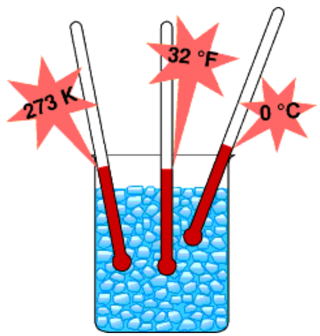
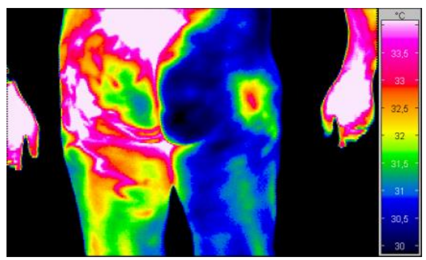
Physical bases of biophysics

Lecture 5 19. 09. 2023.

Ádám Orosz

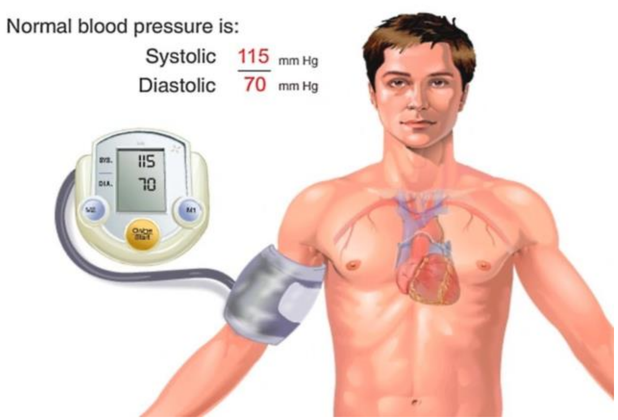
Thermodynamics





1. Internal energy and thermal energy
2. Temperature and its scales
3. Heat
4. Heat capacity
5. Phases
6. Phase transitions
7. Ideal gases

Mechanics – Pressure, Hydrostatics



1. Pressure
2. Pressure of gases
3. Partial pressure
4. Measuring blood pressure
5. Density
6. Hydrostatic pressure
7. Hydrostatic paradox and Pascal's principle
8. Archimedes' law and bouyancy

Thermodynamics

Until now: Conservation of mechanical energy and work-energy theorem

$$\sum E_i = E_{\text{pot}} + E_{\text{kin}} + E_{\text{el}} = const. \qquad W = \Delta E_{\text{kin}}$$

Where does the energy disappear in the case of inelastic collision or friction?

„Warms up the body" (increases the temperature); „Becomes heat"

$$W = \Delta E_{\text{internal}}$$

The fundamental physical quantity of thermodynamics is **internal energy**.
Its origin: 1. **thermal motion** of atomic particles
2. **interactions** among the particles

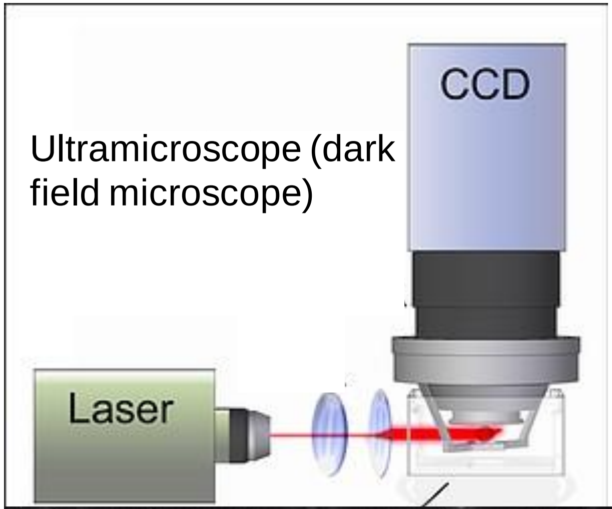
Thermal interaction

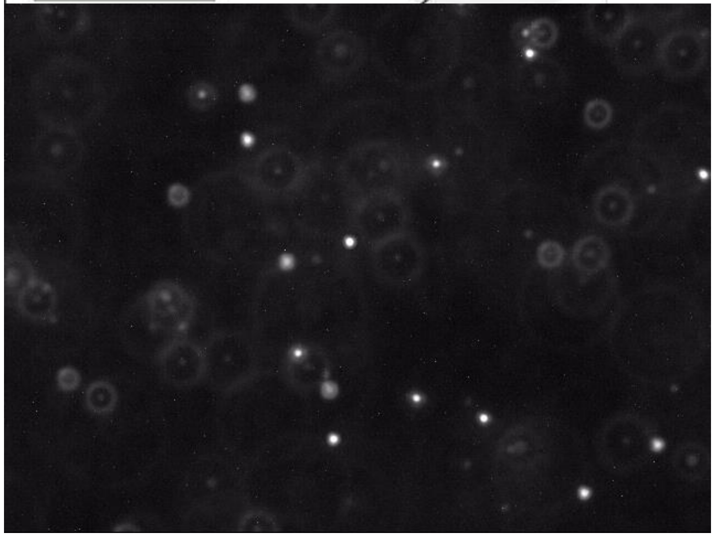
New macroscopic interaction (besides the mechanical one),
heat is added to the body:

$$Q = \Delta E_{\text{internal}}$$

Two new quantities: **heat** (Q) and **temperature** (T)

Thermal motion and thermal energy





$$E_{internal} = E_{therm} + E_{binding} + E_{nuclear\ int}$$

The **thermal energy** of an object includes the **energies of different movements of the particles** that make up the object (translation, rotation, vibration)

- **Temperature** is the **gradation or degree of this thermal energy** of the object.

$$\left(\frac{1}{2}m\bar{v}^2 = \frac{3}{2}kT\right)$$

Temperature and temperature scales

- A central concept is **temperature** (SI base quantity)
- It characterizes the state of a given object and gives **the degree of thermal energy**
- In physics, we use the **Kelvin scale** to measure temperature (unit: Kelvin)
- There is an **absolute zero point** (0 K) on the Kelvin scale, but **no upper limit**
- At the absolute zero point, the **particles would stop moving** — if we could reach 0 K
- Many **properties** of the objects **vary** depending on their **temperature**, e.g.:
  - volume (thermal expansion)
  - color
  - electrical resistance
  - pressure of gases

Thermal expansion coefficients:

Solids (linear)

