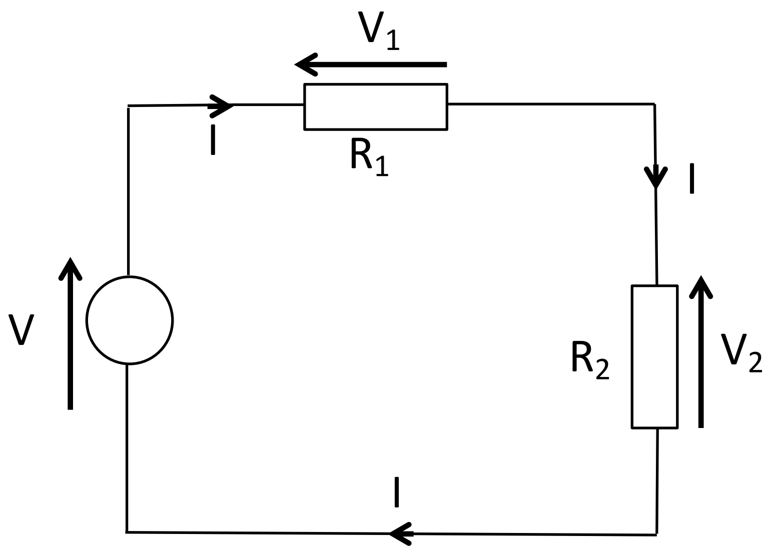
Value of resistor (Ohms, Ω)

- The value of the resistor is measured in Ohms, in honour of Georg Ohm, the discoverer of the law

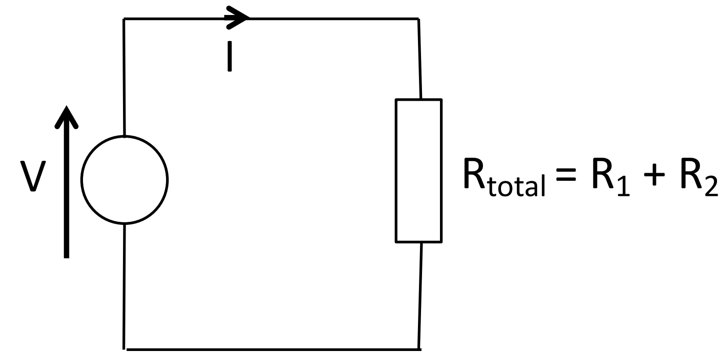


Suppose V = 6 volts and R = 2 Ω.
Then I = 6/2 = 3 A.

Resistances in Series



The values of resistors in series ADD, so this circuit is equivalent to



The two resistors R_1 and R_2 here are said to be *in series*, as they have the same current I through them.

Example: $V = 5$ Volts, $R_1 = 4\ \Omega$, $R_2 = 6\ \Omega$

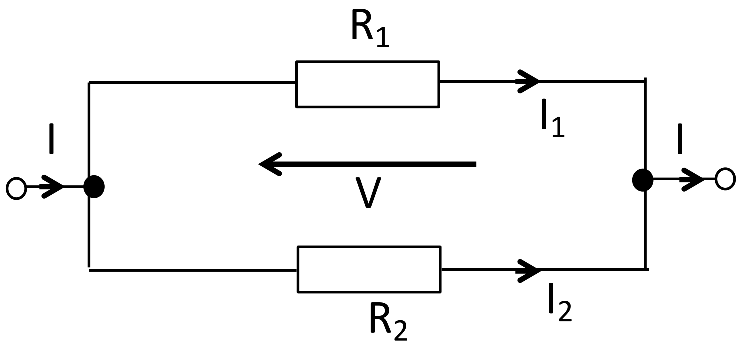
$I = V / (R_1 + R_2) = 5/(4 + 6) = 1/2$ Amp

$V_1 = I\ R_1 = 1/2 \times 4 = 2$ Volts

$V_2 = I\ R_2 = 1/2 \times 6 = 3$ Volts

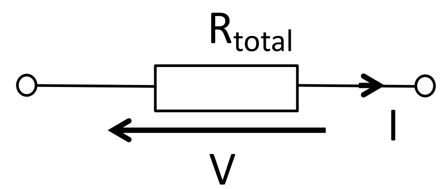
Notice that $V_1 + V_2 = 2 + 3 = 5$ Volts $= V$

Resistances in Parallel



The two resistors R_1 and R_2 here are said to be *in parallel*, as they have the same voltage V across them.

