Introduction to Physics I

Reminder: heat & temperature

Heat transport
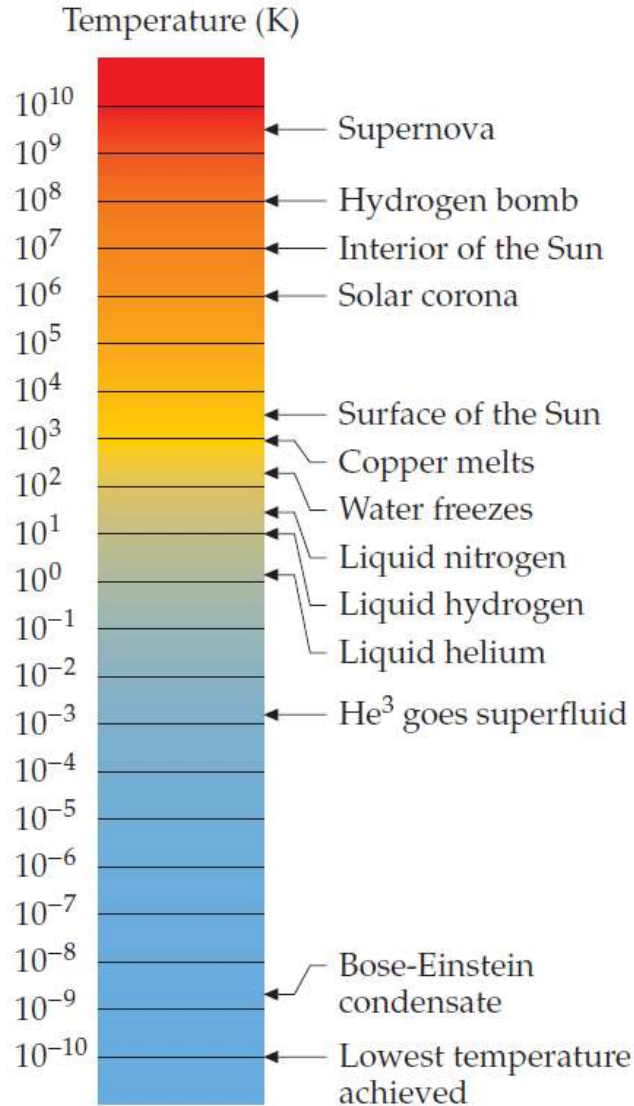
First law of thermodynamics

Ideal gases

Kinetic gas theory

L21, 01.12.2017
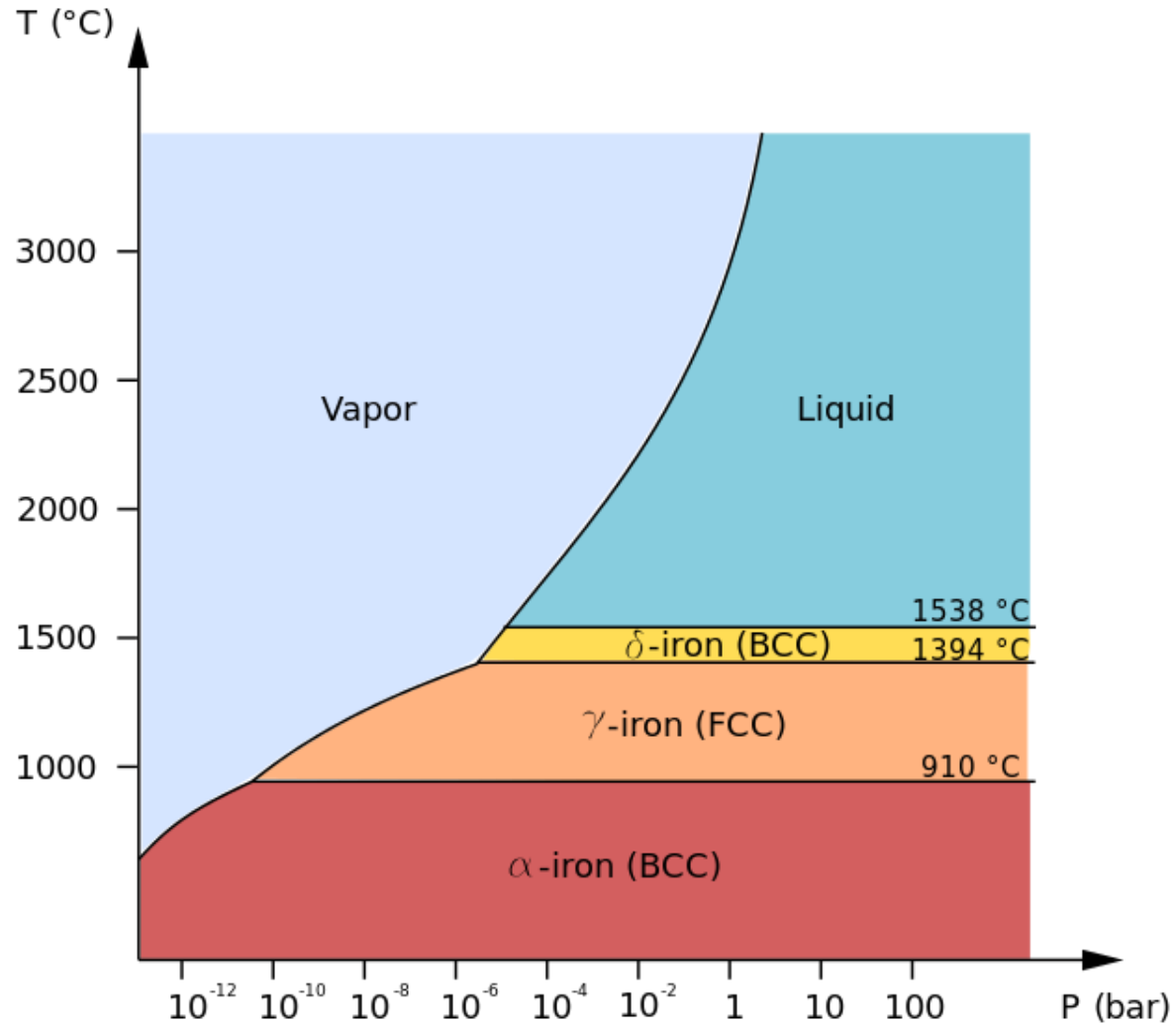
Table 17-1 **The Temperatures of Various Places and Phenomena**