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

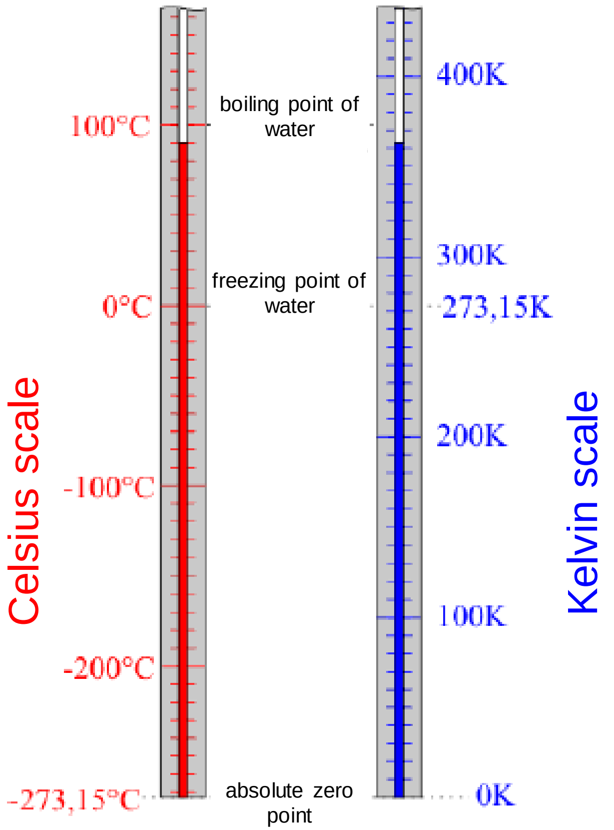
Liquids (volumetric)

$$\beta = \frac{\Delta V}{V \Delta T}$$

- The two temperature scales are shifted relative to each other - but the steps on the two scales are the same

$$t_{\text{Celsius}} = T_{\text{Kelvin}} - 273$$

$$T_{\text{Kelvin}} = t_{\text{Celsius}} + 273$$



Heat and heat capacity

Heat (usual symbol Q): **Thermal energy transferred** from one obejt to another.

Old unit of measurement is calories (cal): 1 cal = 4,186 J

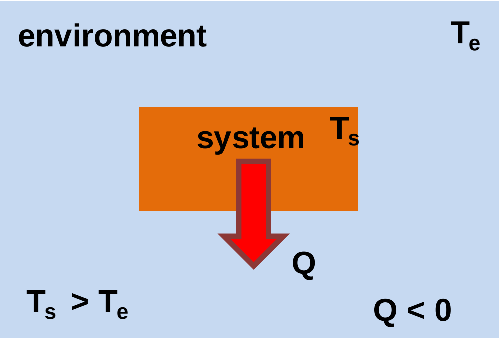
The **heat capacity (C)** can be used to make a **connection** between the **change in the temperature** of an object ΔT and the **heat** absorbed or released Q:

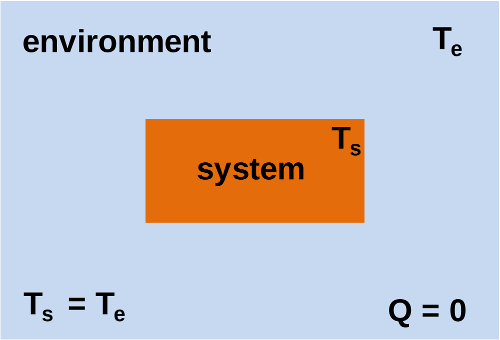
$$C = \frac{Q}{\Delta T} \quad \left(\frac{\mathrm{J}}{\mathrm{K}}\right)$$

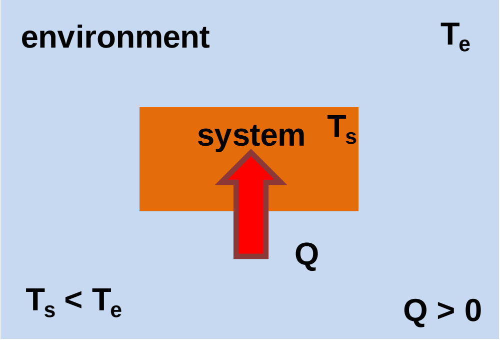
- If we want to increase the temperature of a body, we have to give heat to it: then Q and ΔT are positive
- If we want to reduce the temperature of a body, we have to extract heat: then Q and ΔT are negative
- The **heat capacity** of an object also depends on **the material quality** and the **mass**, $C \sim m$ $\rightarrow$

Specific heat capacity *c*: $c = \frac{C}{m} \quad \left(\frac{\mathrm{J}}{\mathrm{K \cdot kg}}\right)$

From the combination of the two formulas: $Q = c \cdot m \cdot \Delta T$







Problem

We want to cool 2 dl of orange juice from 28°C to 8°C. How much heat do we need to remove from the drink? (The density of orange juice is 1.02 g/cm^3.)

