Bi-metal thermometer

metal A
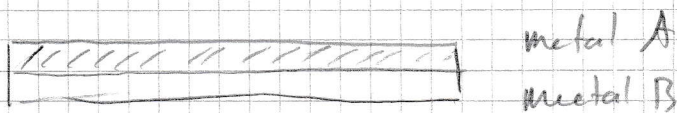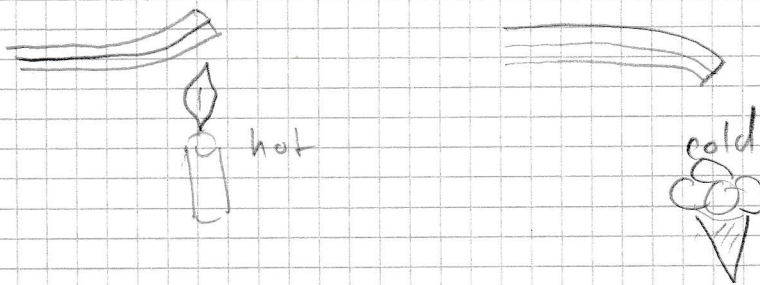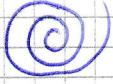metal B

Strip of 2 metals A, B with different coefficient of linear thermal expansion

If $T \nearrow$ (or $\searrow$), metals A & B will expand (contract) differently :

hot

cold

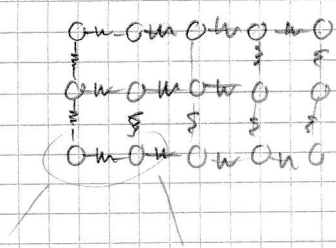[Exp] 1) bi-metal strip

2) snapping metal : thermostat

3) spring thermometer : bi-metal, on retro projector, warming

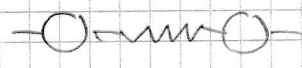[Exp] IR camera to "see" (measure) temperature

- ball (metal) on wood : impact, portion flow,
- rub shoe on floor
- metal plate,

Thermal expansion

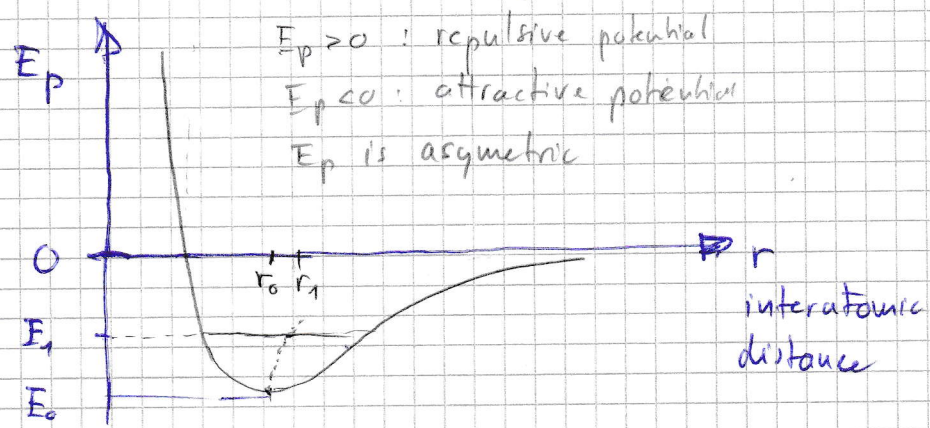• microscopic picture (of matter) & expansion

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

r interatomic distance

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 $T \nearrow$, $r \nearrow$ ∀ 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)

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

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

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

(Slide) linear exp coefficients

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

[Exp] Eisen Draht | (or) $\rightarrow$ do volume expansion first

thermal expansion (1D), reminder

distance between atoms
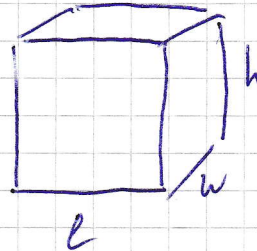increases (on avg)

=> expansion

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

$\uparrow$ linear expansion coefficient

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

(slide) : Linear exp coeff. values (table)

for a volume :

