EUROPEAN UNION
MINISTRY OF EDUCATION, YOUTH AND SPORTS
OP Education for Competitivness

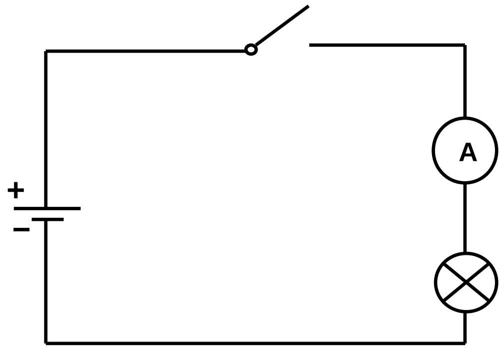
I N V E S T I C E   D O   R O Z V O J E   V Z D Ě L Á V Á N Í

ELECTRIC CURRENT IN METALS

1. Electric current (*I*). Sources of direct current

- **electric current** = the flow of free charged particles between the points at different potential
- positive particles (kations, holes) move in the direction of $\vec{E}$. Conventional direction of *I*: from + to –
- negative particles (electrons, anions) move against $\vec{E}$: from – to +, it is against the conventional current!

- **simple circuit**



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

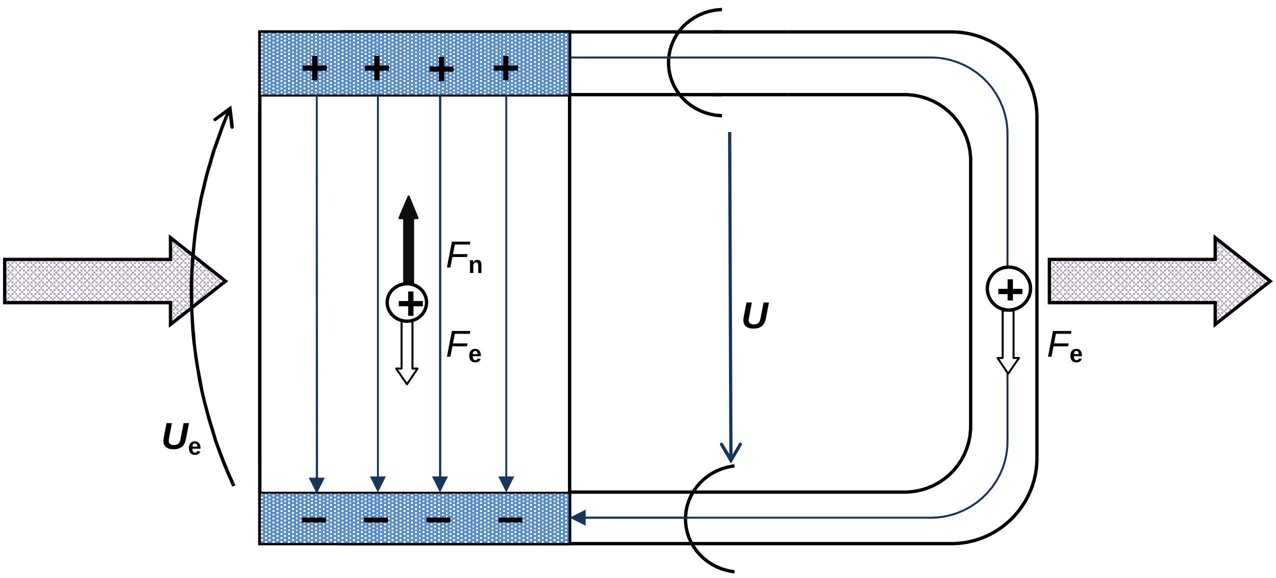
Q ... charge passing any cross-section
t ... time interval

$[I] = \mathrm{A}$ (ampere, amp)

Definition of 1 A – the basic unit of SI system:
2 parallel infinitely long conductors in vacuum
1 m apart, carrying 1 A each
the force (magnetic) between them is then 2×10^{-7} N per metre of their common length

- $Q = It \quad \Rightarrow \quad [Q] = \mathrm{A \cdot s}$

- **sources of d.c.** have to keep the same potential difference (voltage) between the + and – pole, energy must be supplied from "outside"