material	specific heat capacity, *c* (J/kg·K)
orange juice	4100

States of matter

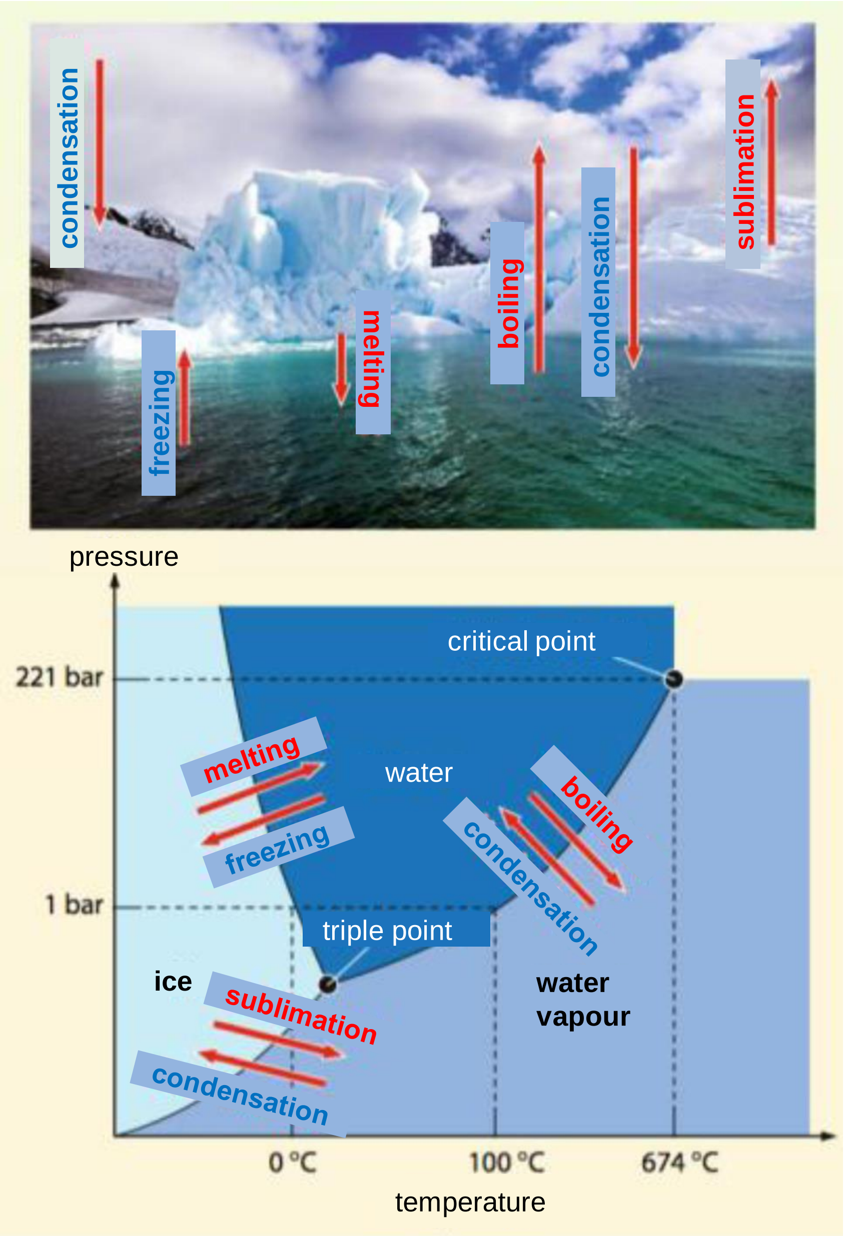
- States are **manifestations of matter** with **different structures** and **properties** in which a substance may exist depending on external conditions (e.g. temperature and pressure).

- The temperature of the transformations **varies as a function of pressure** → **phase diagram**

- We distinguish three states: **solid, liquid,** and **gas**

- Water can appear in three states: ice, liquid water, and water vapor

- Characteristics of the states of matter:
  - *solid*: well-defined **volume** and **shape**
  - *liquid*: definite **volume** but **shape not**
  - *gas*: **no** definite volume or shape

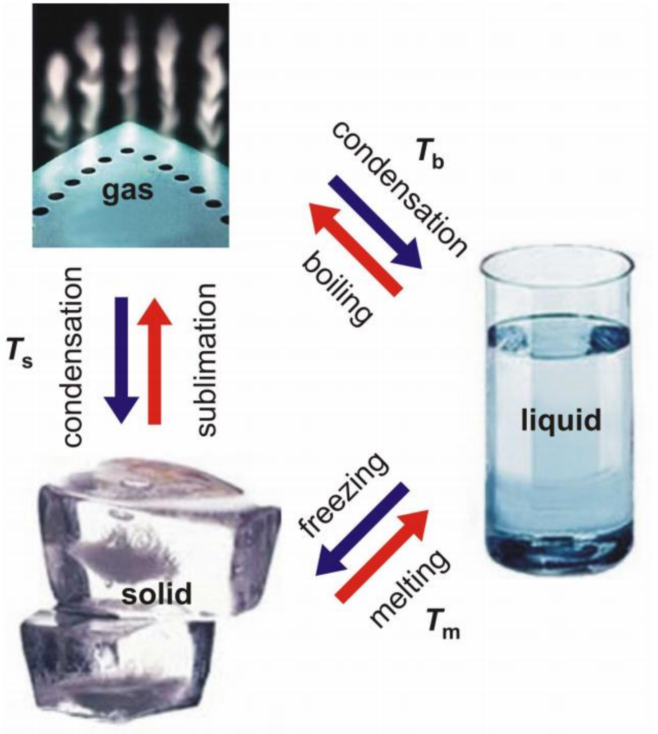


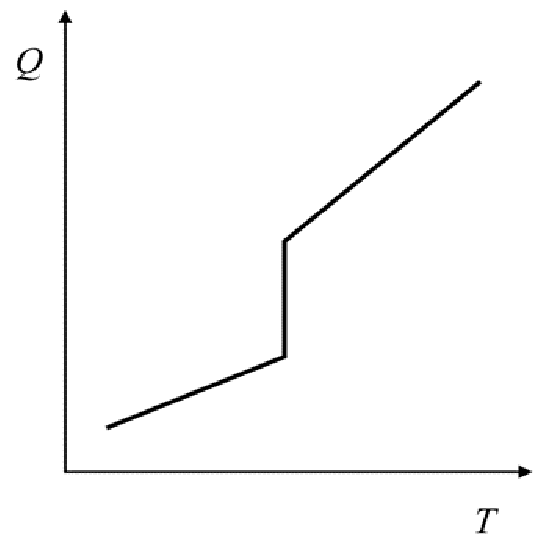
Phase transition and specific latent heat

- **Energy** is also required **for structural change**
- The **heat of transformation** *Q* corresponds to the amount of heat that a body absorbs or releases during phase transition.
- This amount of heat also is proportional to the mass and the following relationship applies to it: $Q \sim m \rightarrow$

specific latent heat: $L = \frac{Q}{m} \left(\frac{\text{J}}{\text{kg}}\right)$

- Depending on the phase transition, we give different names to the phase transition heat e.g.:
  - specific heat of fusion (melting)
  - specific heat of vaporization (boiling or evaporation)





Specific latent heat of some materials

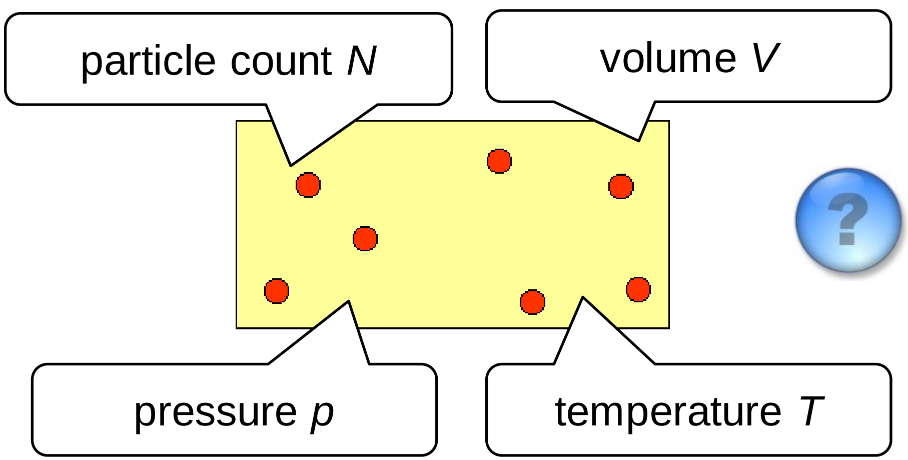
material	*L* (kJ/kg)
gold — *heat of fusion*	67
aluminum — *heat of fusion*	396
table salt (NaCl) — *heat of fusion*	517
ice — *heat of fusion*	334.4
water — *heat of vaporization (at 30 °C and 101 kPa)*	2 400
water — *heat of vaporization (at 100 °C and 101 kPa)*	2 257