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

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

V_2 at $T_2 > T_1$

$V_1 = l \cdot w \cdot h$

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

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

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

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

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

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

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

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

~~slide~~

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)
  correspond to phase transition

$$(1+\varepsilon)^n \approx 1 + n\varepsilon$$
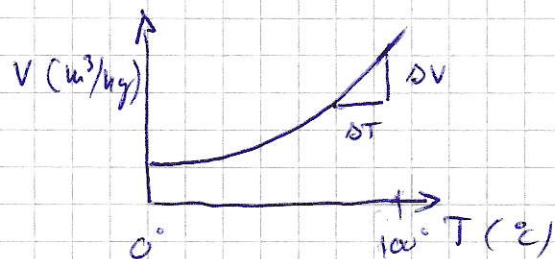$$\varepsilon \ll 1$$

con of water :

def : specific volume v : ratio of a substance volume to
its mass

$$v = \frac{V}{m} = \frac{1}{\varrho} \qquad \varrho : \text{density}$$

$$[V] = m^3/kg$$

$$[\varrho] = kg/m^3$$

(slide) v vs T for water

Volume expansion vs T :

$$\frac{\Delta V}{V} = \alpha_v \cdot \Delta T$$

$$\alpha_v = \left(\frac{\Delta V}{\Delta T}\right) \cdot \frac{1}{V} \quad , \qquad \text{slope of graph } v \text{ vs } T \propto \alpha_v$$
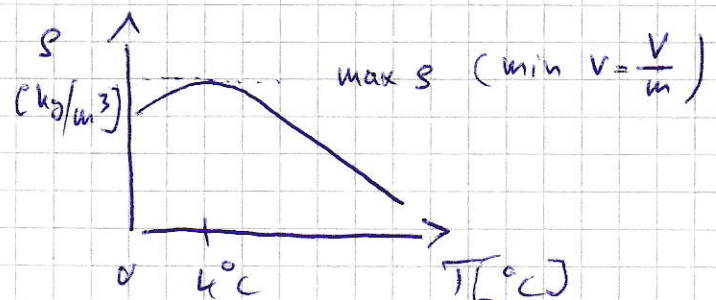
$$\uparrow$$
$$\text{prop. to}$$

Note : $\alpha_v \sim$ const at high T (const. slope)

$\alpha_v \to 0$ as T decreases

$\alpha_v < 0$ below 4°C

show (slide) for ϱ vs T

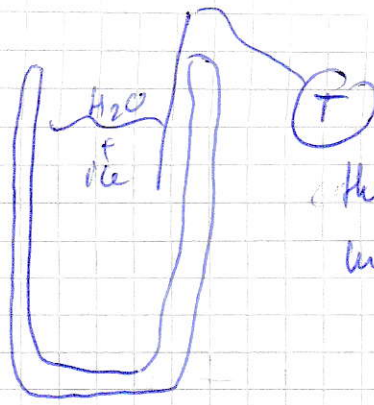| water has a point of max.
| density at 4°C

=> water at 4°C will settle at the bottom
of any water body (lake, pond, ...)

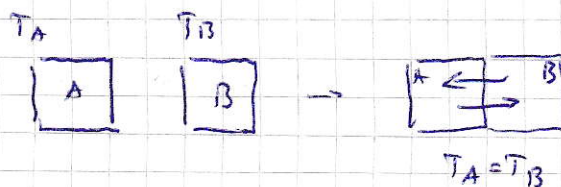(slide)   + Exp 4° water ?

Exp° 4° water

H2O
+
ice

thermocouple
mean T vs depth

Heat transport and exchange

remember: thermal equilibrium reached upon energy exchange

heat = energy that spontaneously passes from a hotter body
Q, $[Q] = J$ to a colder body through thermal contact
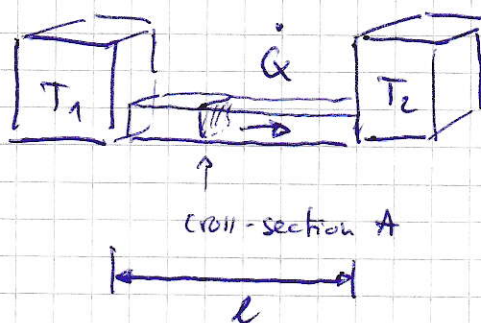(via ~~heat~~ conduction, radiation or convection)

also mentioned : Temperature is a measure of the internal energy of a body, and reflects the kinetic energy of the constituents of this body (atoms, molecules)

It is possible to increase the temp. of an object (body) by doing mechanical work on it as well (not only by transferring heat to it via conduction, radiation or convection)

Exp: - ball thrown on wall (?)
      - shoe sliding on floor

      (observe with IR camera.)

heat conduction

heat Q,

heat current : $\dot{Q} = \dfrac{dQ}{dt}$

cross-section A

$$\left\| \dot{Q} = \lambda \cdot A \cdot \frac{\Delta T}{\ell} \right.$$

λ : thermal conductivity of material

$[\lambda] = \dfrac{W}{m \cdot K}$, $W = \dfrac{J}{s}$

$T_1 > T_2$

thermal conductivity table

NB: graphene, ~500 $\frac{W}{m \cdot h}$ on substrate

~1000 $\frac{W}{m \cdot h}$ free standing

Exp: bar with nails in holes

on Cu side nails fall fast
stainless side, nails fall only later (or not at all)
steel

