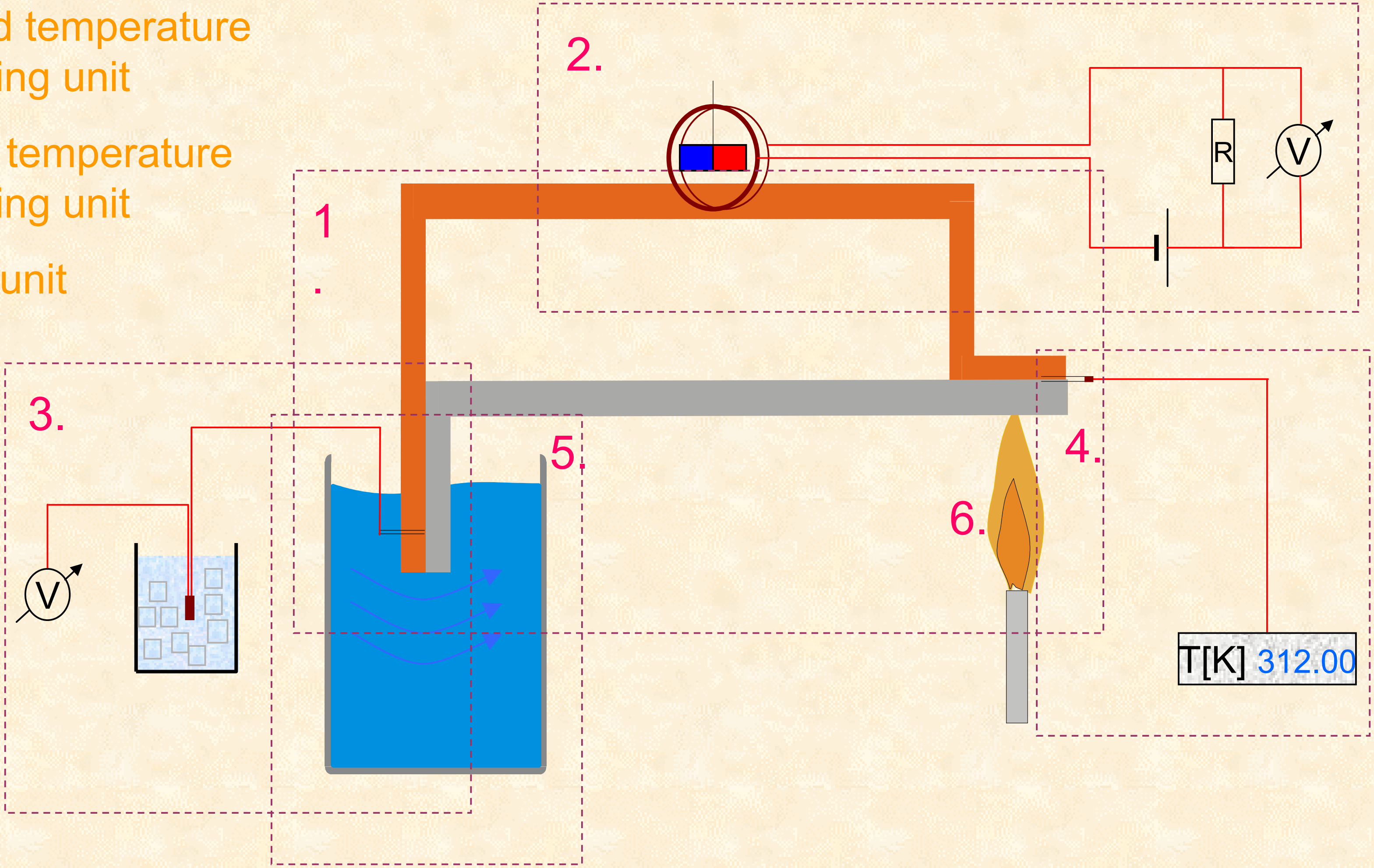
Apparatus

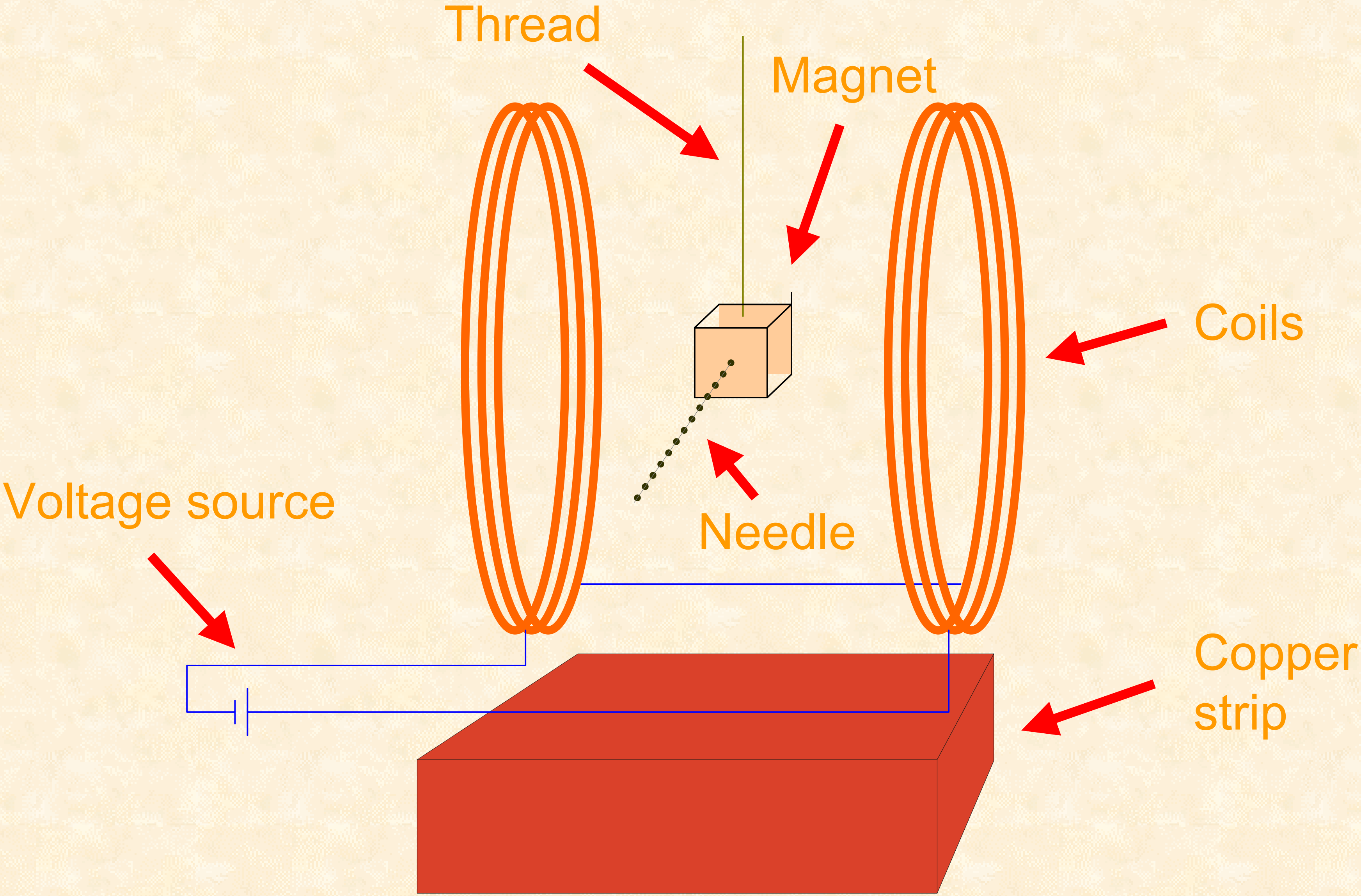
1. thermocouple
2. field measuring apparatus
3. cool end temperature measuring unit
4. hot end temperature measuring unit
5. cooling unit
6. heater