Equivalent to:



For two resistors in parallel:

$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2}$$

$$= \frac{R_2 + R_1}{R_1 R_2}$$

$$R_{total} = \frac{R_1 R_2}{R_1 + R_2}$$

$$R_{total} = \frac{\text{Product of resistance values}}{\text{Sum of resistance values}}$$

- Note that: $\frac{R_1 R_2}{R_1 + R_2} < R_1, R_2$

Example: $I = 4$ Amps, $R_1 = 3\ \Omega$, $R_2 = 6\ \Omega$

$$R_{total} = \frac{3 \times 6}{3 + 6} = \frac{18}{9} = 2\ \Omega$$

$V = R_{total} \times I = 2 \times 4 = 8$ Volts

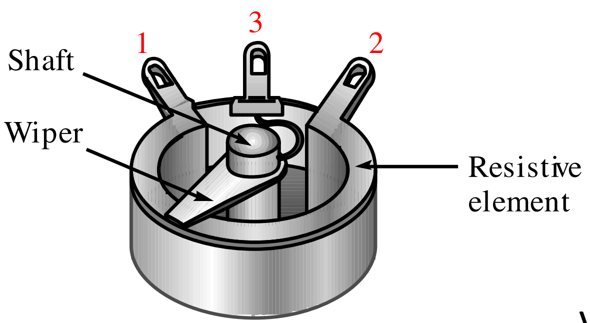
$I_1 = V/R_1 = 8/3$ Amps

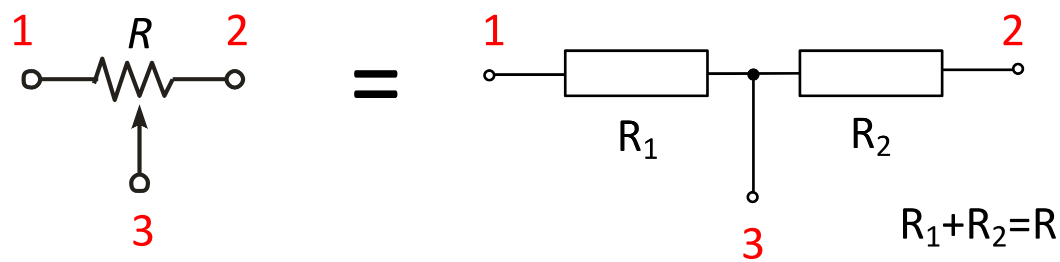
$I_2 = V/R_2 = 8/6 = 4/3$ Amps

Notice that $I_1 + I_2 = 8/3 + 4/3 = 12/3 = 4$ Amps $= I$

Variable Resistors

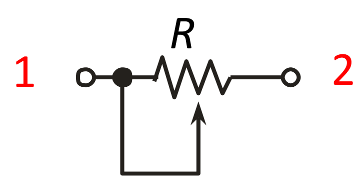
Variable resistors include the *potentiometer* and *rheostat*. The centre terminal of a variable resistor is connected to the *wiper*.



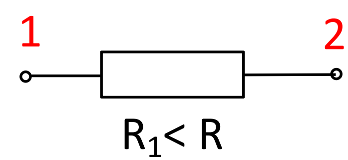


Variable resistor (potentiometer)

To connect a potentiometer as a *rheostat*, one of the outside terminals is connected to the wiper.

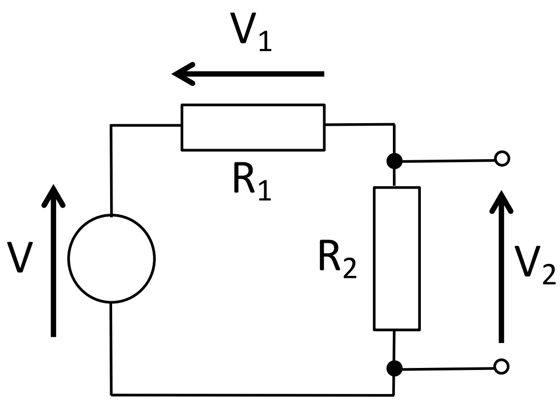


Variable resistor (rheostat)

