Phys. I: Heat & temperature

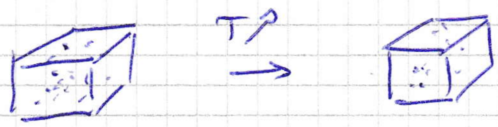
- What is temperature ..? what does it measure?

<u>for instance</u>: 1) gas at temperature T_1, what happens with $T\nearrow$ to $T_2 > T_1$?

<u>gas</u>

$\Rightarrow$ expansion of gas, lower density ρ (kg/m³) : relation T, V
(larger volume V, [m³])

2) if volume fixed (box) and $T\nearrow$ ...?



gas

$V_1 = V = $ const $\qquad$ $V_2 = V$, const

p_1, T_1 $\qquad$ $T_2 > T_1$, $\Rightarrow p_2 > p_1$

$\Rightarrow$ relationship p, V, T $\rightarrow$ gas laws

<u>Thermodynamics</u>

macroscopic description

<u>example, solid system</u> slide . metal plate expansion question
(" " with hole)

if $T\nearrow$, hole $\phi \nearrow$ ... why?

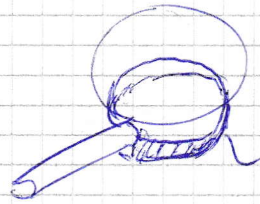
explanation: as $T\nearrow$, the average distance (~~in the material~~) between atoms increase as well, at every point in the material (plate)

that implies that the ϕ ~~with~~ of the hole in the plate will also increase.

<u>Statistical mechanic</u>

microscopic description

$\boxed{\text{Exp}}$



ring + sphere; heate ring
$\Rightarrow$ sphere falls through

Reminder $\boxed{\text{Heat \& temperature}}$ Summary

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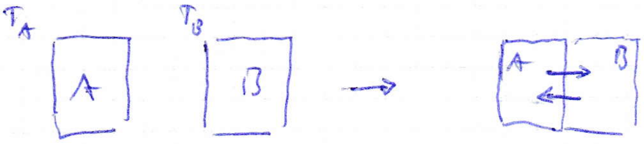
1.12.2017

- def: 2 objects have the same Temperature T
  Temperature | if they are in thermal equilibrium

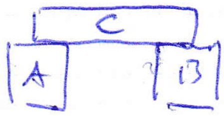
def: thermal equilibrium



energy exchange (heat), symbol Q; $[Q] = J$.

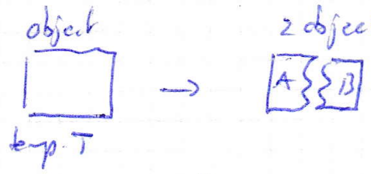
$T_A = T_B$
$[T] = K$

"zeroth" law of thermodynamics
(sets basis to define a temperature scale)



when A and B are in thermal eq. with C, than they are in " " with each other

- Temperature: (qualitatively)
  - measure of energy: kinetic energy of the constituents of an object (atoms, molecules)
    average value (many atoms)
    (12 gr of Carbon ~ $6 \cdot 10^{23}$ atoms of C)
  - is an intensive quantity:



$T_A = T_B = T$

(mass is extensive for instance

$m = m_1 + m_2$

- microscopic picture: when $T \nearrow$, avg distance between neighboring atoms $(r) \nearrow$

  e.g.: melting criterion (Lindemann), qualitative guess
  u: amplitude of vibration for 1 atom
  $\langle u^2 \rangle$: mean square thermal average amplitude of vibration

  melting $(T = T_m)$ when $\langle u^2 \rangle = c_L \cdot a^2$
  a: interatomic distance
  c_L: constant (Lindemann)
  $c_L \leq 0.5$

slide Temperature of places / phenomena

Temperature measurement (and scale)

Quest: how to measure T without having access to the microscopic motion of atoms and molecules?

