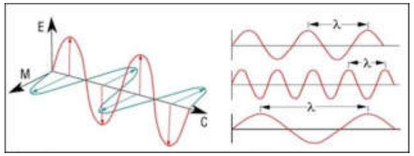
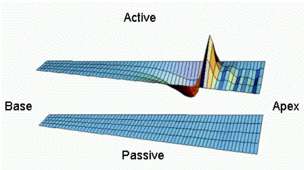
Physical Basics of Biophysics

Lecture 6 25. 09. 2020.

Ádám Orosz

Mechanics – Waves

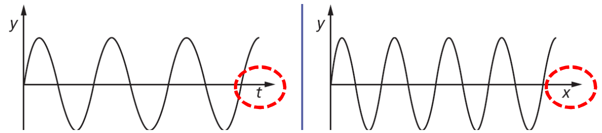




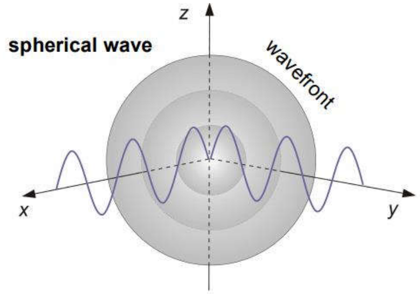
Thermodynamics

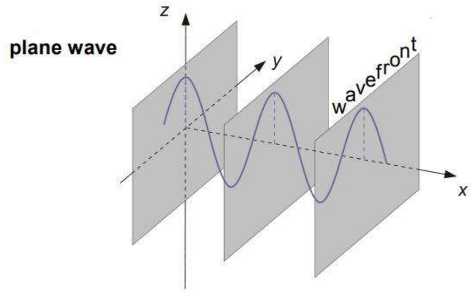
Waves – basic concepts

- Propagation of an oscillation in a medium capable of oscillation.
- Periodic (repeated) changes in a physical quantity over **time** and **space**.

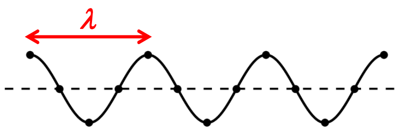


Wavefront: The surface containing points of waves in identical phase - in the same state of oscillation.



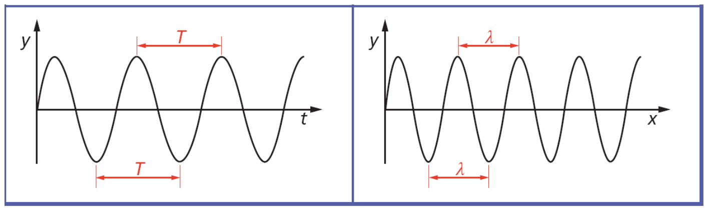


Wavelength



Wavelength (λ): The length of a wave, the distance between two consecutive points of the same phase.

- The **wavelength** is an amount analogous to the **period**. **Wavelength** characterizes **spatial** periodicity, while **period** is **temporal** periodicity.



Correlation between wavelength and period time (or frequency):

$$c = \frac{\lambda}{T} = \lambda \cdot f$$

celeritas (lat.) - swiftness

Velocity of propagation

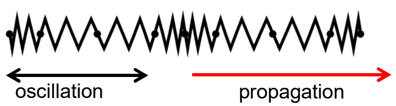
Comment:
The relation is generally valid for all types of waves (be they mechanical, electromagnetic or even material waves).

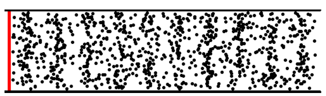
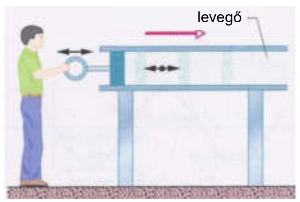
Longitudinal and transverse waves

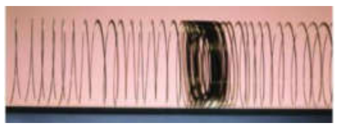
Depending on the relationship between the **direction of displacement (oscillation)** and the **direction of propagation**, we can distinguish between longitudinal and transverse waves.:

- **Longitudinal waves:** The direction of oscillation is **parallel** to the direction of propagation.
- **Transverse waves:** The direction of oscillation is perpendicular to the direction of propagation.