Temperature (K)

Temperature (K)	Phenomenon
10^{10}	
10^{9}	Supernova
10^{8}	Hydrogen bomb
10^{7}	Interior of the Sun
10^{6}	Solar corona
10^{5}	
10^{4}	
10^{3}	Surface of the Sun
	Copper melts
10^{2}	Water freezes
10^{1}	Liquid nitrogen
10^{0}	Liquid hydrogen
10^{-1}	Liquid helium
10^{-2}	
10^{-3}	He^3 goes superfluid
10^{-4}	
10^{-5}	
10^{-6}	
10^{-7}	
10^{-8}	Bose-Einstein condensate
10^{-9}	
10^{-10}	Lowest temperature achieved

Tipler

Linear expansion coefficient

Tabelle linearer Ausdehnungskoeffizienten α

fester Stoff	α (K^{-1})
Kupfer	$16.8 \cdot 10^{-6}$
Eisen	$12.2 \cdot 10^{-6}$
Thüringer Glas	$8.5 \cdot 10^{-6}$
Pyrex-Glas	$3.2 \cdot 10^{-6}$
Invar Stahl	$1.5 \cdot 10^{-6}$
Quarzglas	$0.45 \cdot 10^{-6}$
Edelstahl	$16 \cdot 10^{-6}$
Dentalmaterial:	
Zahnsubstanz	$11.4 \cdot 10^{-6}$
Silikatzement	$7.6 \cdot 10^{-6}$
Dentalamalgam	$25.0 \cdot 10^{-6}$
Porzellan	$4.1 \cdot 10^{-6}$
Polymethylmethacrylat	$81.0 \cdot 10^{-6}$

Iron (Fe) wire expansion

Iron (Fe) wire expansion

912 C

α

γ

BCC

FCC

(body centered cubic)

(face centered cubic)
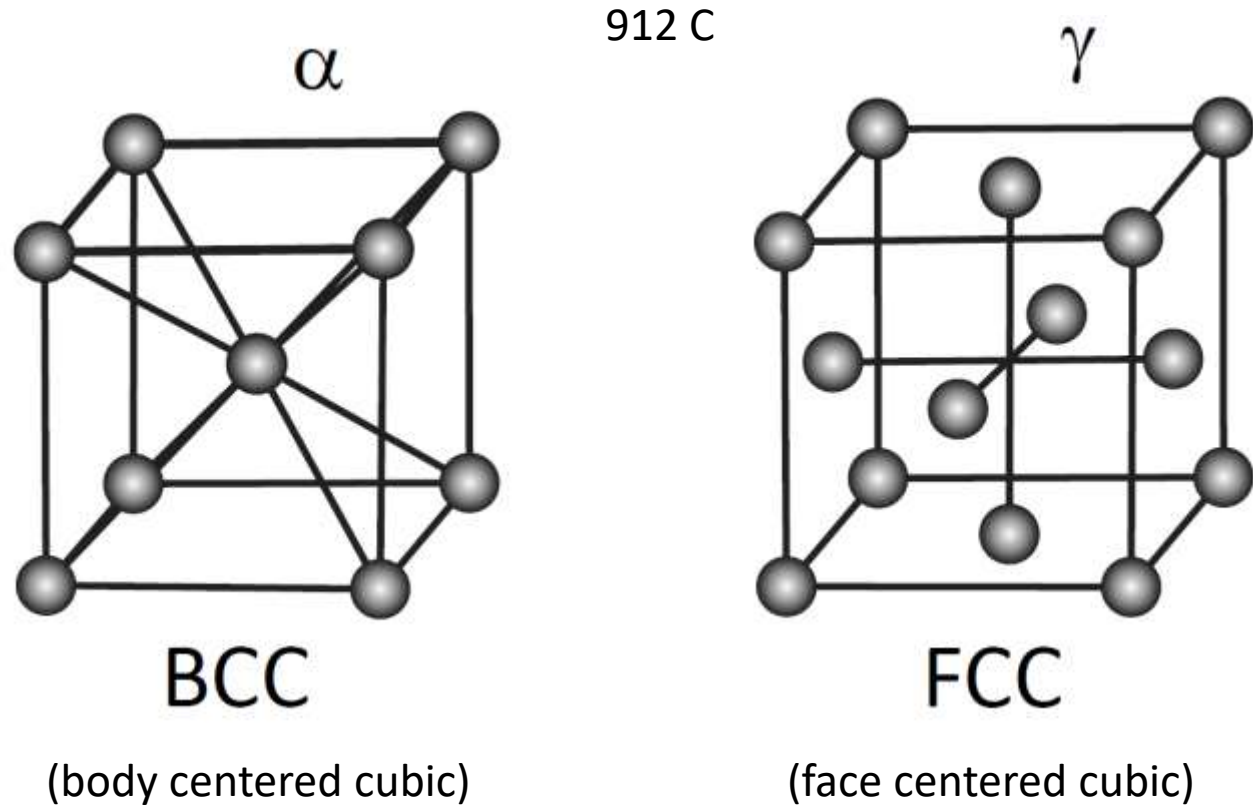
Thermal expansion coefficients