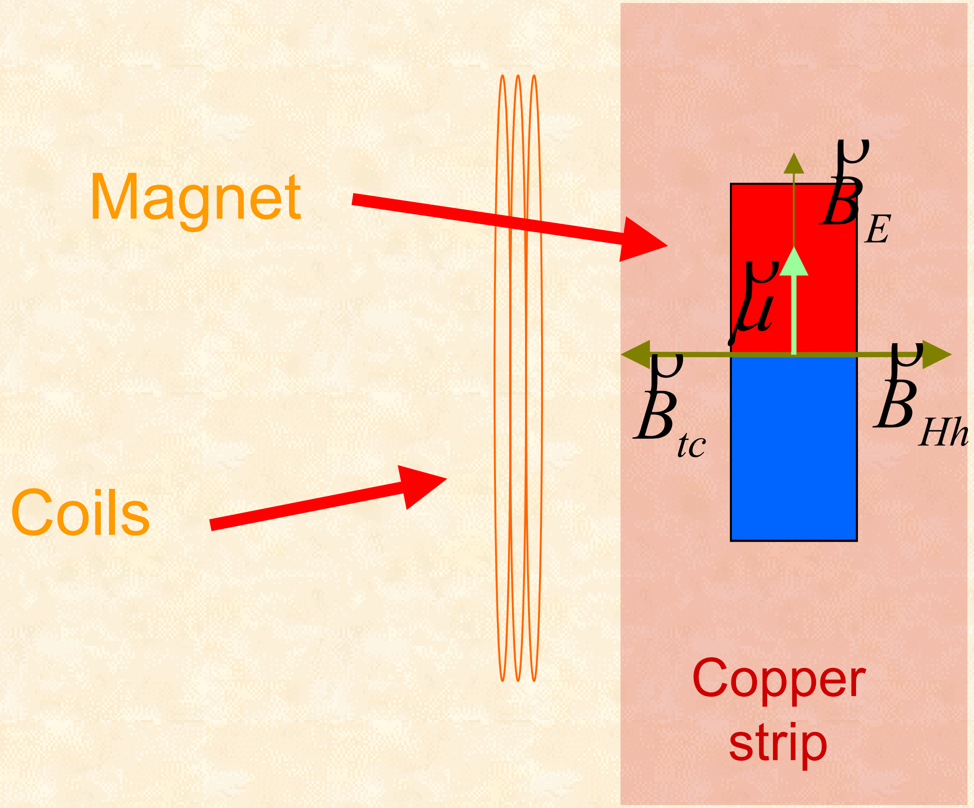
1. Thermocouple

- Material: copper – aluminium
- Width of metal strip: 3 cm
- Height of metal strip: 1 cm
- Net lenght: 17 cm

2. Field measuring apparatus



Principle of work



B_{tc} – thermocouple magnetic field

B_{Hh} – magnetic field of the coils

B_E – field of the Earth

μ – magnetic moment of the magnet

- When the field of the coils equals the thermocouple field the only remaining field acting on the magnet is the Earth field

- The magnet turns in the direction of the resultant field because of its magnetic moment:

$$\boldsymbol{\tau} = \boldsymbol{\mu} \times \mathbf{B}$$

τ – torque

μ – magnetic moment of the magnet

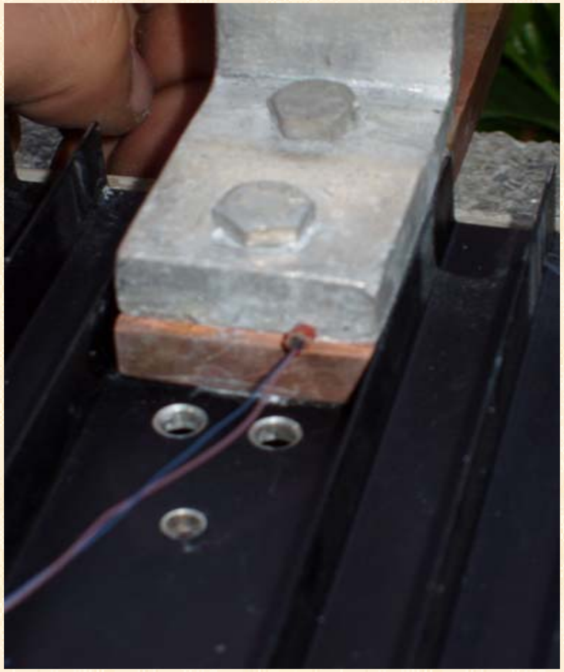
B – external magnetic field

- That torque causes rotation of the magnet until its magnetic moment is aligned with the field
- The equality of coils and thermocouple fields enables us to measure the thermocouple field easily

3. Temperature measuring units

Cool end

- A thermocouple was used



- The temperature was calculated from the obtained voltage

Hot end

- Because of high temperatures it was appropriate to use Pt - Rh thermocouple

4. Cooler and heater

- The cooling was accomplished by
    - constant water flow over the cooling rib
    - Liquid nitrogen

- The heater was a Danniel burner

- The temperature range of the whole system was

Cool end	Hot end
-150 °C to 50°C	0°C to 600°C

Theoretical approach

Describing the conduction electrons

- Electron gas properties:
    - Great density
    - Momentum conservation (approximately)
    - Free electrons (lattice defects and interactions neglected)

For many metals the free electron model is not valid – introduction of correction parameters

- Mathematical description – Fermi - Dirac energy distribution:

$$f(u) = \frac{1}{1 + e^{\frac{u-\eta}{kT}}}$$

f(u) – probability of finding an electron with energy *u*

η – highest occupied energy level - ˝Fermi level˝

k – Boltzmann constant

T – absolute temperature

(I. Supek: Teorijska fizika i struktura metreije, vol. 2)

- The Fermi level is a characteristic of the metal and depends of electron concentration and temperature:

$$\eta(T) = \eta_0 \left[1 - \frac{\pi}{12} \left(\frac{kT}{\eta_0} \right)^2 + \dots \right]$$

η_0 – Fermi level at 0 K

Contact potential

- At the join of two different metals a potential difference occurs
- This is due to different electron concentrations in the metals i.e. different Fermi levels
- Concentrations tend to equalize by electron diffusion
- The final potential difference is:

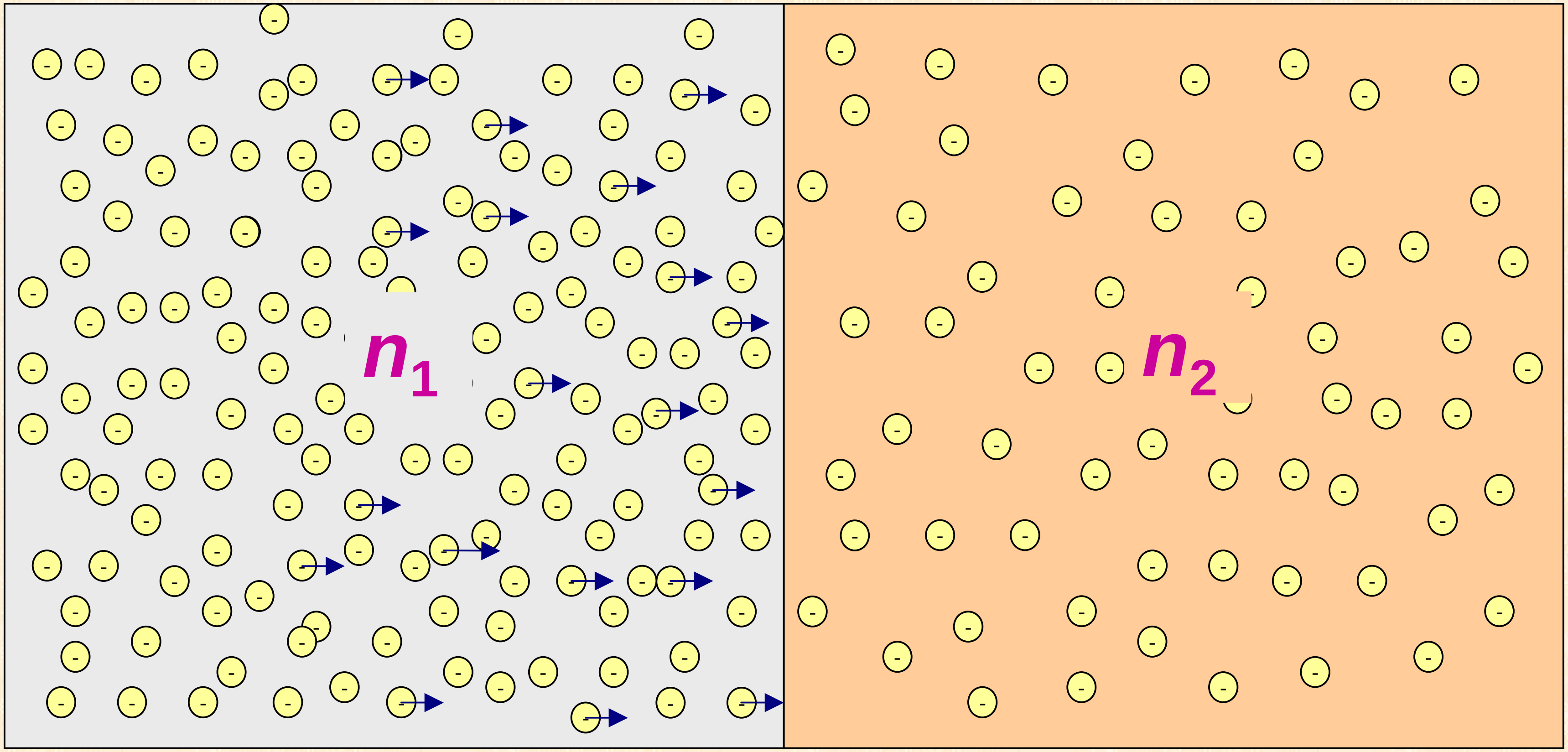
$$\Delta V = \frac{\eta_1 - \eta_2}{e}$$