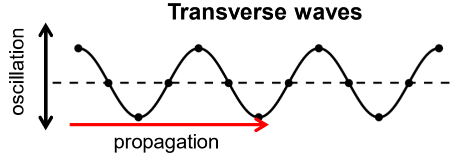
Longitudinal waves

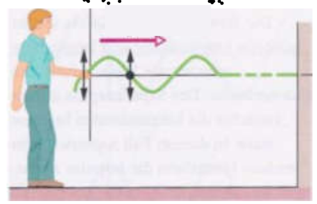




Transverse waves

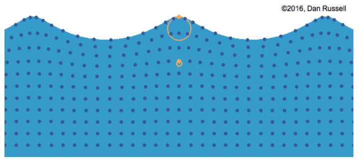



Mechanical waves

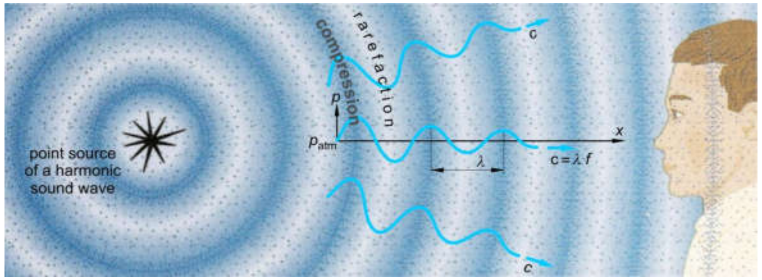
- They are bound to material movements (they need a medium to propagate)
- The movement of the components of the medium e.g.:
  - waves of water (water)
  - sound waves (air)

- They can also be longitudinal and transverse waves.



- **Mechanical longitudinal** waves are able to propagate in **all media**, **mechanical transverse** waves **only in solids**. (However, the surface waves of water are partially transverse).
- The propagation of waves is accompanied by **energy transport**, but **not** by material transport.

Sound



- Sound waves are mechanical waves, which can be divided into four ranges based on human hearing:

Range of sounds

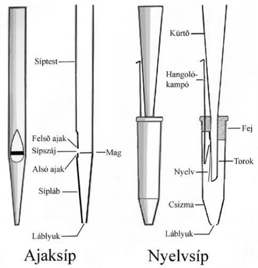
sound range	infrasound	audible sound	ultrasound	hypersound
frequency (Hz)	< 20	20–20 000	20 000–10^9	10^9 <

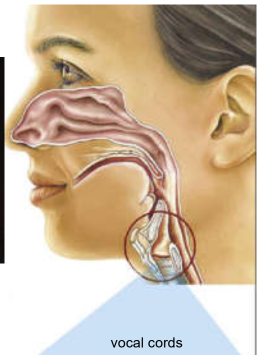
- The speed of sound is generally lower in gases than liquids and lower in liquids than in solids.

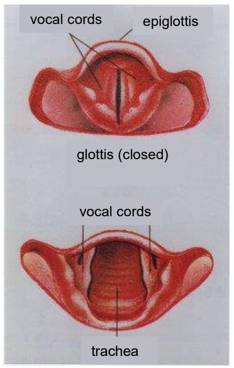
Speed of sound in various media

medium	c_{sound} (m/s)
air (0 °C, 101 kPa)	330
helium gas (0 °C, 101 kPa)	965
water (20 °C)	1 483
fatty tissue	1 470
muscle	1 568
bone (compact)	3 600
iron	5 950

Generating sound waves







Problem

The dolphin emits a sound with a wavelength of 7 mm.

a) Calculate the frequency in water!