	linear (1D)	volumic (3D)
Material	α_l $(10^{-6}K^{-1})$	α_V $(10^{-6}K^{-1})$
Gasoline	317	950
Ethanol	250	750
PP	150	450
PVC	52	156
Aluminium	23	69
Kapton	20	60
Copper	17	51
Iron	**12**	**36**
Steel	11	33
Invar	1.2	3.6
Quartz	0.3	1

$$\alpha_V = 3\alpha_l$$

Volume expansion
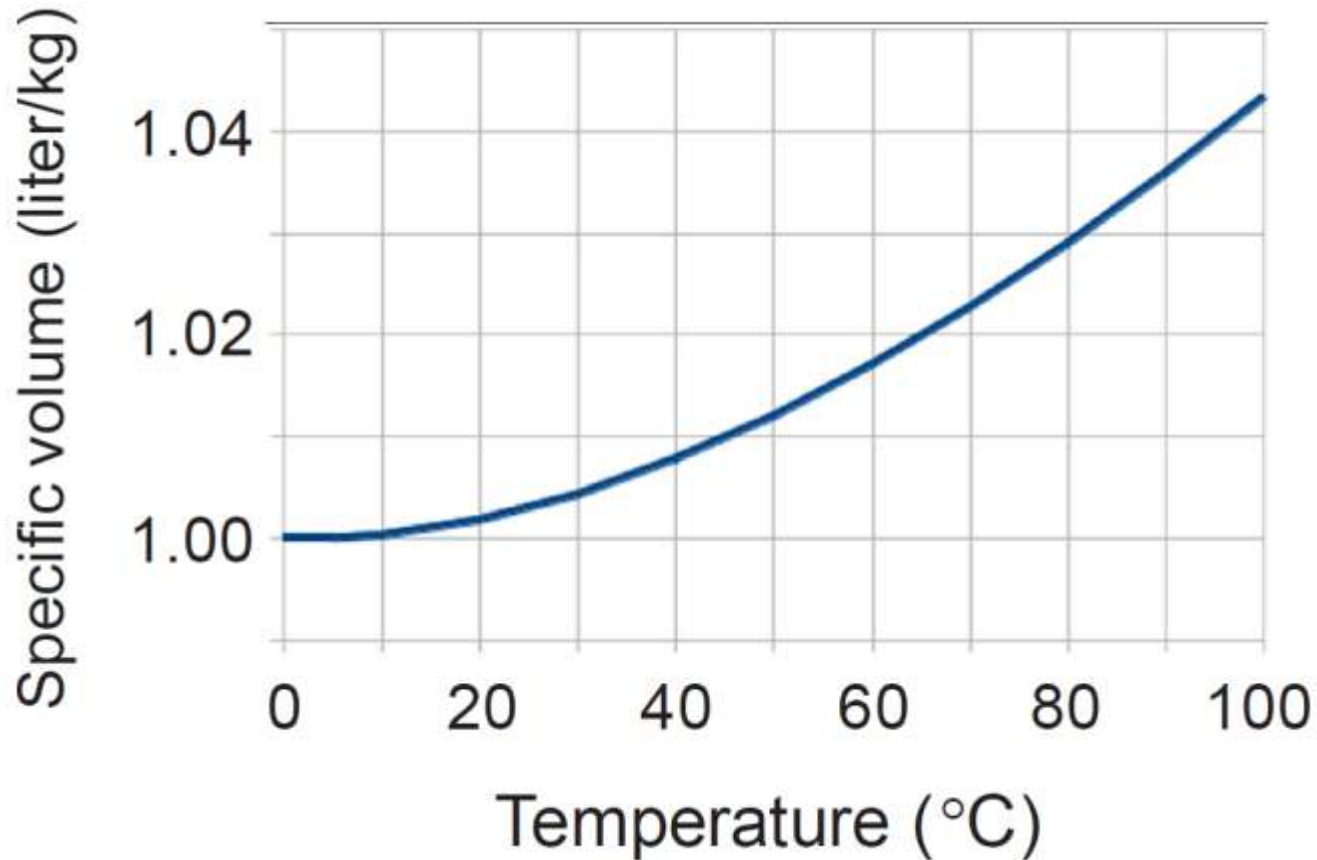
Thermal expansion of water