Ideal gas

A **model** in which we make the following assumptions:

- The gas particles are **point-like**
- The gas particles have **no volume**
- **No interaction** between individual particles (with one exception: **elastic collision** with each other and with the wall)

Comment:
Unlike the highly simplified ideal gas model, all particles of real gases have a volume and interact with each other through attractive and repulsive forces.



$$p \sim T, \quad p \sim N, \quad p \sim \frac{1}{V}$$

Ideal gas law:

$$pV = NkT$$

Boltzmann's constant
$k = 1{,}38 \cdot 10^{-23}$ J/K

$$kN_A = R$$
$$N/N_A = \nu$$

Alternative form: $pV = \nu RT$

universal gas constant
$R = 8{,}31$ J/(mol K)

Repetion - Pressure

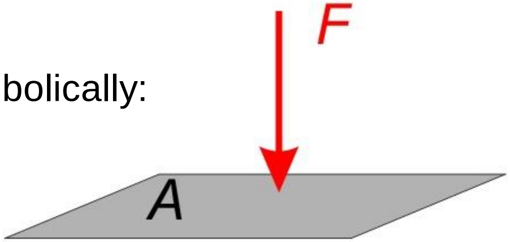


- The deformation of an object depends not only on the force acting on it, but also on the surface on which the force is applied.
- Power alone is not always enough to describe the interaction. We need a new quantity that also takes the surface into account. → „**pressure**".

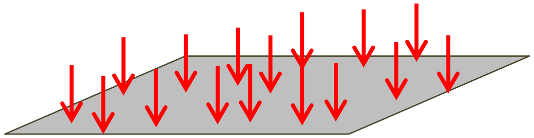
pressure (*p*): $p = \frac{F}{A} \quad \left(\frac{\mathrm{N}}{\mathrm{m}^2} = \mathrm{Pa}\right)$

Pascal

symbolically:



in reality:



(even distribution)

Other commonly used units:
bar (bar) = 100 kPa, atmosphere (atm) = 101, 325 kPa,
millimetre of mercury (mmHg) = 133,3 Pa

Problem

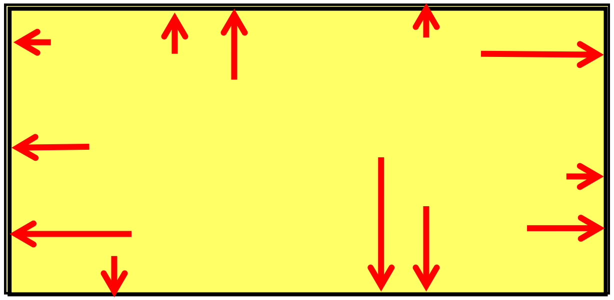
How much pressure does an 80 kg man in a standing position exert on the ground if

a) if there is nothing on his feet? (the surface of the two soles is 200 cm^2)

b) if the man skiing? (joint surface of the two skis is 3300 cm^2)

c) if he is ice skating? (surface of the edge of the ice skates is 4 cm^2)

Pressure of gases



- Due to their **thermal energy**, the gas particles move in all directions (thermal energy is converted into **kinetic energy**).

- **Gas particles collide with** the tank **wall**, and according to the ideal gas model this means a series of **elastic collisions**.

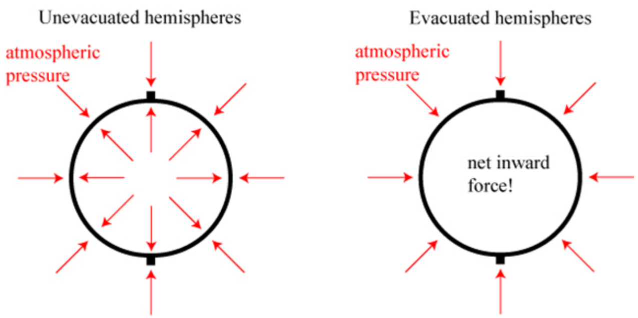
- When the particles collide with a wall, a **change in momentum** occurs, which according to Newton II. law results in **short surges of force**.

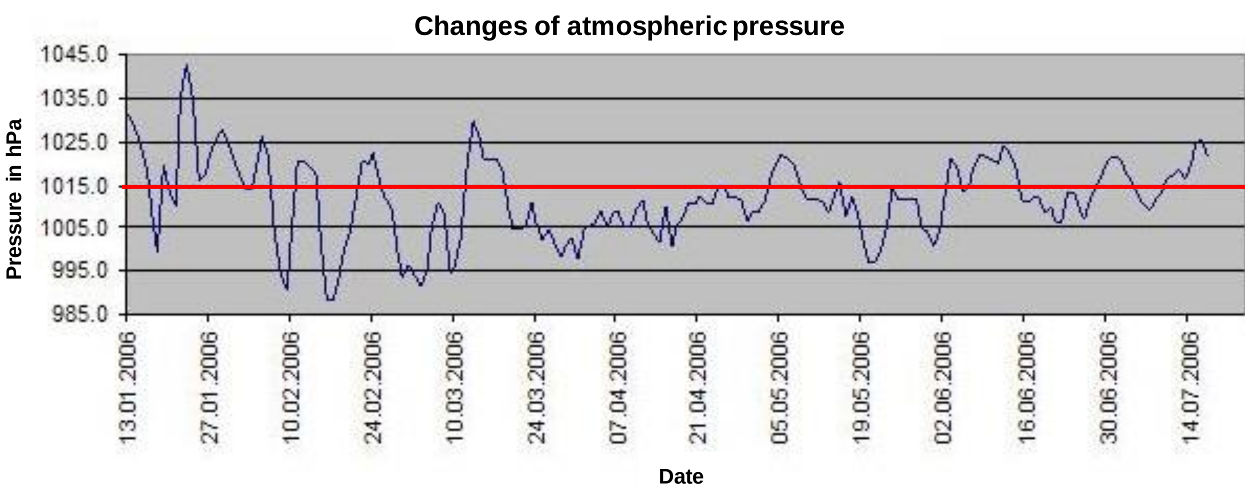
- The pressure of the gas will be the sum of the force shocks exerted on surface the wall.