- **sources of d.c.**

a) simple cell – 2 different metals separated by some electrolyte – the work in the source is done because of chemical reaction – the chemicals change
b) photocell – energy carried by electromagnetic wave is converted into el. energy – renewable source
c) thermocouple – 2 different metals and 2 junctions between at different temperature – steady flow of very small *I* – see Y4 measurement of temperature
d) rectification of a.c. – widely used, will be explained later within a.c. topic

2. Conduction in metals

- structure of metals – kations form a crystal lattice, valency electrons are free to move – shared – “sea of electrons“
- 2 types of motion of free electrons

  - random chaotic motion – always present, $v \approx 10^{5 \text{ or } 6}$ m·s^{-1}
  - because of the outer electric field – drift velocity, just mm·s^{-1}!

$v = \mu_e E$

μ_e ... material constant

depends on number of el. in m^3

for Cu wire I = 1 A, A = 0.1 mm^2 drift velocity equals only about 0.6 mm·s^{-1}

- **resistance *R***

  represents an “obstacle“ to electric current

  $R = \frac{U}{I}$ The resistance is the ratio of the p.d. across the component (metal) to the current flowing through it

  $[R] = \frac{\text{V}}{\text{A}} = \Omega$ (ohm)

Ohm’s law for part of a circuit
The resistance of a metallic conductor does not change with p.d. provided the temperature is constant

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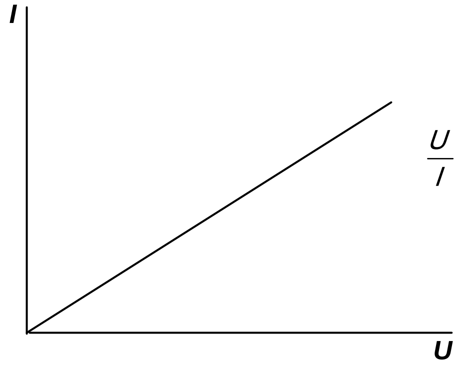
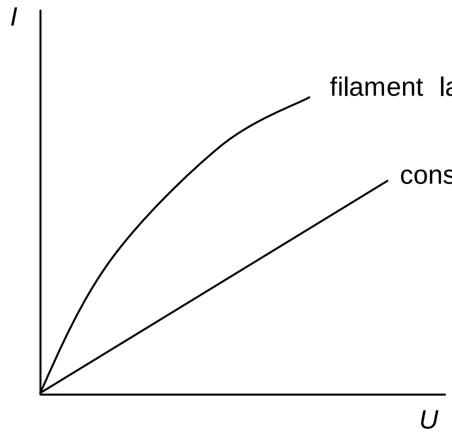
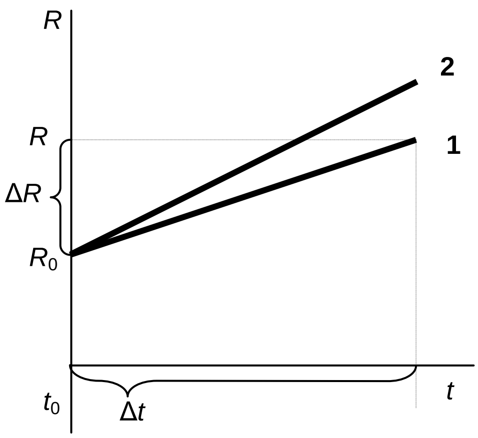
- *I*-*U* graph or the characteristic of a component



$\frac{U}{I} = R = \text{const.}$ when t = const.

- **What if the temperature of metal changes?**
  When *temperature rises* (e.g. due to current passing) the crystal lattice vibrates more – bigger obstacle to current, but the number of free e^- stays the same (sea of e^- = e^- from the last shell) $\Rightarrow$ *resistance of metals rises as well*





$\Delta R \approx \Delta t$, R_0 (at 20 ^{0}C), material (α) ... temperature coefficient of resistance

$$\alpha = \frac{\Delta R}{R_0 \Delta t}$$

$\Delta R = R_0 \alpha \Delta t$ change in resistance

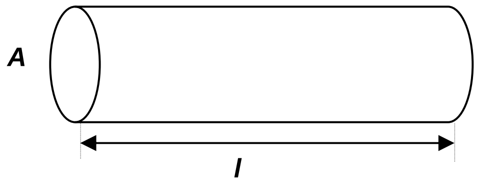
$R = R_0 + \Delta R = R_0 (1 + \alpha \Delta t)$ new resistance