ΔV – potential difference

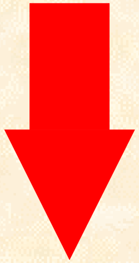
η_i – Fermi level of the *i* – th metal

e – charge of the electron

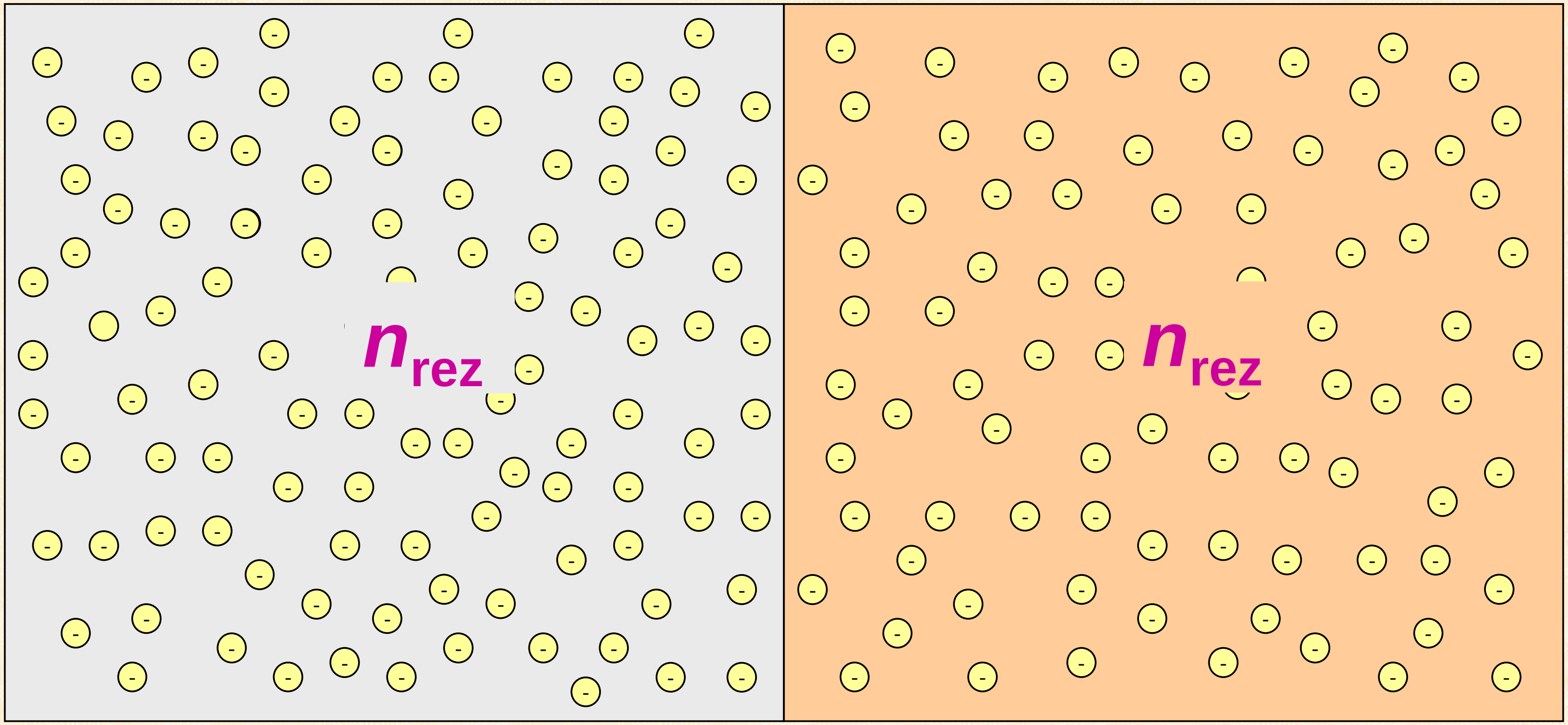
Noneqilibrium



diffusion



Equilibrium

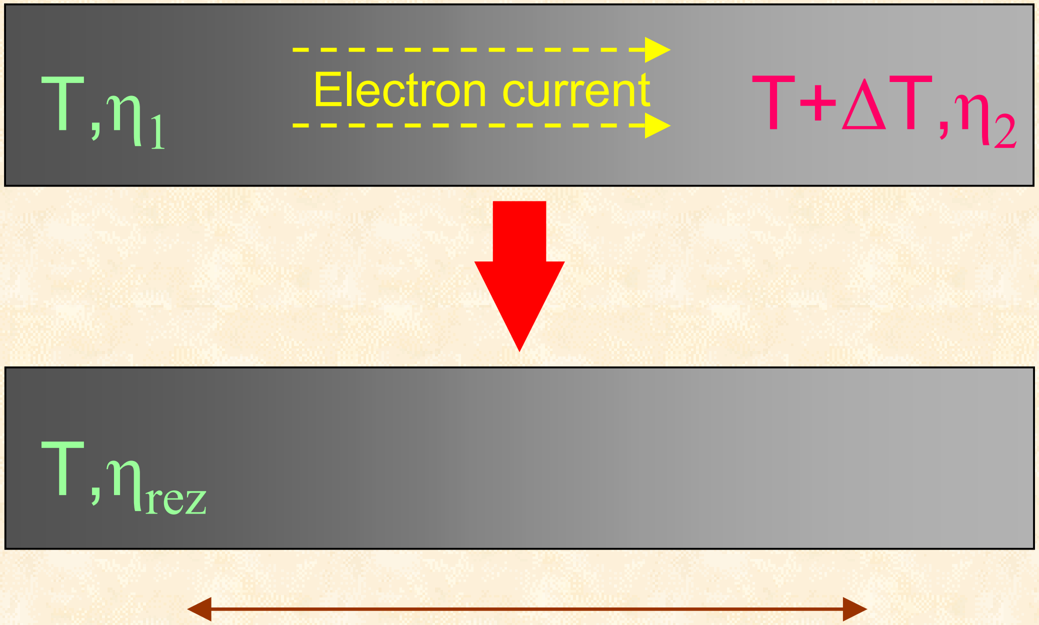


Shortage of electrons – net charge is positive

Surplus of electrons – net charge is negative

Thompson effect

- In a metal strip with ends at different temperatures a potential difference occurs (Thompson effect) because of different Fermi levels:



Nonequilibrium

T, η_1

Electron current

$T+\Delta T, \eta_2$

η_1, η_2 – initial Fermi energies

Equilibrium

T, η_{rez}

η_{rez} – equilibrium Fermi energy

Voltage difference

Seebeck effect

- The voltage in the thermocouple is:

$$dV = S_{AB}\,dT$$

dV – voltage difference

S_{AB} - ˝Seebeck coefficient˝ of the metal pair

$$S_{AB} = S_{AB}(T) \qquad S_{AB} = S_A - S_B$$

S_A, S_B – Seebeck coefficients of single metals (compared to a reference metal)

dT – temeprature difference of the joins

- The Seebeck coefficients can be determined considering the Thompson effect

$$S_A = \frac{\pi^2 k^2 T}{6\eta_0 e}$$

k – Boltzmann constant

T – temeprature of the metal

η_0 – Fermi level at 0 K

e – elementary charge

- For correcting the free electron model a correction constant of order 1 has to be introduced

$$S_A = \frac{\chi \pi^2 k^2 T}{6\eta_0 e}$$

$$\Rightarrow V_{AB} = a\left(T_B - T_A\right)^2 + b\left(T_B - T_A\right)$$

a, *b* – constants

T_A, T_B – junction temperatures

Seebeck coefficents

metal	Fermi - level at 0 K [eV]	measured S_A [μV/K]	theoretical S_A (free electrons) [μV/K]	hi
Na	3,10	-2,00	7,80	-0,26
Al	11,60	3,50	2,08	1,68
K	2,00	-9,00	12,09	-0,74
Cu	7,00	6,50	3,45	1,88
Ag	5,50	6,50	4,40	1,48
Au	5,50	6,50	4,40	1,48

Source for measured data:

www.materials.usask.ca

Experimental results

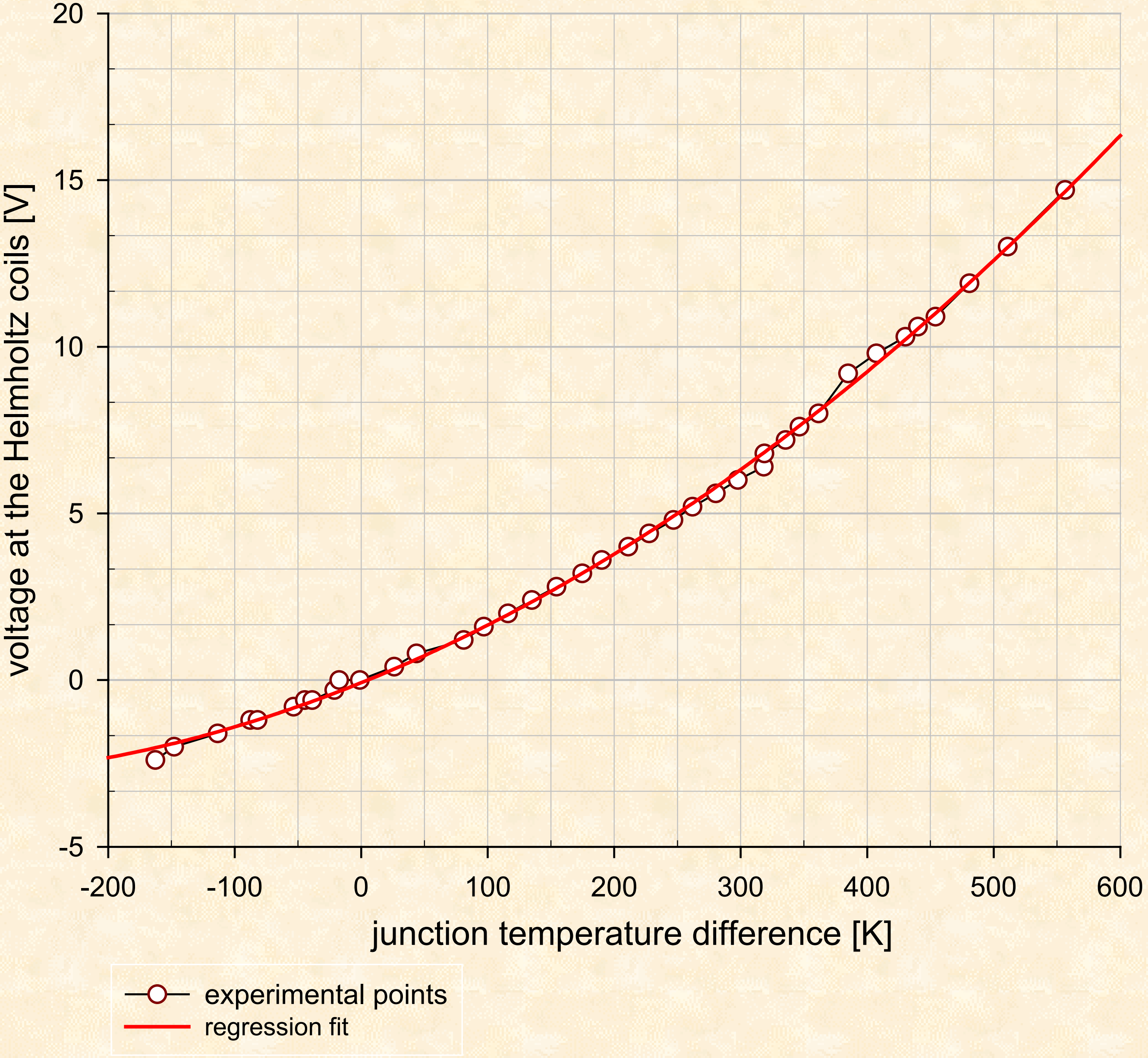
- The field we measured is approximately proportional to the potential difference:

$$\left|\vec{B}_{tc}\right| = \alpha\left(T_B - T_A\right)^2 + \beta\left(T_B - T_A\right)$$

α, β – constants

B_{tc} – thermocouple field

- The constants α and β have been obtained experimentally but a direct nimerical comparation to the theoretical voltage was impossible due to the unknown coefficient of proportionality:



Fit:

$$\Delta V_{Hh} = 0.0153\Delta T^2 - 0.0784\Delta T$$

ΔT – junction temperature difference

Field constants:

Conclusion

- Thermocouple voltage (and mgnetic field of the couple) will have a maximum if:
    - The constant *a* in the thermocouple equation is negative
    - The constant *b* in the thermocouple equation is positive

- The sign of these constants depends on the metals used in the couple
- For our Cu – Al couple the function $B(\Delta T)$ showed a minimum and no maximum