Thermal expansion of water

Density of ice and water
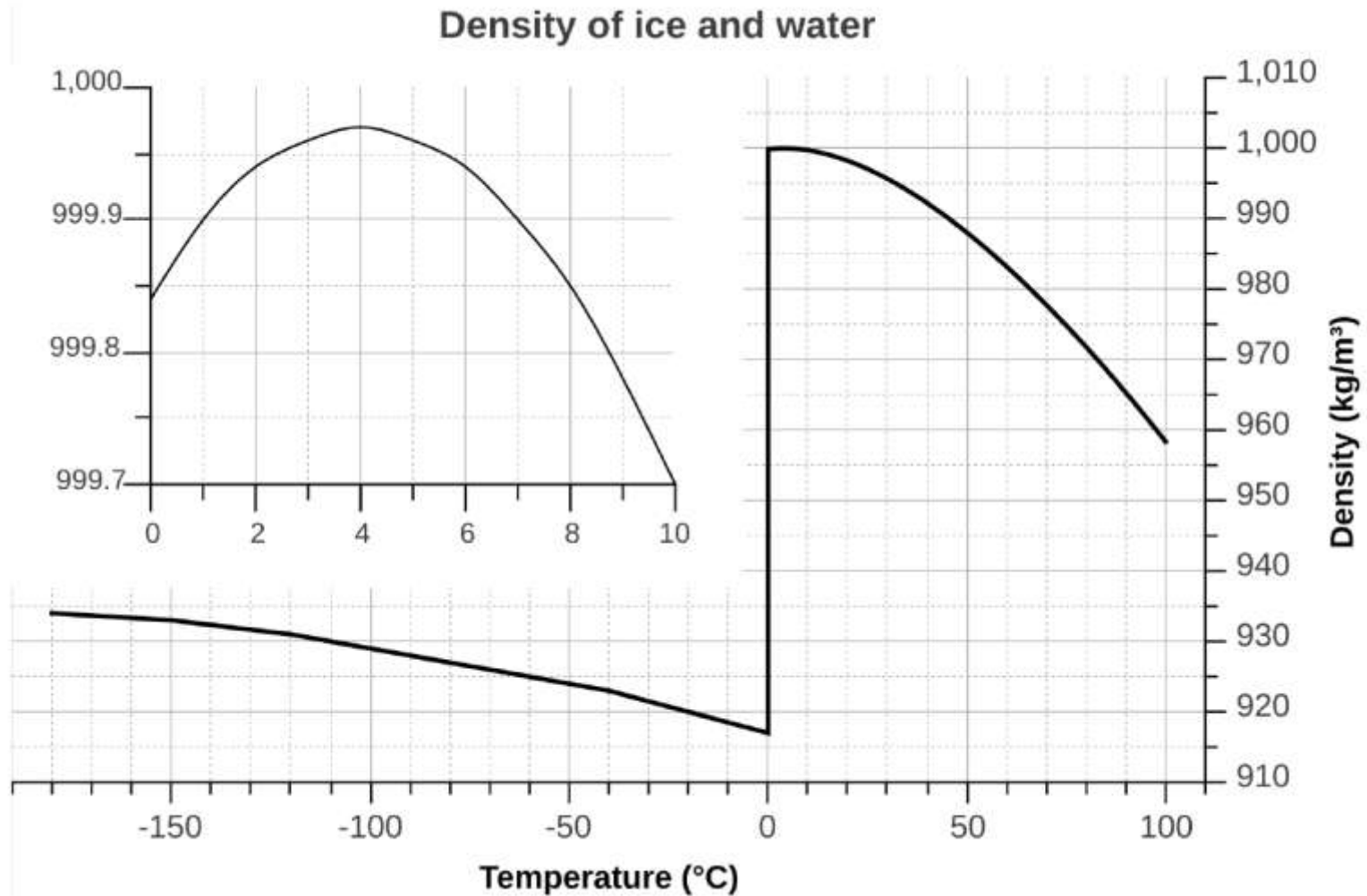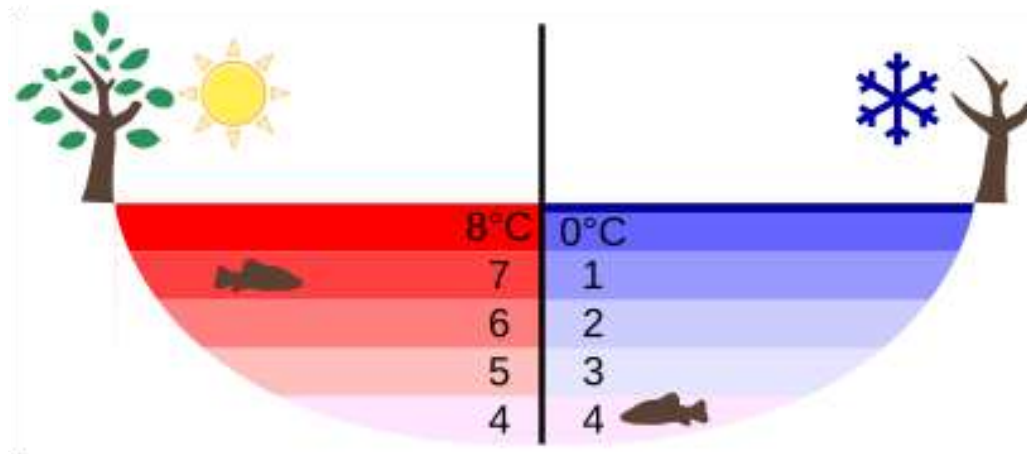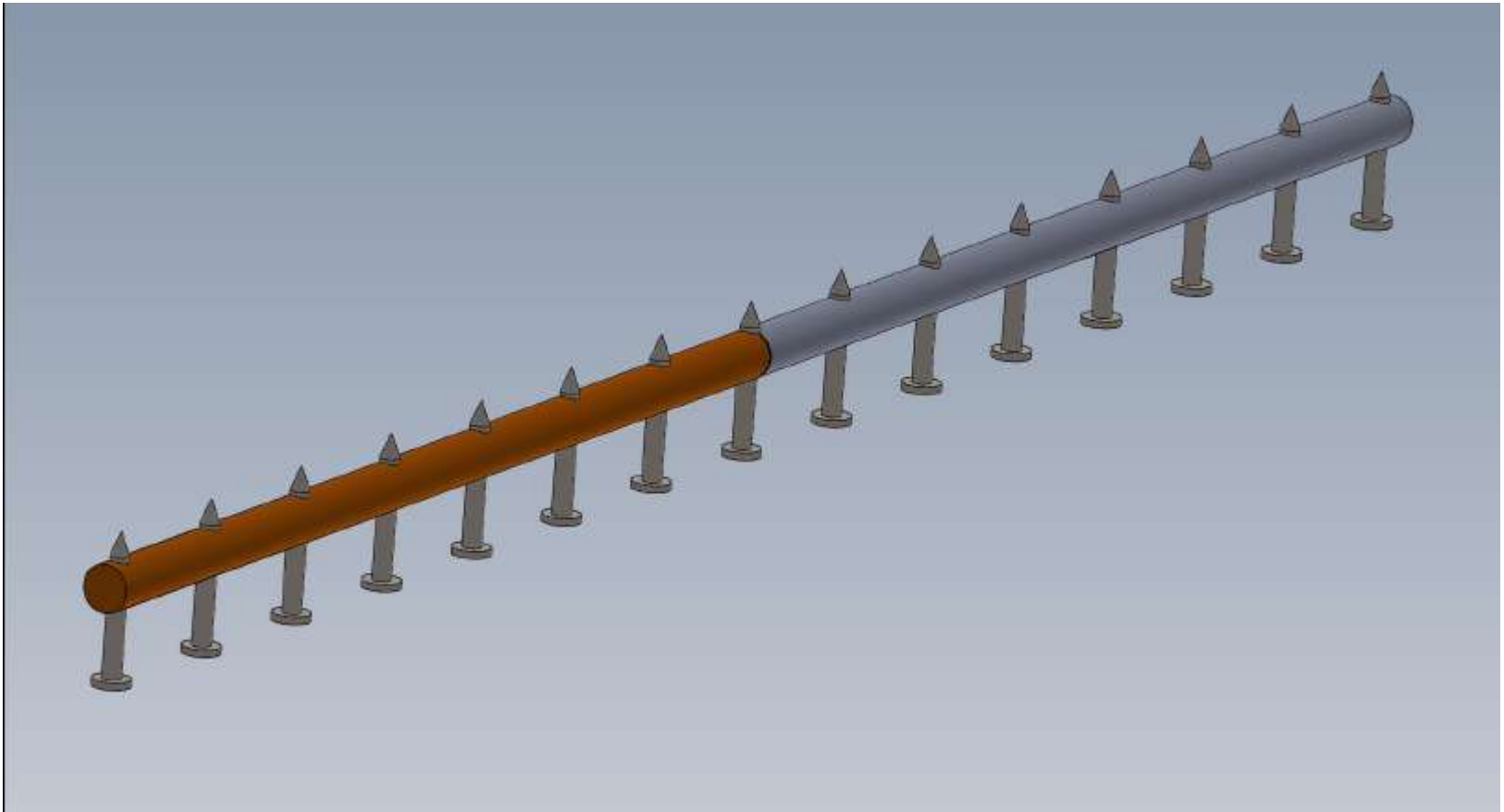
Thermal expansion of water
density of water vs T