- Considering the **large number of collisions** (N ~ $6 \cdot 10^{23}$), **the quotient of the average force** and the **surface o**f the tank gives the **pressure of the gas**.

Atmospheric pressure

Experiment of Otto von Guericke „The Magdeburg hemispheres”:

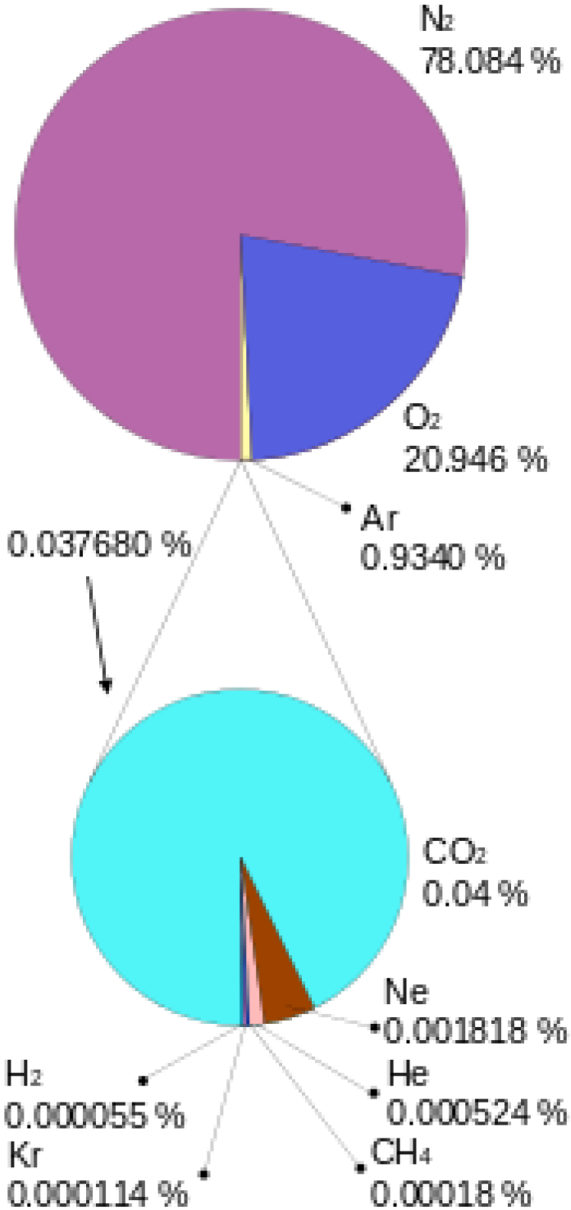




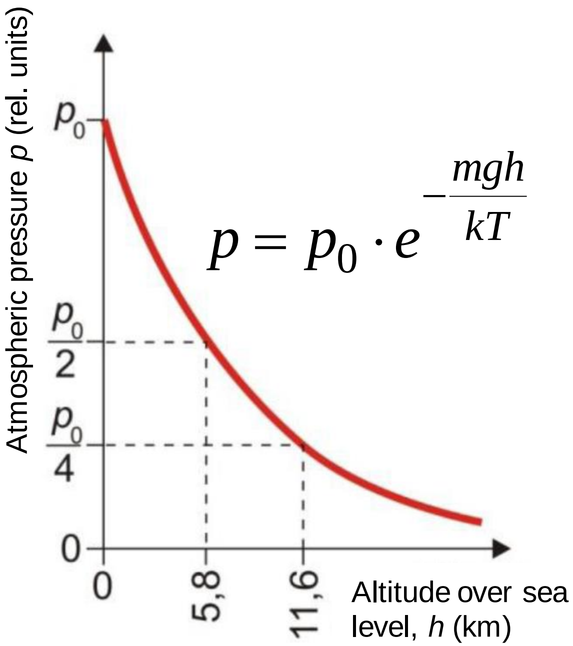
Normal atmospheric pressure= 101 kPa = 1010 hPa

Partial pressure

- A concept **for gas mixtures**.
- Air is a mixture of gases (nitrogen, oxygen, carbon dioxide,…)
- **Each component** of the gas mixture **contributes** to the total gas pressure.
- The **partial pressure** corresponds to the pressure that one of the components of the gas mixture would exert if it filled the total volume available on its own.
- The sum of the partial pressures of the components gives the pressure of the gas.
- **Example**: the proportion of O_2 in the air is ~ 21%, so of the total pressure of 101 kPa, the partial pressure of O_2 is 21.2 kPa.

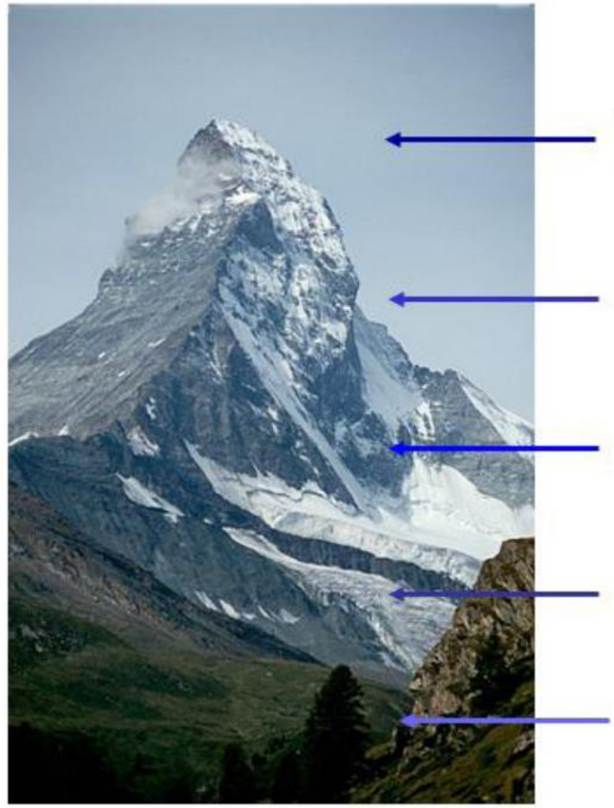


Breathing at high altitudes



$$p = p_0 \cdot e^{-\frac{mgh}{kT}}$$

High altitude air and „hypoxia”