- **conductance** G

$G = \frac{1}{R} = \frac{I}{U}$ $[G] = \Omega^{-1} = \mathrm{S}$ (siemens)

- **resistivity** ρ

The resistance of a metallic conductor depends on its dimensions (valid for other materials as well)



$R \approx l, \frac{1}{A}$, material (ρ) $R = \rho \frac{l}{A}$

$$\{\rho\} = \{R\} \Leftrightarrow l = 1\mathrm{m} \wedge A = 1\mathrm{m}^2$$

$$\rho = R \frac{A}{l}$$

$$[\rho] = \Omega \frac{\mathrm{m}^2}{\mathrm{m}} = \Omega \cdot \mathrm{m}$$

resistivity and change of temperature – the same as for resistance

$$\rho = \rho_0 (1 + \alpha \Delta t)$$

Questions:

1. Suppose a charge 15 C passing in 20 min through a conductor which is joined to the source of voltage 4.5 V. Find the resistance of the conductor.

2. What length of constantan wire of diameter 0.40 mm has a resistance of 20.0 ohms? Assume that resistivity of constantan is 5.0×10^{-7} Ω·m.

L5/58-63, 66-68, x71, 72, 74-82

material	**resistivity** in $\Omega \cdot m$	$\boldsymbol{\alpha}$ in 10^{-3} K^{-1}	**use**
silver	1.6×10^{-8}	3.8	
copper	1.7×10^{-8}	4	
aluminium	2.4×10^{-8}	4	
constantan	4.9×10^{-7}	0.05	
nichrome	1.1×10^{-6}	0.18	
carbon	3×10^{-5}		
germanium	0.6		
silicon	2 300		
glass	10^{10}-10^{14}		

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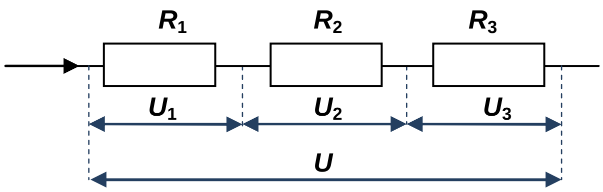
3. Resistor networks

- **resistors in series**



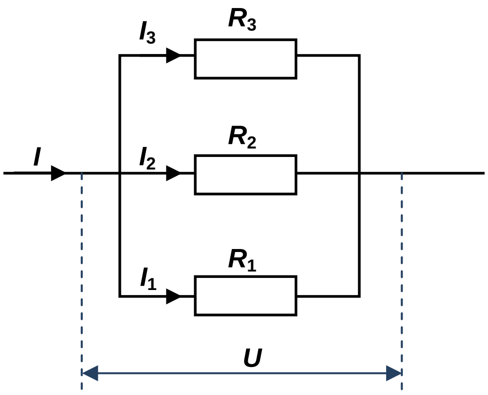
$$U = U_1 + U_2 + U_3$$

$$I = I_1 = I_2 = I_3 \qquad U = RI$$

$$RI = R_1 I + R_2 I + R_3 I$$

$$R = R_1 + R_2 + R_3$$

- **resistors in parallel**



$$U = U_1 = U_2 = U_3$$

$$I = I_1 + I_2 + I_3$$

$$\frac{U}{R} = \frac{U}{R_1} + \frac{U}{R_2} + \frac{U}{R_3}$$

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

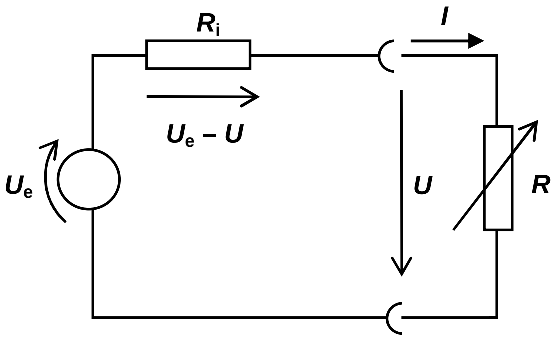
Questions:

3. Calculate the total resistance of two resistors (15 Ω , 20 Ω) connected in a) series b) parallel. Take the voltage across both to be 24V. Calculate the voltages on each resistor and the currents passing both for a) and b) connection.