Thermal conductivity

Material	Thermal conductivity (W/(m*K))
Diamond*	2300
Copper	390
Lead	35
Stainless steel	15
Granite	3
Ethanol	0.17
Cotton	0.06
Paper	0.01
Glass wool	0.005

Exp. heat transport

Heat capacity

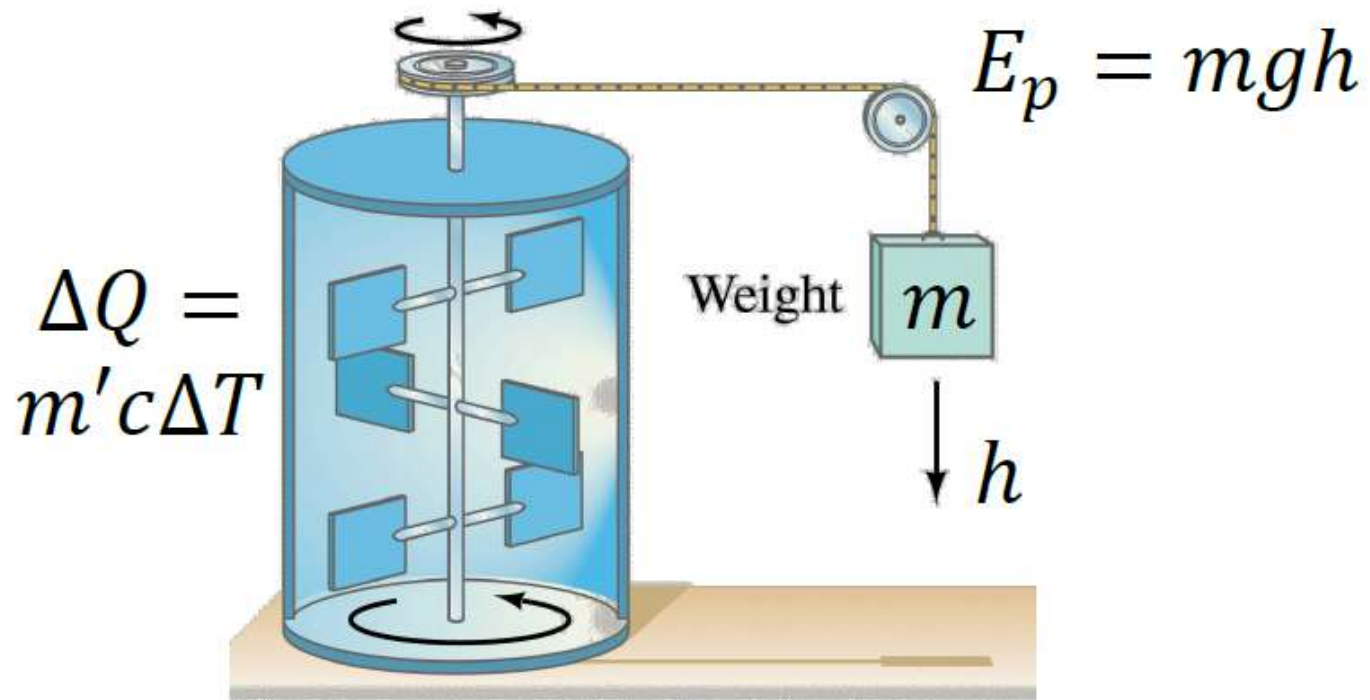| Material	c (J/(K*kg))
Hydrogen	14000
Sea water	3900
Ice	2100
Aluminium	900
Granite	840
Iron	450
Copper	390
Lead	130
Platinum	130