Answer: use the dependence of physical properties on temperature to create/build thermometers.

e.g. · volume (of a fluid?) of a gas (versus temperature)
· length (dimensions) of a metallic rod (vs T)
· pressure of a fixed volume gas cell
....

|| Any thermometric (i.e.: temperature dependent) property can be used to define a temperature scale

(slide) Examples: · mercury (Hg) thermometer
· disappearing filament pyrometer

· Definition of the Kelvin scale (or absolute temperature scale)

1 Kelvin [K] : SI unit for temperature

Uses triple point of water: · more precisely defined than freezing or boiling point of water

· ~~Temp.~~ where water vapor, water and ice (and pressure) coexist in equilibrium

(slide) p-T phase diagram of water + ice

Definition || $T_{tr} = 273.16\ K$ ($p_{tr} = 611.657\ Pa$)
for the temperature of the triple point of water. pressure

absolute zero temp $T_0 = 0\ K$
(no microscopic motion)

| Celsius → °/c
Fahrenheit

Celsius scale : $0^\circ C$: temperature of melting ice

$100^\circ C$: temperature of boiling water (pressure dependent...)

both at $p = 1\,atm$

$= 1.01325\,10^5\,Pa$ (Pascal) ($1.01\,10^5\,Pa$)

$= 1.01325\,bar$ " N/m^2

$$T_K = T_{^\circ C} + 273.15\,K \; ; \; T_{^\circ C} = T_K - 273.15\,^\circ C$$

$$\Delta T_K = \Delta T_{^\circ C}$$

For info : Fahrenheit scale def : freezing point of water : $32\,^\circ F$

boiling " " $212\,^\circ F$

Slide Temperature of places & phenomena again briefly

Gas thermometer & fluid thermometer

can work at $p = \text{const}$ (pressure) or $V = \text{const}$ (volume)

example: $V \propto T \quad (p = \text{const})$

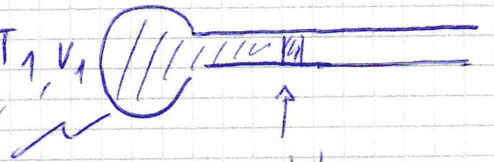
a gas expands when heated and $V \propto T$ (linear)

i.e. $\frac{V_1}{T_1} = \frac{V_2}{T_2} = \ldots = \text{const}$

$\Rightarrow \quad T = \frac{V}{k_{\text{onst}_V}}$ (Charles law)

experimental system:

T_1, V_1

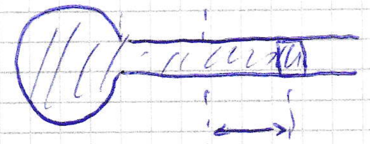


$P = \text{const}$

glass vial with gas

mobile "plug", moves when T changes, indicating the effective gas volume at pressure p