L5/ 84-95, 125-127, 132, 134-6, 139-142

4. Electromotive force, internal resistance (R_i)

When we take a source e.g. a simple cell and measure the voltage when it is not used as a source – **no current passing**, we have measured in fact its **electromotive force**. If we measure the voltage of the same cell when it supplies current e.g. for a bulb in a torch, the value is smaller than the electromotive force. It is a general property of any source. The good quality sources have almost no effect in the value of voltage. We can describe the behaviour of the source using a theoretical quantity internal resistance. HQ sources have small R_i.



Ohm's law for the whole circuit: $U_e = R_i I + RI = R_i I + U = I(R_i + R)$

Questions:

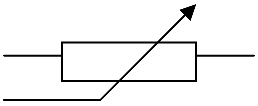
4. A battery with an e.m.f. 12 V and internal resistance 2 Ω is connected to a wire-wound resistor of resistance 10 ohms. a) Calculate the p.d. across the 10 ohm resistor. b) What will the p.d. across the 10 ohm resistor be if a 15 ohm resistor is connected in parallel with the 10 ohm resistor? Sketch figures for both situations.

5. Suppose a high-resistance voltmeter reads 1.5 V when connected across a dry battery on open circuit, and 1.2 V when the same battery is supplying a current of 0.35 A through a lamp of resistance R. What is:
a) the e.m.f. of the battery
b) the internal resistance of the battery
c) the value of R

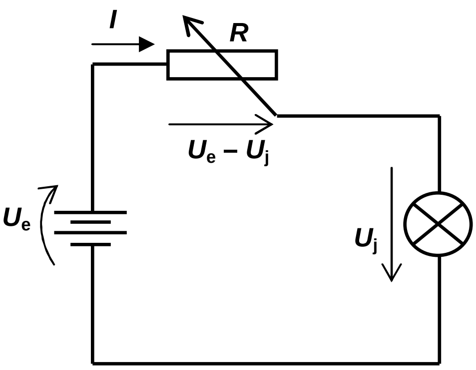
L5/ 96-100, 102-105, 109, 111, 115

5. Components in electric circuits

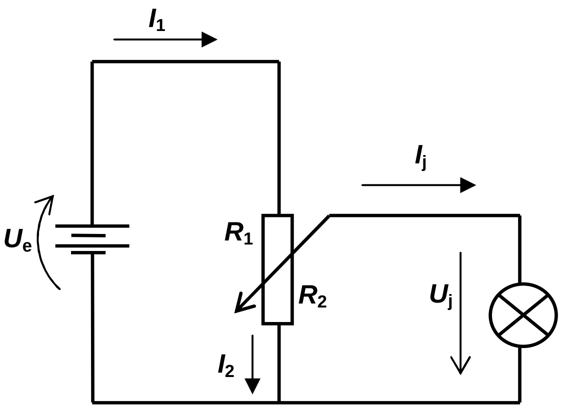
- **potentiometer**



as a **RHEOSTAT** – changing resistance in the circuit



as a **POTENTIAL DIVIDER** – when smaller voltage than the source offers is needed



- **ammeter**

measures the current passing THROUGH IT, so it must have negligible resistance to cause a minimum disturbance to the outer circuit.
It is connected ONLY IN ....

Sketch the circuit with a source, bulb and ammeter:

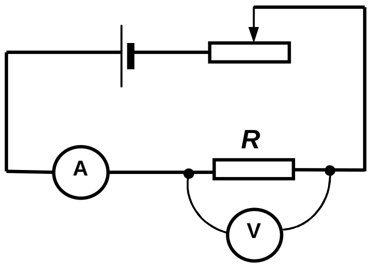
- **voltmeter**

measures the voltage across any component, source or part of a circuit.

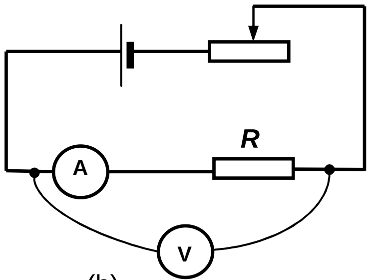
It is connected ONLY IN ....