Heat and work

Joule's experiment

FIGURE 18-2 Schematic diagram for Joule's experiment. Insulating walls surround water. As the weights fall at constant speed, they turn a paddle wheel, which does work on the water. If friction is negligible, the work done by the paddle wheel on the water equals the loss of mechanical energy of the weights, which is determined by calculating the loss in the potential energy of the weights.

Tipler

Heat and work

Joule's experiment

$$E_p = mgh$$

$$\Delta Q = m'c\Delta T$$

$$mgh = m'c\Delta T$$

universal gas constant

$$PV = nRT$$

$\frac{PV}{nT}, J / mol \cdot K$

8.60

—8.314 J / mol · K = R

H_2

8.40
8.314
8.20

N_2
CO

8.00

7.80

O_2

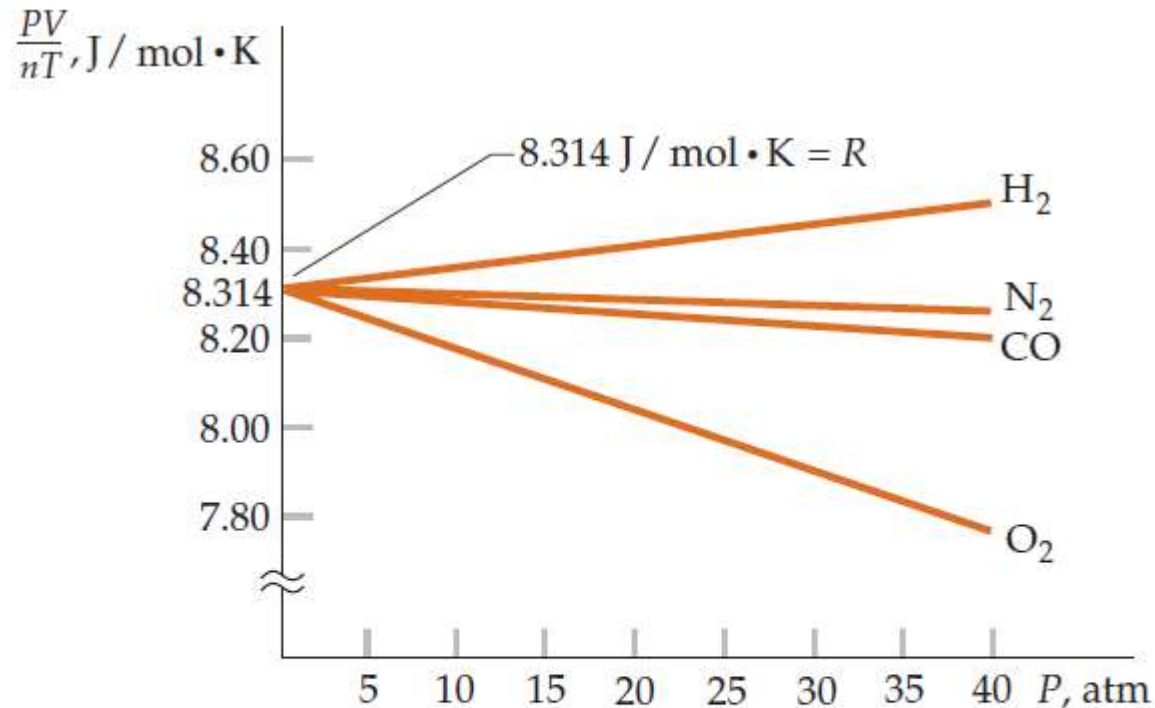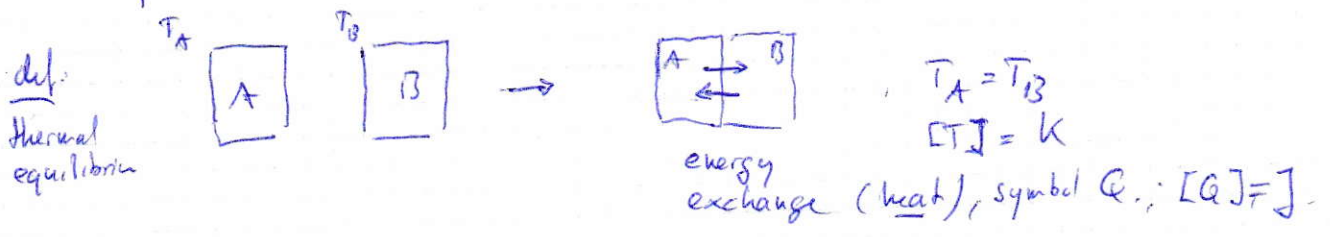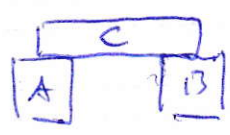5   10   15   20   25   30   35   40   P, atm

FIGURE 17-8 Plot of PV/nT versus P for real gases. In these plots, varying the amount of gas varies the pressure. The ratio PV/nT approaches the same value, 8.314 J/(mol · K), for all gases as we reduce their densities, and thereby their pressures, of the gases. This value is the universal gas constant R.