Heat capacity : ratio of heat added to (or removed from) a body to the resulting temperature change

heat added (or removed)

$$\alpha = \frac{\Delta Q}{\Delta T}$$

heat capacity

resulting change of temperature

$$[\alpha] = \frac{J}{K}$$

specific heat capacity : (heat capacity per unit mass)

mass of the object

$$\Delta Q = c \cdot m \cdot \Delta T \qquad\qquad [c] = \frac{J}{kg \cdot K}$$

specific heat capacity

also molar heat capacity,

$$\Delta Q = C \cdot N \cdot \Delta T$$

nb of moles

Remember

1 mole of a material

$= N_A$ elementary entities of this material (atoms, molecules).

$N_A = 6.02 \cdot 10^{23}$, Avogadro number

(slide) tabel for heat capacities
specific

if c large it means that one needs a large amount
of heat (ΔQ) to increase the temperature (ΔT) of
the ~~object~~ considered
material
i.e material "stores" a lot of energy per degree

Heat and work

(slide) Joule's experiment

increase the temp. of a system by doing work on it (or by adding
_____   heat: e.g.
i.e., its internal energy   (Joules)   radiation)

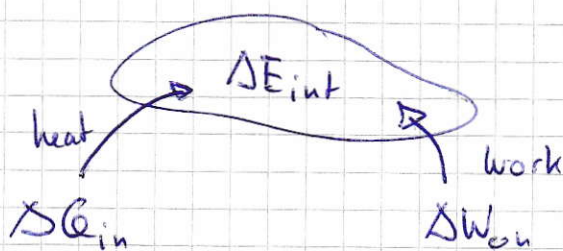$\Rightarrow$ equivalence mechanical energy and heat

4.184 J of mechanical energy needed to increase the temp of
1g of water by 1°C

$$(mgh = m'c.\Delta T)$$
       ↑   ↑
    mass   mass of
   falling   water

%

$\Rightarrow$ | relationship between internal energy (or measured by the temperate),
  | work done on a system and the heat transfered to a system ?

ΔE_{int} : change of internal energy
          of the system

ΔQ_{in} : heat transfered to the
          system

δW_{on} : work done on the system

|| 1st law of thermodynamics || $\Delta E_{int} = \Delta Q_{in} + \Delta W_{on}$ conservation of energy

- if the system is a machine and does/produces a work,
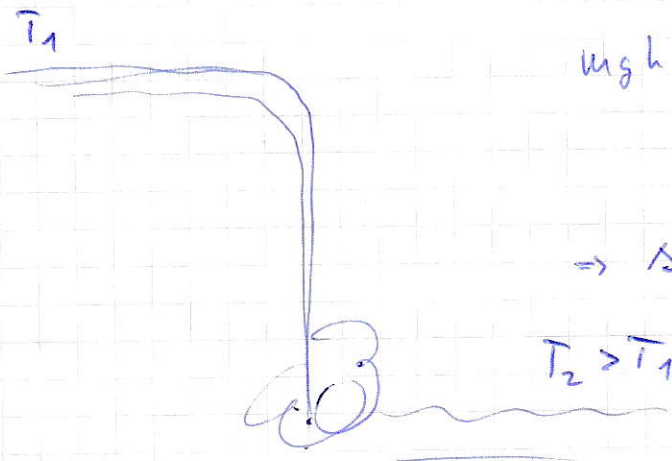
$$\Delta E_{int} = \Delta Q_{in} - \Delta W_{by}$$ ΔW_{by} : work done by machine

- note : E_{int} is a function of the state of the system and depends
  on pressure, volume, temperature.
  Q, W are independent of the state of the system; they are a measure of
  transfered energy

example: waterfall $\rightarrow$ $T_2 > T_1$, $\Delta T = ?$

T_1

$$m g h = m \cdot c \, \Delta T$$

↑ specific heat capacity

$$\Rightarrow \Delta T = \frac{g h}{c}$$

the same if we consider a given mass of water in before and after fall

$$T_2 > T_1$$

for a 100 m (!) waterfall

$$= \frac{N}{kg}$$

$$\Delta T = \frac{9.81 \, \frac{m}{s^2} \cdot 100 \, m}{4.184 \, \frac{J}{kg \cdot K}} \cong 0.2 \, K$$

$$\left(4,184 \, \frac{J}{g \cdot K} \right)$$