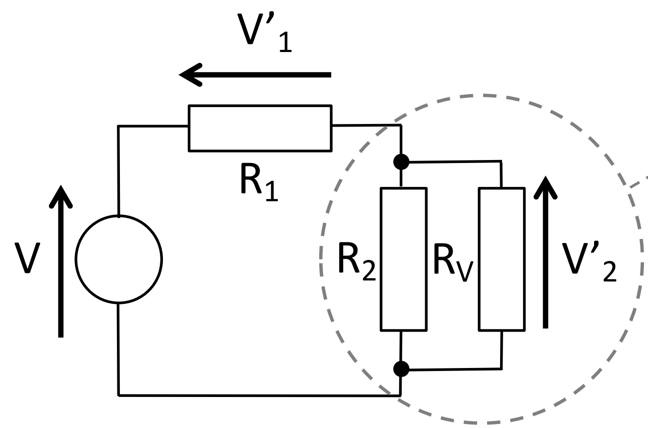


Measuring Voltage

- Suppose we want to measure the voltage V_2 across the resistor R_2



- To do so, we attach a voltmeter *across* the resistor R_2
- But the voltmeter has an *internal resistance* equal to R_V



$$R' = \frac{R_2 R_V}{R_2 + R_V}$$

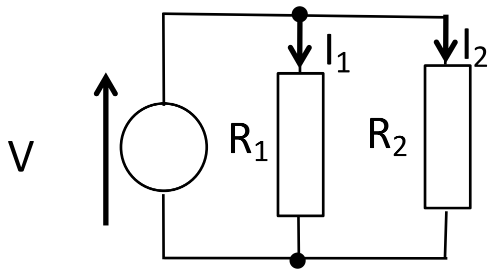
- So introducing the voltmeter *lowers* the effective resistance of R_2 and hence *lowers* the voltage across R_2
- But if $R_V >> R_2$:

$$R' = \frac{R_2 R_V}{R_2 + R_V} \approx \frac{R_2 R_V}{R_V} = R_2$$

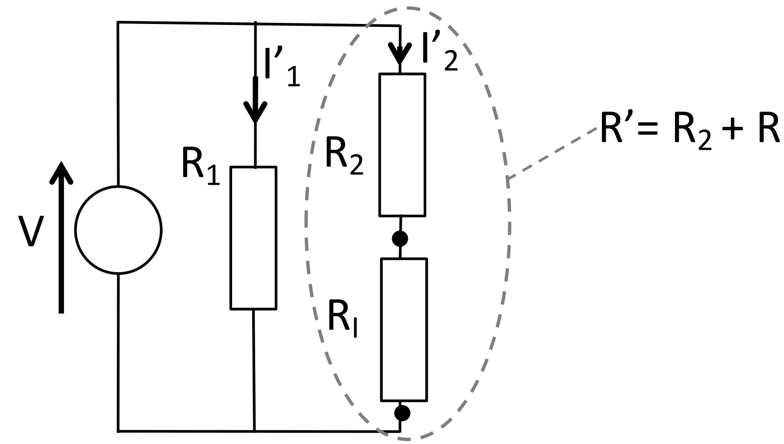
- Hence when measuring voltage:
  - The voltmeter goes *across* (in parallel with) the component whose voltage we wish to measure
  - The voltmeter must have a much *higher* resistance (impedance) than the resistance of the component

Measuring Current

- Suppose we want to measure the current I_2 flowing in the resistor R_2



- To do so, we attach a current meter *in series with* R_2
- But the current meter has an *internal resistance* equal to R_I



- So attaching the current meter *increases* the effective resistance of R_2 and hence *lowers* the current flowing in R_2
- But if $R_I << R_2$, $R' \approx R_2$
- Hence when measuring current:
  - The current meter goes *in series* with the component whose current we wish to measure
  - The current meter must have a much *lower* resistance (impedance) than the resistance of the component

Meters in the Lewin Lab

- These are interchangeable as voltage/current meters.
- The DigiTek meter can also measure frequency and temperature

Summary

- We started by discussing electric charge and electric current (electrons flowing in a material)
- Electric potential (voltage) was then introduced
- This led on to a simple circuit and introduction of a voltage source (battery) and a resistor (lamp).
- Similarities to a water circuit were discussed
- Ohm's Law: $V = IR$
- Resistors in series and in parallel
- Variable resistors
- Implications of internal resistance of meters when measuring voltage and current in a circuit