Reminder | Heat & temperature |

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

  def:
  thermal
  equilibrium

  T_A [A] T_B [B] $\rightarrow$ [A $\leftrightarrows$ B] , $T_A = T_B$

  $[T] = K$

  energy
  exchange (heat), symbol Q ; $[Q] = J$
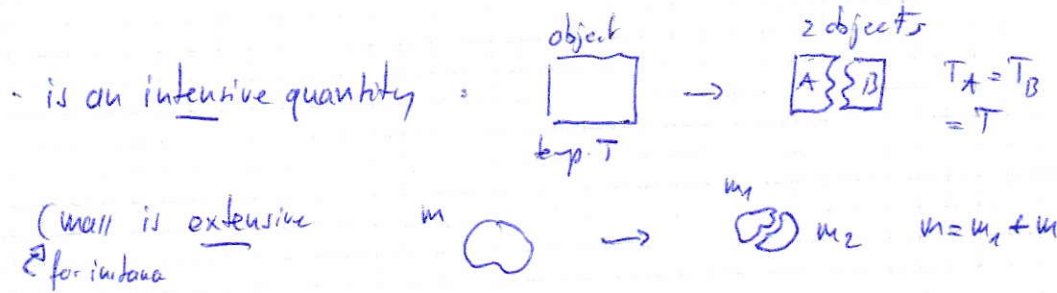
  "Zeroth" law
  of thermodynamics

  [C]
  [A] [B]

  When A and B are in thermal eq.
  with C, then they are in " "
  with each other

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

  - is an intensive quantity :
    object
    [   ]
    temp. T
    $\rightarrow$
    2 objects
    [A ≥≥ B] $T_A = T_B$
    $= T$

    (mass is extensive
    for instance
    m ◯ $\rightarrow$ m_1 ◯ m_2 $m = m_1 + m_2$

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

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

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

(slide) Temperature of
places / phenomena

thermal expansion (1D), reminder
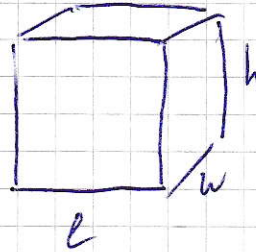
distance between atoms
increases (on avg)
=> expansion

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

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 $T_2 > T_1$

$V_1 = l \cdot w \cdot h$

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

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

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

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

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

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

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

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

exp : Iron wire expansion ← (slide)

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

exp Fe wire

75 V, 28A = 2.1 kW

$l = 2.80$ m

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

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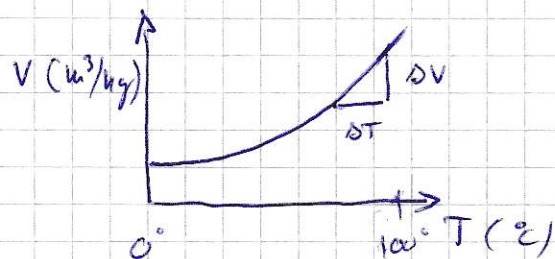$$\varepsilon \ll 1$$

con of water :

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

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

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

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

(slide) v vs T for water

Volume expansion vs T:

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

$$\alpha_v = \left(\frac{\Delta V}{\Delta T} \right) \cdot \frac{1}{V} \quad , \quad \text{slope of graph } v \text{ vs } T \quad \alpha \quad \alpha_v$$

$$\uparrow$$
$$\text{prop to}$$

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

$\alpha_v \to 0$ as T decreases

$\alpha_v < 0$ below 4°C

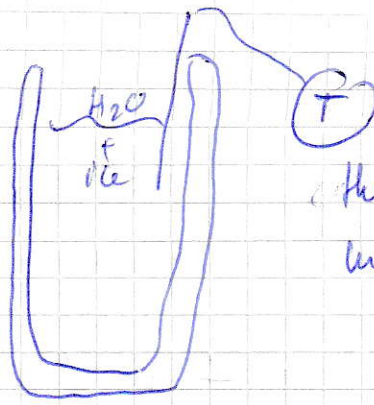show (slide) for ς vs T

max ς (min $v = \frac{V}{m}$)
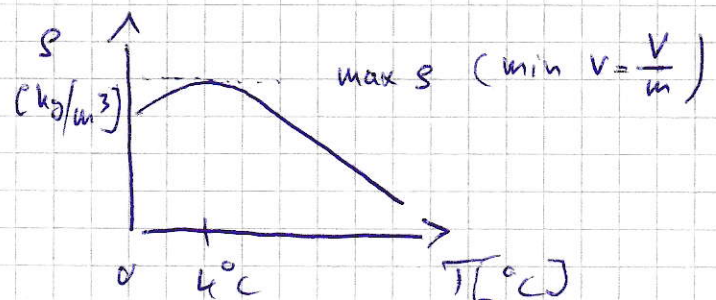
water has a point of max. density at 4°C

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

(slide) + Exp. 4° water %

Exp⁰ 4° water

H₂O
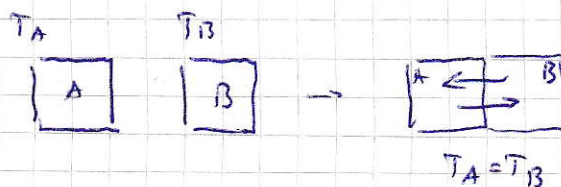+
ice

T

thermocouple

mean T vs depth

Heat transport and exchange

remember: thermal equilibrium
reached upon
energy exchange

T_A T_B

A   B → A ⇄ B $T_A = T_B$

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

$\dot{Q}$ $T_1 > T_2$

cross-section A

l
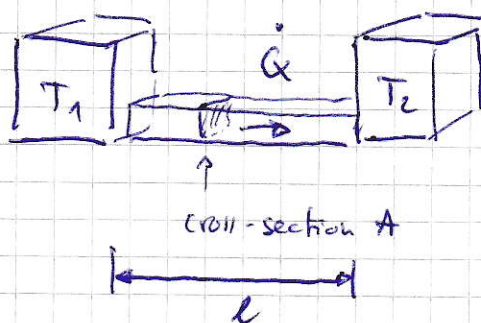
$$\left\| \dot{Q} = \lambda \cdot A \cdot \frac{\Delta T}{l} \right.$$
, λ: thermal conductivity of
material
$[\lambda] = \dfrac{W}{m \cdot K}$, $W = \dfrac{J}{s}$ %