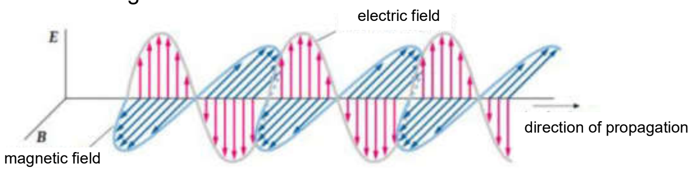
b) Which frequency range does this sound belong to?

c) Sound waves travel from water to air. Calculate the frequency in the air!

d) Calculate the wavelength in air!

Electromagnetic waves

- Waves of electric and magnetic fields

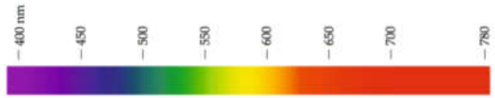


- Electromagnetic field is the oscillating medium, so these waves **can propagate in a vacuum.**
- Transverse waves (so these can be polarized)
- All electromagnetic waves propagate in a vacuum at the same speed, the speed of light:

c = 299 792 458 m/s ≈ $3 \cdot 10^8$ m/s

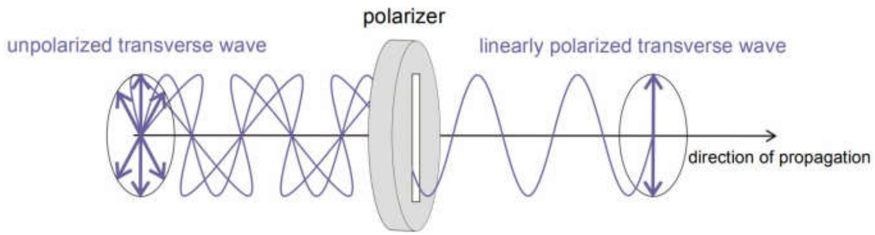
Light - the best known electromagnetic wave

- The spectrum of visible light is approx. 380 nm to 780 nm (VIS-range) → **400 nm–800 nm**



(Linear) polarisation

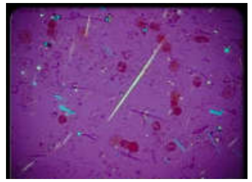
- In the case of transverse waves, the direction of oscillation and the direction of propagation are perpendicular to each other
- The direction of the oscillation is not yet precisely determined, although it is always perpendicular to the direction of propagation (= unpolarized wave)
- The "selection" of **one** direction of oscillation (plane of oscillation) by means of a polarizer is called linear polarization.



Using polarized light:

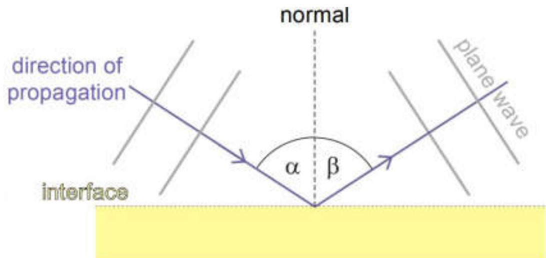
Polarised light in microscopy

gout



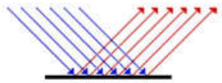
uric acid crystals in a microscope with polarizer

Interface phenomena: reflection

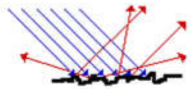


The law of reflection:

$$\alpha = \beta$$

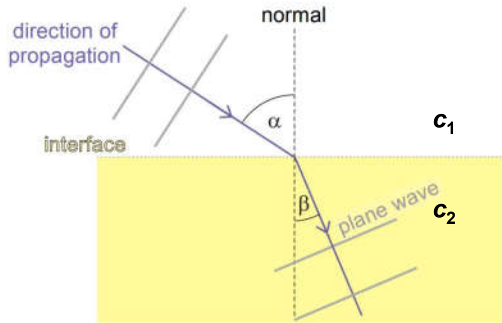


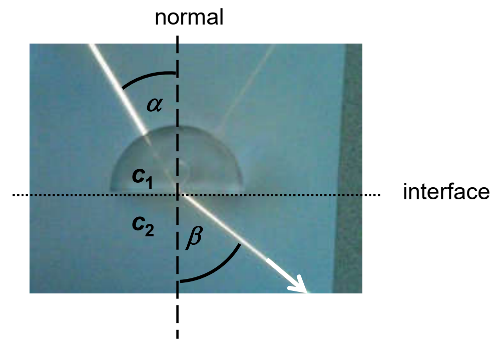
specular reflection



diffuse reflection

Interface phenomena: refraction



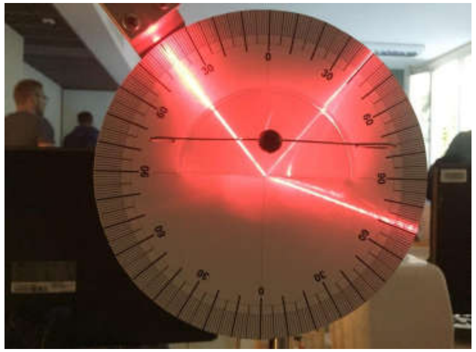


The law of refraction:

$$\frac{\sin\alpha}{\sin\beta} = \frac{c_1}{c_2}$$

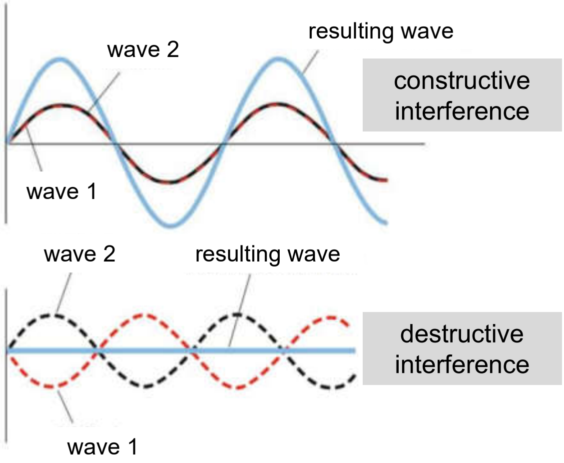
Problem

A beam of light arrives from the plexiglass to the plexiglass / air interface. The angle of incidence and refraction are shown in the image. Calculate the speed of light in plexiglass!

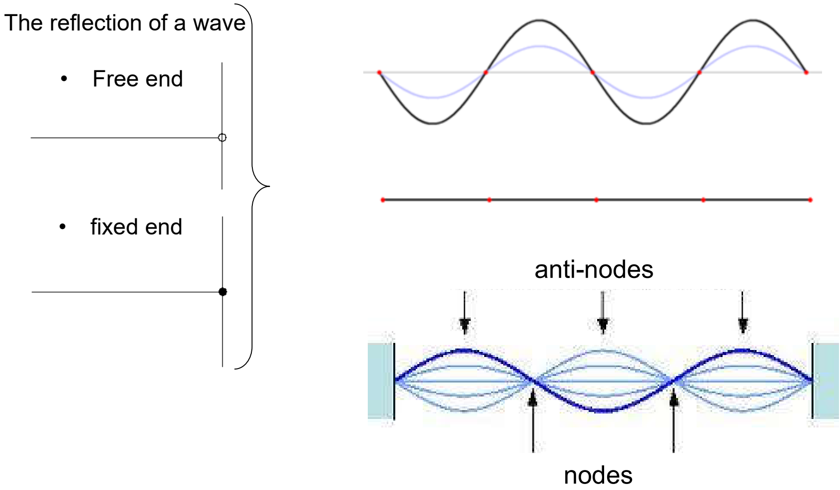


Interference

A phenomenon that occurs when two or more waves meet. Will appear when:
- Waves have the same wavelenght
- Their phase relationship is constant over time