T_2, V_2 $(T_2 > T_1)$



$P = \text{const}$

Δl

$\Delta V = A \cdot \Delta l$, A cross section of glass tube

By measuring ΔV, we obtain $\Delta T \; (= \Delta V / k_V)$

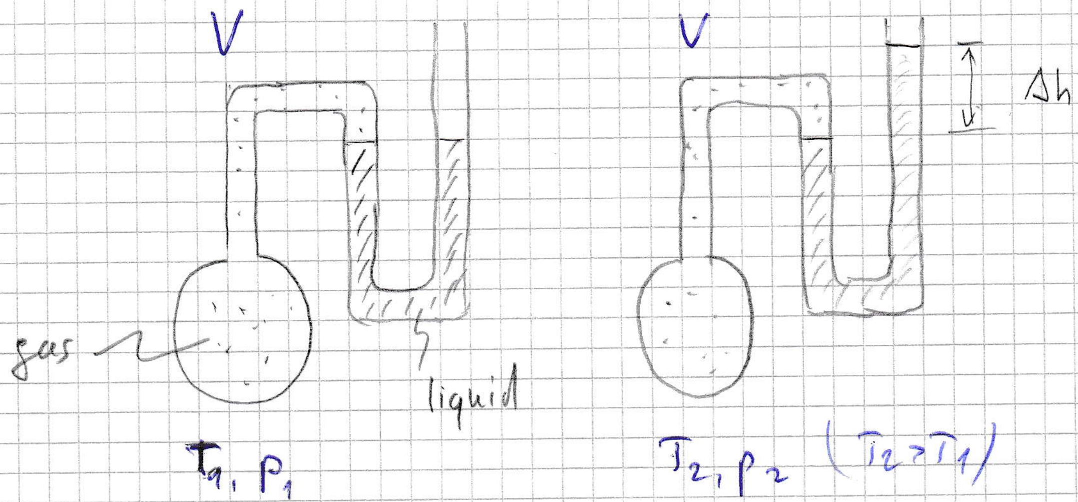
example: $p \propto T$, $V = const$

at constant volume, the pressure of a gas increases when T increases and $p \propto T$ (linear)

thus $\frac{p_1}{T_1} = \frac{p_2}{T_2} = const$ ~~α_p~~

and $T = \cancel{\frac{p}{\alpha_p}} = \frac{p}{const_p}$

exp. system:



Total gas volume ~ const (V) (gas container with larger volume than capillar tubes)

When $T \nearrow$, $p \nearrow$ and the liquid is pushed higher up in the tube $\Rightarrow$ $\Delta h > 0$

$\Delta h \propto \Delta p$, pressure increase, $\Delta p = p_2 - p_1 \propto \Delta T$

↑ proportional to

$\Rightarrow \Delta h \propto \Delta T$

$\boxed{Exp}$: 1) gas thermometer

2) fluid thermometer: Hg; exp: water, here

Thermocouple thermometer

- Seebeck effect (qualitative)

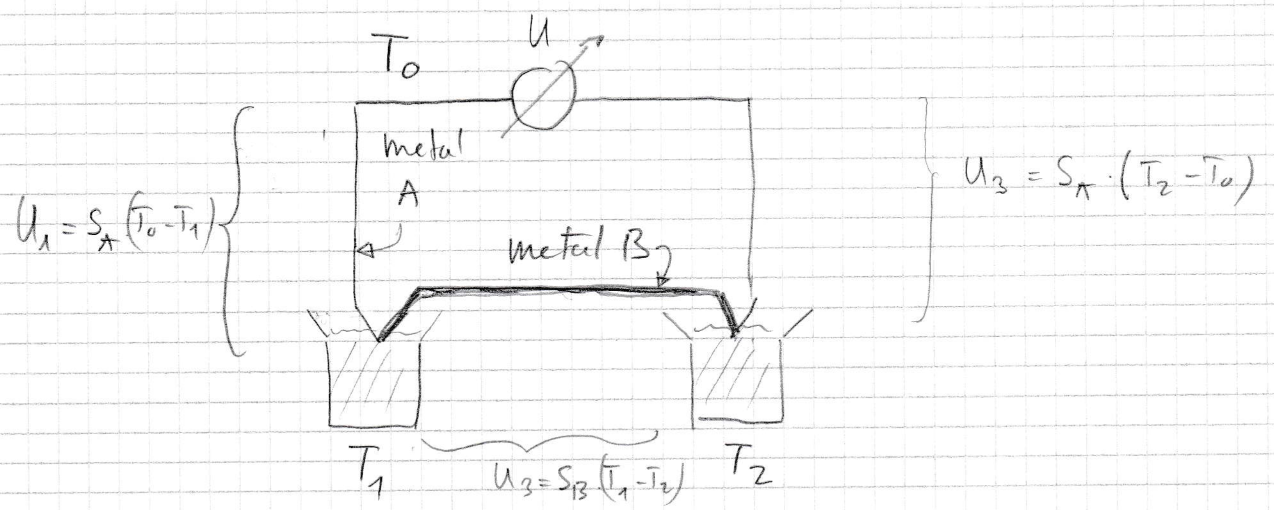
$$U = S \cdot \Delta T \quad , \text{ with } S \sim \text{few } \mu V/K$$

U ↑ Voltage (potential difference)

S ↑ Seebeck coefficient

Slide Seebeck coeff.