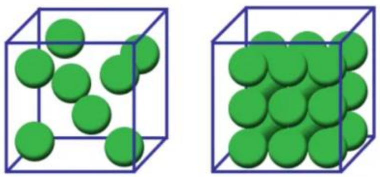


altitude (m)	p air (hPa)	p O_2 (hPa)	O_2 (%)
4.000	616	129	20,9
3.000	701	147	20,9
2.000	795	166	20,9
1.000	898	188	20,9
NN	1.013	212	20,9

- The percentage composition of air does not change with altitude in the airspace relevant to humans.
- Nevertheless, it becomes difficult to breathe as the height increases, our performance decreases. (→ altitude training - to increase performance)
- The cause of this phenomenon is the **decreasing air pressure**, which also means a **decreasing partial pressure of oxygen**. This affects the body's uptake and release of oxygen.
- The body is **able to adapt** - the amount of **hemoglobin** and red blood cells **increases**.

Density

density (ρ): $\rho = \frac{m}{V} \left(\frac{\text{kg}}{\text{m}^3} \right)$

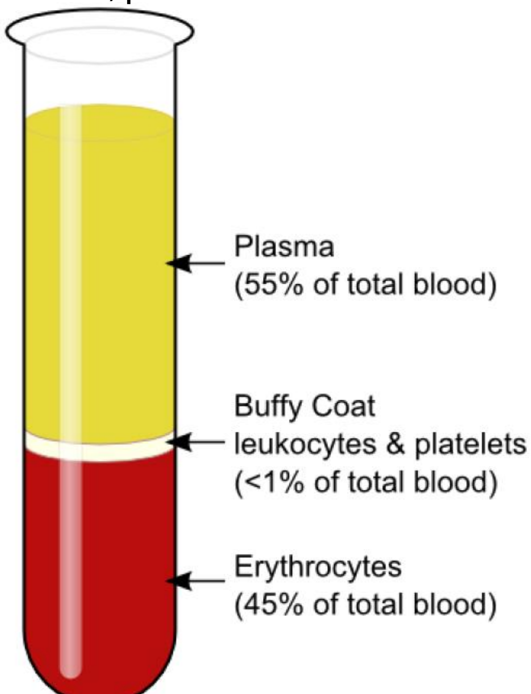


The densitiy of an object is **influenced** by:

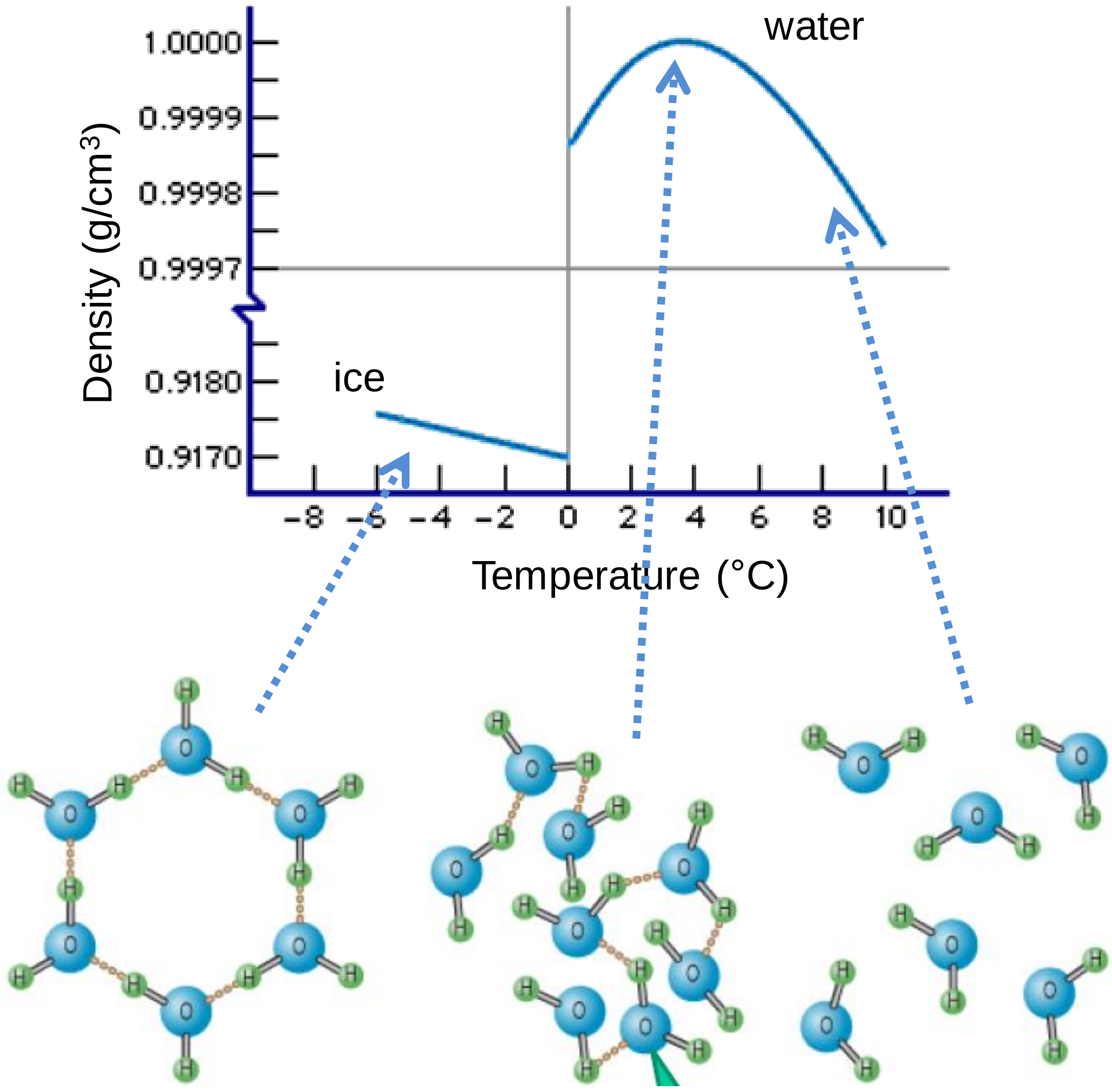
- **material**
- **pressure**
- **temperature**