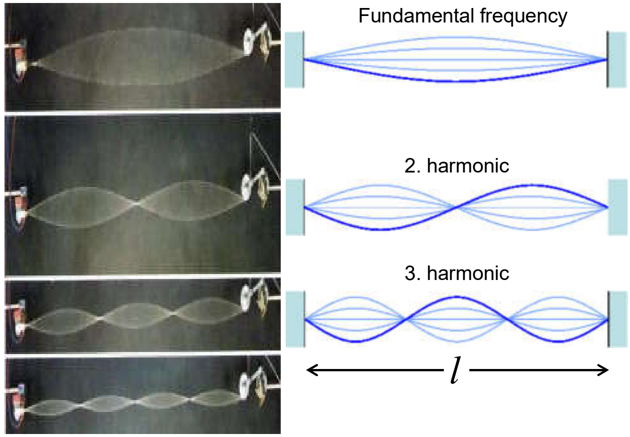
Standing waves



- It is the result of the interference of two plane waves of the same frequency and amplitude but in opposite propagation directions (e.g. superimposition of reflected and incident waves)
- Each point within a node oscillates with the same phase but different amplitude
- At the fixed end there is a node
- At the free end an anti-node

Standing waves

Example: A system with two fixed ends (both nodes)



$\lambda_0 = 2 \cdot l \Rightarrow f_0 = \frac{c}{2l}$

f_0 – fundamental frequency

$\lambda_1 = l \Rightarrow f_1 = \frac{c}{l} = 2 \cdot f_0$

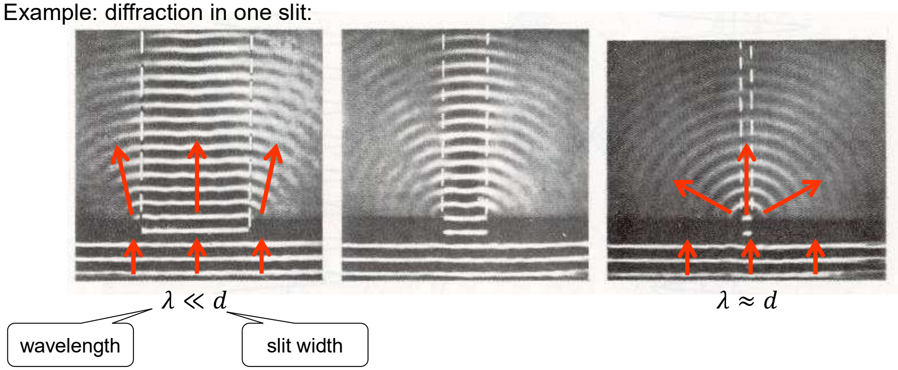
$\lambda_2 = \frac{2}{3} \cdot l \Rightarrow f_2 = \frac{3c}{2l} = 3 \cdot f_0$

Comment:
The basic frequency of a string of a violin can be set e.g.:
- by changing the length of the string
- By changing the vibration state of the string (→ speed of propagation)

Diffraction

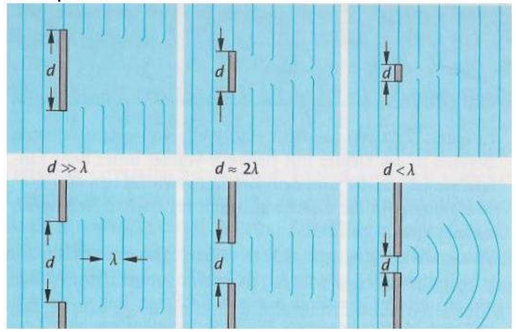
Change of the direction of wave propagation on obstacles and openings in the path of the wave (not at the interface of two media!).

Example: diffraction in one slit:

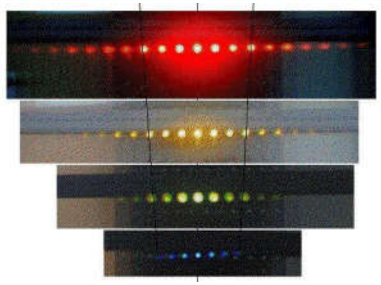


The waves also penetrate behind an opening into a range that could be termed as "shadow space" based on a simple geometric expectation.