Sketch the circuit with a source, bulb, voltmeter and ammeter:

Discuss the difference between the following connections and values of current and voltage measured in each:



(a)



(b)

- **multimeter** (see additional materials)

is a combined device used to measure currents, voltages, resistances and sometimes other special quantities. It contains AD (analogue-digital) converter. You can change the scale as can be seen on the figure (in add. mat). Values can be seen on the display. Be careful about the connection of an ammeter (why?).

6. Kirchhoff's laws

are the statements that have been made about steady currents and electromotive forces in series and parallel circuits.

- **First Kirchhoff's Law**

At a junction in a circuit,

$$\sum_{k=1}^{n} I_k = 0$$

the current arriving equals to the current leaving.

- **Second Kirchhoff's Law**

Round any closed circuit or loop,

the algebraic sum of the electromotive

$$\sum_{i=1}^{m} U_{ei} = \sum_{k=1}^{n} R_k I_k$$

forces equals to the algebraic sum
of the products of current and resistance.

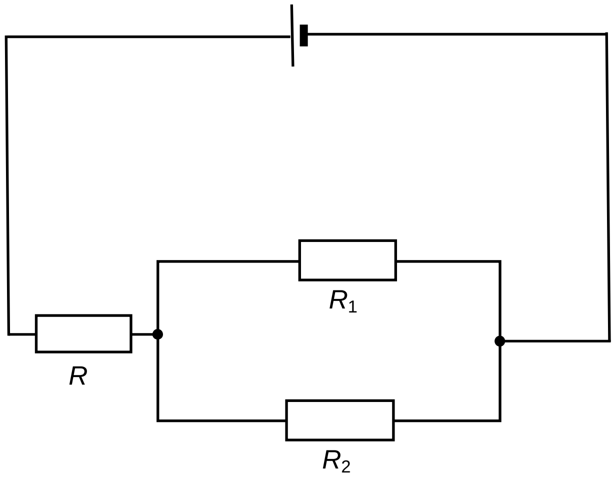
Using the laws we are expected to get the set of independent equations to solve the currents through different branches of the circuit etc. To be successful requires the understanding of proper SIGN CONVENTION, which is applied later.

METHOD:

1. *CHOOSE:*
    - *the loops – all components must be included*
    - *direction of calculation – recommended clockwise as it is more natural*
    - *direction of current – if the real is opposite we get negative value of the particular current*
2. *LABEL: the gain in potential across the source – from – to +*
3. *Write eqns - 1. KL and 2. KL*
   When the direction of calculation is against the direction of the current passing through the resistor, take RI as negative. When the gain in potential is against the direction of calculation, take U_e as negative.

Questions:

6. Stipulate currents in particular resistors if R = 2.6 Ω, R_1 = 4 Ω, R_2 = 6 Ω, U_e = 10 V
a) without Kirhoff´s laws b) using Kirhoff´s laws



4. Electric work, power and efficiency

- **electric work** (W)

rev.: $\varphi_B - \varphi_A = U = \dfrac{W}{Q}$

$$W = UQ = UIt = RI^2 t = \frac{U^2}{R}t$$

$[W] = \mathrm{J}$

- **electric power** (P)

$$P = \frac{W}{t} = UI = RI^2 = \frac{U^2}{R}$$

$[P] = \mathrm{W}$ (watt)

- **efficiency** (η)

$$\eta = \frac{W_{out}}{W_{in}} = \frac{E_{out}}{E_{in}} = \frac{P_{out}}{P_{in}} = \frac{U}{U_e} = \frac{R}{R + R_i} \leq 1$$

Questions:

7. A bulb is labelled 24 V, 150 W. Calculate the resistance and the current passing.

8. A resistor has the resistance $100\,\Omega$ and power 0.25 W. Calculate the current passing through it and voltage across it.

9. A cell of electromotive force 4.8 V and internal resistance 1.3 Ω is used as a source for a small bulb and then it supplies a current of 0.35 A. State the voltage on the bulb, power input and efficiency.

L5/170-201, x202-209

Answers:

1. 360 Ω
2. 5.0 m
3. a) 0.69 A; 10.3 V; 13.7 V   b) 1.6 A; 1.2 A; 24 V
4. 10 V; 9 V
5. 1.5 V; 0.86 Ω; 3.43 Ω
6. I = 2 A, I_1 = 1.2 A, I_2 = 0.8 A
7. 3.84 Ω; 6.25 A
8. 0.05 A; 5V
9. 4.345 V; 1.68 W; 90.5%