- Experimental system: needs 2 metalli junctions (1 metal $\to U = 0$) see below



Where do thermovoltages appear ...? U_1, U_2, U_3

Overall voltage $U = U_1 + U_2 + U_3$

$$= S_A \cdot (T_0 - T_1) + S_B \cdot (T_1 - T_2) + S_A \cdot (T_2 - T_0)$$

$$= S_A \cdot (T_2 - T_1) - S_B (T_2 - T_1)$$

$$\| \; U = (S_A - S_B) \cdot (T_2 - T_1)$$

if $S_A = S_B$, $U = 0$. $\Rightarrow$ need 2 different metals with $S_A \neq S_B$.

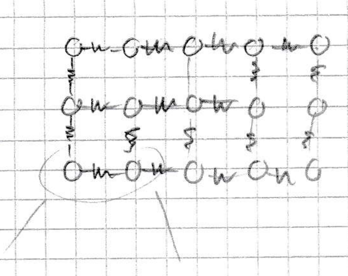
$\Rightarrow$ We can measure a temperature difference, not the absolute temperature (using the Seebeck effect)

$\boxed{\text{Exp}}$ thermocouple : metal A: Cu

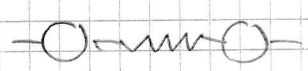
metal B :

Thermal expansion

- microscopic picture (of matter) & expansion



lattice of atoms with interatomic interaction (= crystal structure)

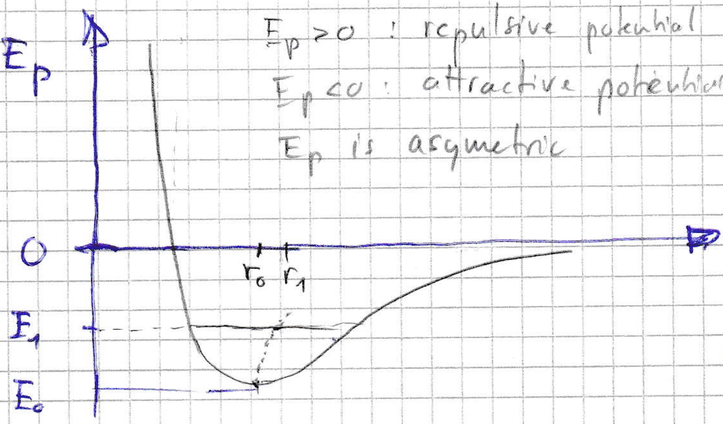


binding energy between atoms : E_p potential energy

(remember coupled oscillators)

interatomic potential (potential energy)

$E_p > 0$: repulsive potential
$E_p < 0$: attractive potential
E_p is asymetric



at $T = 0$, $E_{kin} = E_k = 0$, no kinetic energy (atoms at rest)

and $E_0 = E_k + E_p = E_p$ / r_0 : avg. distance between 2 atoms

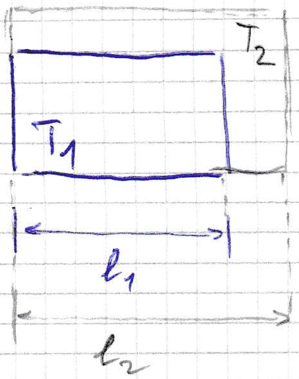
at $T_1 > 0$, $E_1 = E_k + E_p > E_0$, as $E_k > 0$

$r_1 > r_0$

As $T \nearrow$, $r \nearrow$ $\forall$ atoms in a crystal / material

Macroscopically : if all atoms grow further apart from each other with increasing temperature, the solid (macroscopic object composed of many atoms) will expand with temperature (increase its volume)

· macroscopic picture (of expansion)



$$l_2 - l_1 = \Delta l$$
$$T_2 - T_1 = \Delta T$$

$$\frac{\Delta l}{l} = \alpha_L \cdot \Delta T$$

linear expansion coefficient $[\alpha_L] = \frac{1}{K}$

Slide linear exp coefficients

typ. $\sim 10^{-6}\ K^{-1}$

Exp Eisen Draht

or → do volume expansion first

thermal expansion (1D), reminder

distance between atoms increases (on avg) => expansion

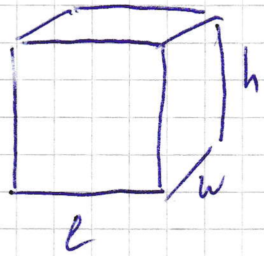
$$\left\| \frac{\Delta l}{l} = \alpha_l \cdot \Delta T \right.$$