- Depending on the size of the obstacle or opening and the ratio of the wavelength, the diffraction is more or less pronounced
- The phenomenon of diffraction is all the more pronounced:
  - the smaller the obstacle or slit (for a given wavelength)

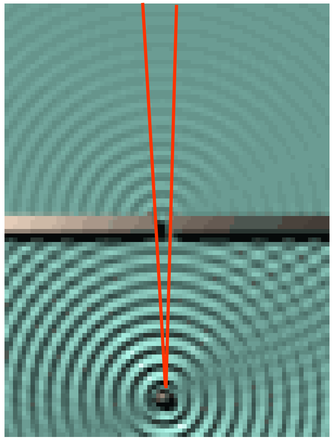


  - The larger the wavelength (for a given slit width)

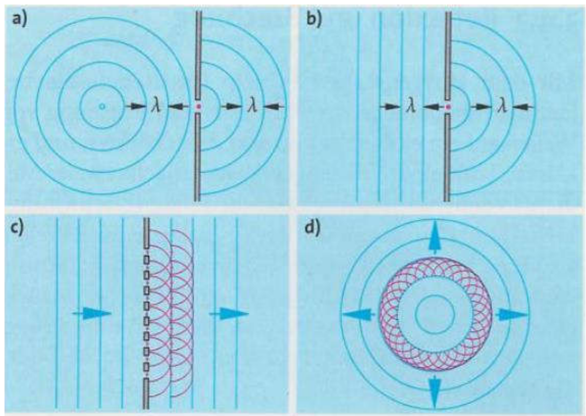


Comment:
Diffraction is the reason for the finite resolution of all optical devices, e.g. microscope, eye.

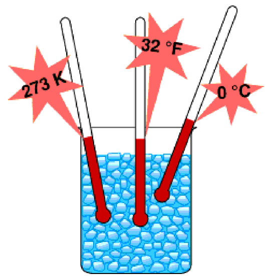
Huygens–Fresnel principle

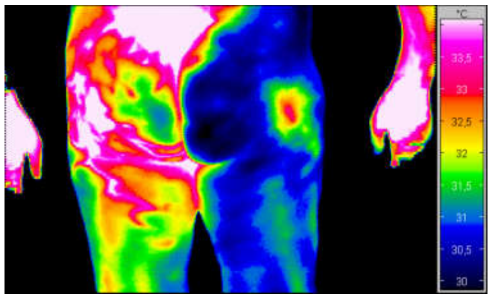


- A model to describe wave propagation
- Each point on the wavefront can be considered as the starting point for a new spherical wave, called the elementary wave
- The elementary wave propagates at the same speed and frequency as the original wave
- The common envelope of the elementary waves results in a new wavefront



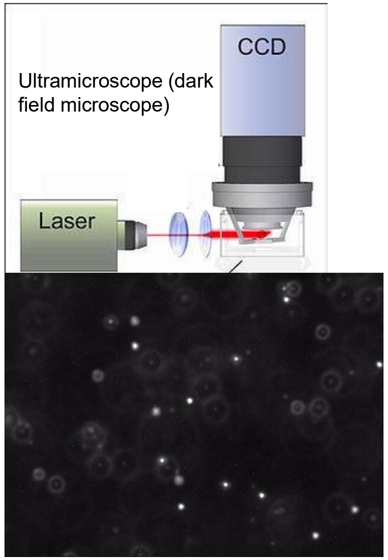
Thermodynamics





1. Thermial energy
2. Temperature its scales
3. Heat
4. Heat capacity and specific heat capacity
5. States of matter
6. Phase transition and specific latent heat
7. Ideal gas modell

Thermal motion and thermal energy



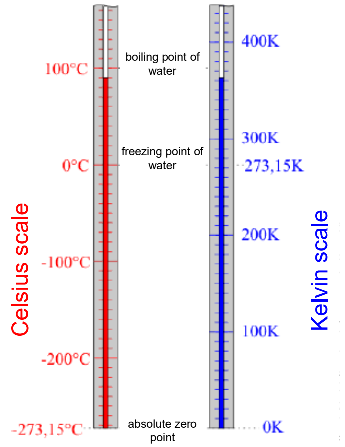
The thermal energy of an object includes the energies of different movements of the particles that make up the object (translation, rotation, vibration)