Material	ρ (g/cm³)
air (0°C, 101 kPa)	0,00129
water (4°C)	1
adipose tissue	≈ 0,9
blood	≈ 1,05
bones	≈ 1,8
body tissue (avarge)	≈ 1,04
gold (Au)	19,3
mercury (Hg)	13,6

When anticoagulated blood is centrifuged, three distinct fractions are obtained due to the different densities of the components: red blood cells (erythrocytes); white blood cells (leukocytes) and platelets; plasma:

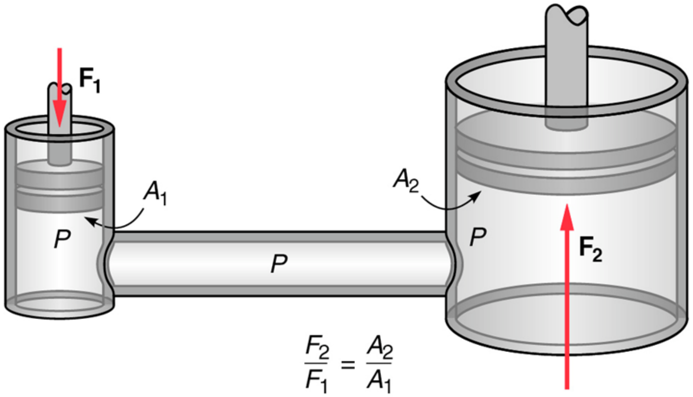


Density of water

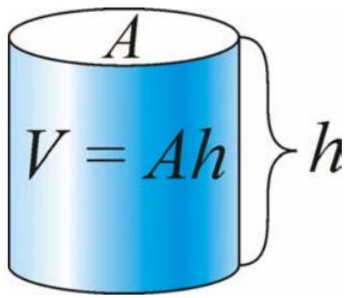


Static fluids - hydrostatics

Pascal's principle: Pressure is transmitted undiminished in fluids because they are incompressible (κ_{water} = 0,5 GPa-1). (hidraulic jack, brakes)



Hydrostatic pressure: originates from the weight of fluid. In a static fluid on the Earth (simplest case):



Hydrostatic paradox: The hydrostatic pressure exerted by the liquid on the bottom of the vessel depends only on the filling level of the vessel, but not on the shape of the vessel and thus on the volume of liquid in it.

Hydrostatic pressure

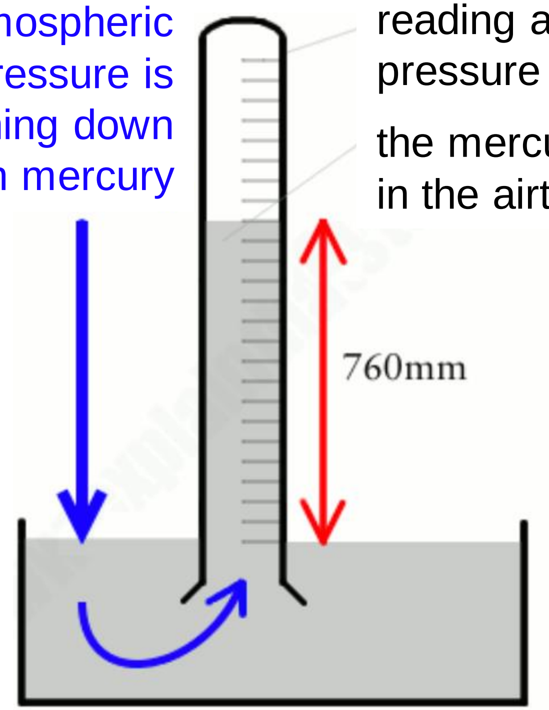
Pressure in gases and liquids due to gravity :

$$p = \rho \cdot g \cdot h$$

Comment:
The pressure thus increases linearly as a function of depth. However, this is only true in the case of an incompressible substance, when the density is constant.

Calculate the pressure exerted by the 1 mm high mercury column!

1 mmHg = 133 Pa



Evangelista Toricelli Barometer (1643)

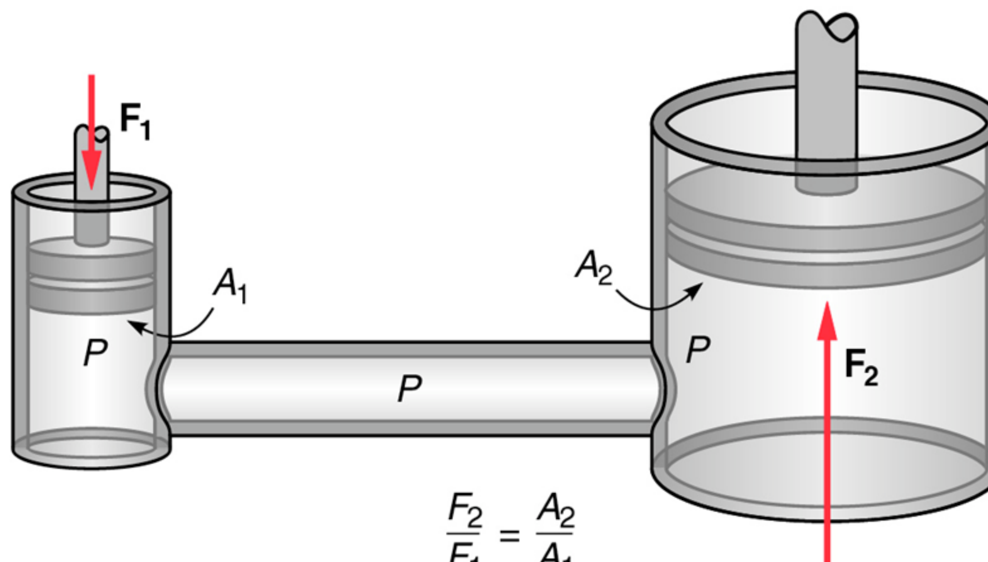
Hydrostatic paradox

The **hydrostatic pressure** exerted by the liquid on the bottom of the vessel **depends only on the filling level** of the vessel, but **not on the shape** of the vessel and thus on the volume of liquid in it.