α_l ↑ linear expansion coefficient

$$[\alpha_l] = \frac{1}{K}$$

slide: Linear exp. coeff. values (table)

for a volume:



$V_1 = l \cdot w \cdot h$ at ambient T

V_2 at $T_2 > T_1$

$$\frac{\Delta V}{V} = \frac{V_2 - V_1}{V_1}$$

$$V_1 = l \cdot w \cdot h$$

$$V_2 = (l + \Delta l) \cdot (w + \Delta w) \cdot (h + \Delta h) = l\left(1 + \frac{\Delta l}{l}\right) \cdot (w + \Delta w) \cdot (h + \Delta h)$$

$$= \underbrace{l \cdot w \cdot h}_{V_1} \cdot \left(1 + \frac{\Delta l}{l}\right) \cdot \left(1 + \frac{\Delta w}{w}\right) \cdot \left(1 + \underbrace{\frac{\Delta h}{h}}_{\alpha_l \cdot \Delta T}\right)$$

$$= V_1 \cdot (1 + \alpha_l \cdot \Delta T)^3$$

$$\cong V_1 \cdot (1 + 3\alpha_l \cdot \Delta T)$$

%

$\alpha_l \sim 10^{-6}$

$\Rightarrow \alpha_l \cdot \Delta T \ll 1$ at "reasonable" temperatures

and $\dfrac{\Delta V}{V} = \dfrac{V_2 - V_1}{V_1}$

$$\boxed{\frac{\Delta V}{V} \cong 3\alpha_l \cdot \Delta T = \alpha_V \cdot \Delta T} \quad , \quad [\alpha_V] = \frac{1}{K}$$

~~slides~~

exp: Iron wire expansion + slide %

slides: 1) α_l, α_V; 2) volume expansion / road exp Fe wire

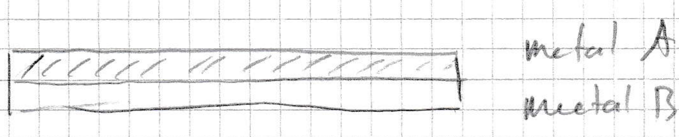
75 V, 28 A = 2.1 kW

$l = 2.80\,m$

- upon cooling, check the "hicup" (down and up again) corresponds to phase transition

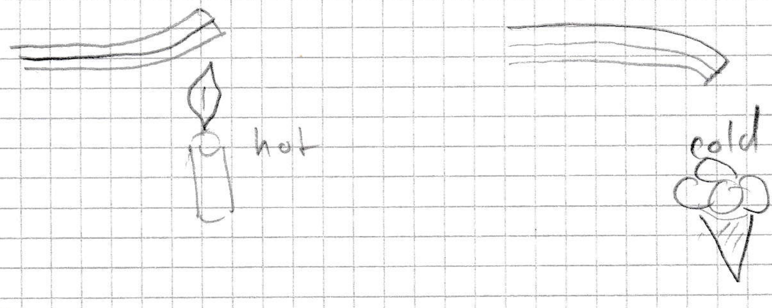
$$(1+\varepsilon)^n \underset{\varepsilon \ll 1}{\approx} 1 + n\varepsilon$$

Bi-metal thermometer



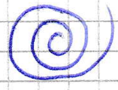
strip of 2 metals A, B with different coefficients of linear thermal expansion

If T ↗ (or ↘), metals A & B will expand (contract) differently :



$\boxed{\text{Exp}}$ 1) bi-metal strip

2) snapping metal : thermostat

3) spring thermometer :  bimetal, on retro projector, warm up

$\boxed{\text{Exp}}$ IR camera to "see" (measure) temperature

- ball (metal) on wood : i-pact position flow
- rub shoe on floor
- metal plate,