- 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

- The central concept of thermodynamics 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



- 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

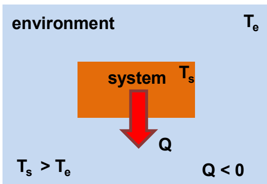
The **heat capacity** (*C*) can be used to make a connection between the *change in the temperature* of an object ΔT and the *heat* absorbed or released Q:

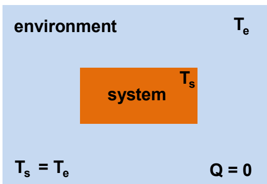
$$C = \frac{Q}{\Delta T} \quad \left(\frac{\text{J}}{\text{K}}\right)$$

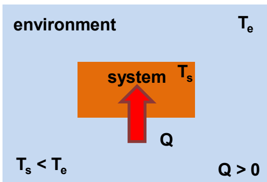
- If we want to increase the temperature of a body, we have to give heat to it: then Q and ΔT are positive
- If we want to reduce the temperature of a body, we have to extract heat: then Q and ΔT are negative
- The **heat capacity** of a body also depends on **the material quality** and the **mass**,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

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

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

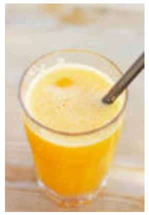






Problem

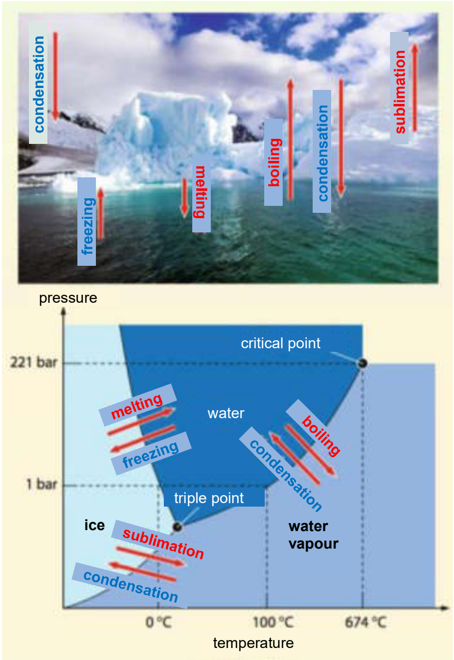
We want to cool 2 dl of orange juice from 28°C to 8°C. How much heat do we need to remove from the drink? (The density of orange juice is 1.02 g/cm^3.)



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

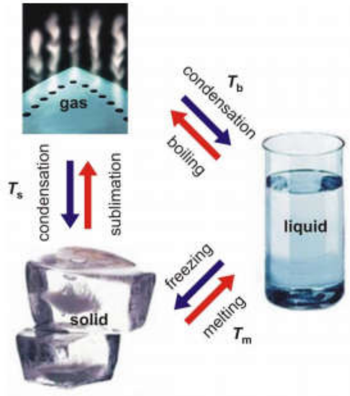


Phase transition and specific latent heat

- 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 depends on the mass and the following proportionality 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 are talking about, 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

Problem

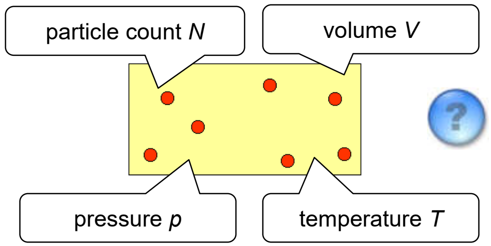
To continue the previous problem:
We want to cool the orange juice with ice cubes (the temperature of the freezer is -18 ° C). How many grams of ice do we need? (How many ice cubes should we throw into the glass if a piece weighs 50 g?)

material	*c* (J/kg·K)	*specific heat of fusion L* (kJ/kg)
ice	2090	334,4

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.



$p \sim T$

$p \sim N$

$p \sim \frac{1}{V}$

Ideal gas law:

$$pV = NkT$$

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

Alternative form: $pV = \nu RT$

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

Homework: Chapter 8. and 9.