Pascal's principle

Blaise Pascal (1623 –1662)

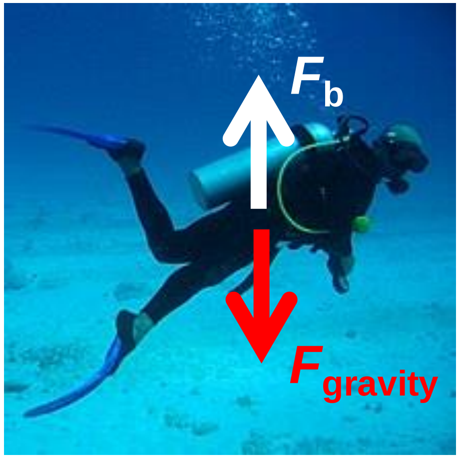
Pressure is transmitted undiminished in fluids because they are incompressible.
(κ_{water} = 0,5 GPa-1)
(hidraulic jack, brakes)



$$\frac{F_2}{F_1} = \frac{A_2}{A_1}$$

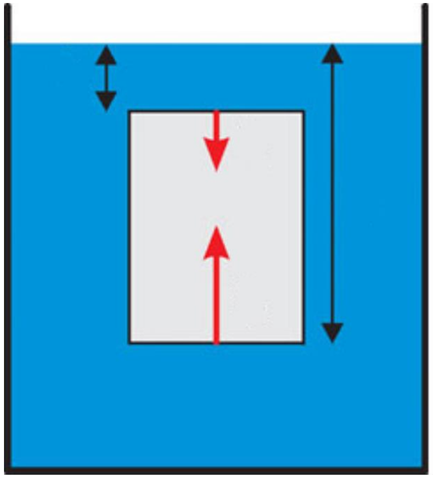
Consequence of hydrostatic pressure: buoyant force

Archimedes' principle: Every body immersed in a liquid is subjected to a buoyancy equal to the weight of the liquid displaced by the body. *Every body immersed in water loses as much weight as the weight of water it displaces*.



floating
(v = 0)

$$a = 0$$



A body that is submerged in a fluid is buoyed up by a force:

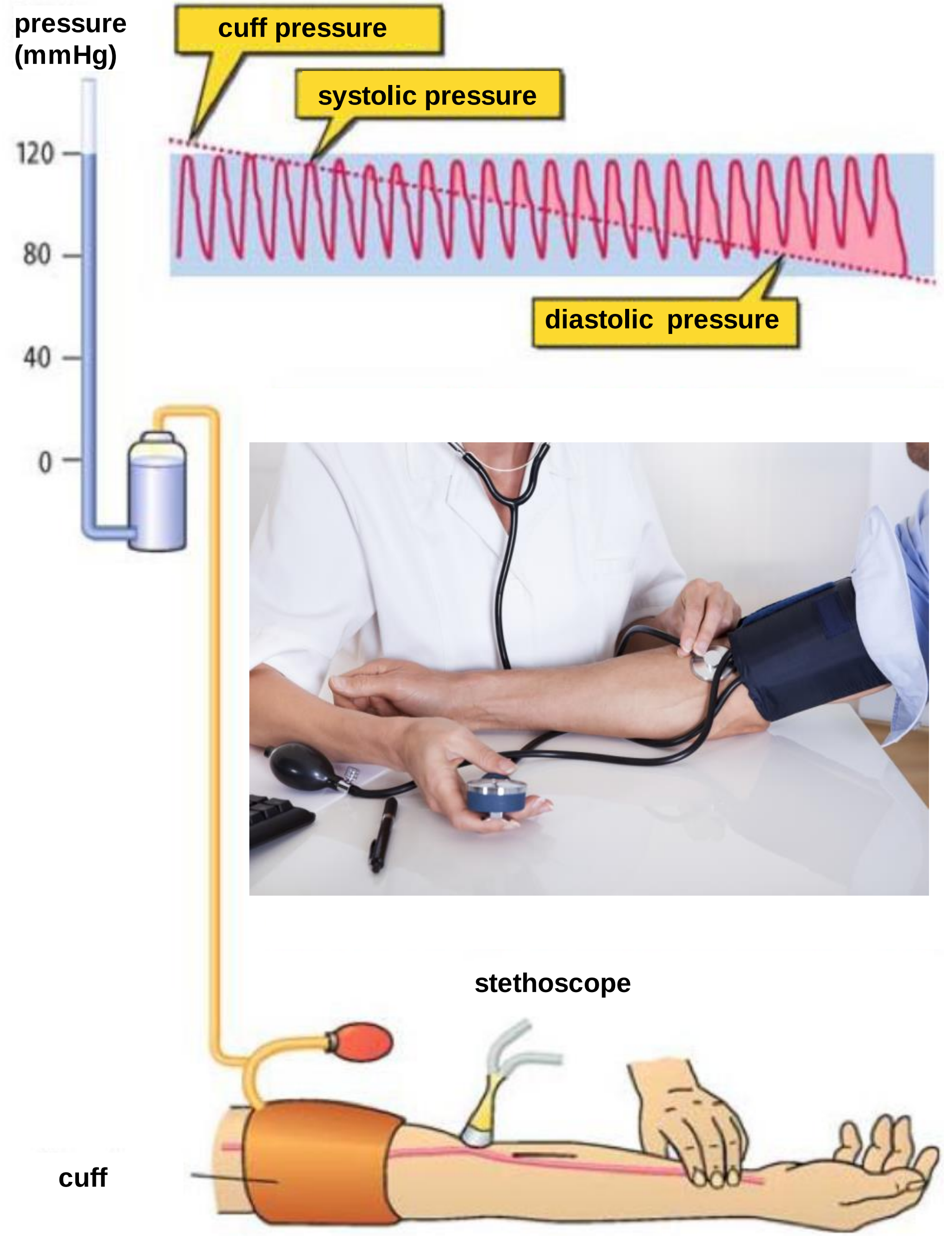
$$F_b = \rho_{fluid} g V$$

$$\sum F = F_{\text{gravity}} - F_{\text{b}} = 0$$

$$F_{\text{gravity}} = F_{\text{b}}$$

Blood pressure and its measurement

- We Inflate the cuff until the pressure the pressure in the *Arteria brachialis* by approx. 20 mmHg.
- No blood flows into the arm (or out of it).
- Place the stethoscope over the *A. brachialis* and slowly begin to reduce cuff pressure.
- As soon **as the cuff pressure drops just below the systolic pressure**, the blood starts to flow again, then we hear sounds = **Korotkov sounds**
- As long as the cuff pressure is between the systolic and diastolic values, we can hear the sounds because the **blood flow** in this range will be **turbulent**.
- Once the diastolic value is reached, the sound effect - and the turbulent flow - ceases.



Comment:
The measured pressure value is overpressure (= pressure above normal atmospheric pressure).

Homework: Chapter 6. and 9.