(slide) thermal conductivity table

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

~2000 $\frac{W}{m \cdot K}$ 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)

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

heat capacity

resulting change of temperature

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

specific heat capacity : (heat capacity per unit mass)

mass of the object

$$\Delta Q = c \cdot m \cdot \Delta T$$

specific heat capacity

$$[c] = \frac{J}{kg \cdot K}$$

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) table 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   (Joule)   radiation)

⇒ equivalence mechanical energy and heat
   _____

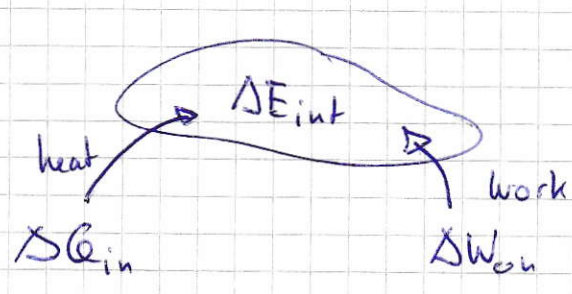4.184 J of mechanical energy needed to increase the temp of
1g of water by 1°C

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

⇒ | relationship between internal energy (or measured by the temperature),
   | work done on a system and the heat transfered to a system ?

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

heat   work ΔQ_{in} : heat transfered to the
ΔQ_{in} ΔW_{on} 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,
                              _____

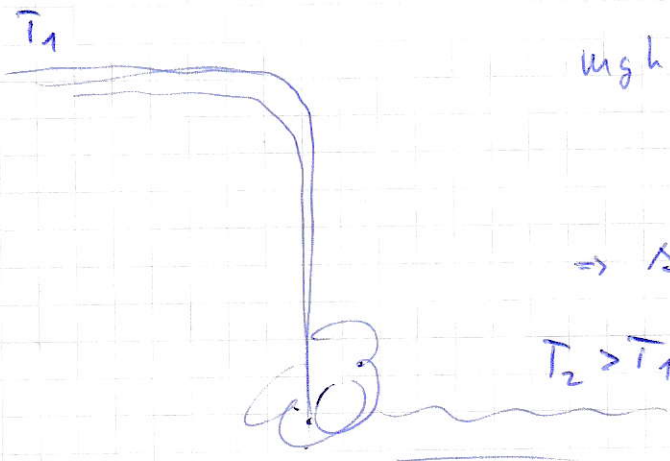$$\Delta E_{int} = \Delta Q_{in} - \Delta W_{by}$$ ΔW_{by} : work done by
                                                     machine

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

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

T_1

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

$\uparrow$ specific heat capacity

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

the same

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

$T_2 > T_1$

for a 100 m (!) waterfall

$= \dfrac{N}{kg}$

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

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

Ideal gases   low density gases :
- microscopic billiard/pool : elastic shocks between atoms (molecules)
- no intermolecular forces (well separated atoms)

• energy (internal energy) : kinetic energy of atoms/molecules
   of gas
                               => any change in energy results in a Temp. change

(exp) • exp. observation : $P \cdot V$ = constant , for a given T
Boyle -   (R.Boyle , 17th Century)   ↑volume
Ramiott   pressure

      exp. observation : $P \cdot V$ = const $\cdot T$ (const is > 0)
(exp)   (J. Charles 18th-19th)
Gay-   (J. Gay-Lussac Cent)   ↑temperature
Lussac

   • const = ... ?   take 2 containers P, V, T P, V, T $\frac{p \cdot V}{T} = const$
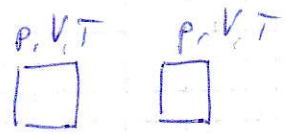
                           → merge as one $p \cdot \frac{2V}{T} = const'$
                             system

                           hence : const $\propto$ nb of gas molecules   (const' = 2·const)
                                       (amount of gas)

                           and, def :   const = $k_B N$
                                              ↑nb molecules
                                         R other constant ..(!)
                           and $p \cdot V = N \cdot k_B \cdot T$

                                    $k_B = 1.38 \cdot 10^{-23}$ J/k ,   Boltzmann constant
                                                                          (value found exp.)
                                    $N = n \cdot N_A$

                                    $N_A = 6.022 \cdot 10^{-23}$ mol^{-1} , Avogadro number
                                    n : nb of moles (mol)

                           def : 1 mol of a substance contains N_A elements
                                                                              (atoms or
                                  (measure of the amount of a gas, here)   molecule)

thus
                        $P V = N \cdot k_B \cdot T = n \cdot N_A \cdot k_B \cdot T$

ideal gas   ‖ $P \cdot V = n \cdot R \cdot T$, $R = N_A \cdot k_B = 8.314 \frac{J}{mol \cdot K}$
law
(slide) univ. gas constant   note $[P \cdot V] = \frac{N}{m^2} \cdot m^3 = N \cdot m = J$ universal gas constant
                                              energy/work