Physical bases of biophysics

Lecture 5 22. 09. 2020.

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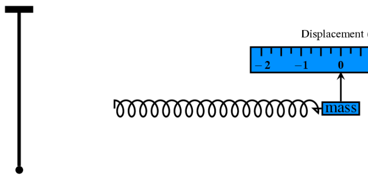
1. Mechanics – Pressure, Hydrostatics

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

2. Mechanics - Oscillations



1. Basic concepts of oscillations
2. Types of oscillations
3. Harmonic oscillations
4. Restoring force
5. Free oscillation and eigenfrequency
6. Mass-spring oscillator
7. Driven oscillation
8. Resonance

Repetion - Pressure

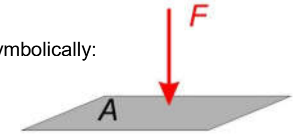


- The deformation of an object depends not only on the force acting on it, but also on the surface on which the force is applied.
- Power alone is not always enough to describe the interaction. We need a new quantity that also takes the surface into account. → „pressure".

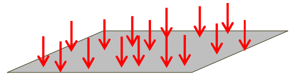
pressure (p): $p = \frac{F}{A}$ $\left(\frac{\mathrm{N}}{\mathrm{m}^2} = \mathrm{Pa}\right)$

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

Fluid mechanics

Fluid statics

Hydrostatics
(description of non-compressible fluids at rest)

Aerostatics
(atmosphere at rest)

↓

Characterization of the internal state of gases and liquids

↓

Pressure ↔ Density

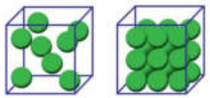
Fluid dynamics

↓

Flow of fluids and gases

Density

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

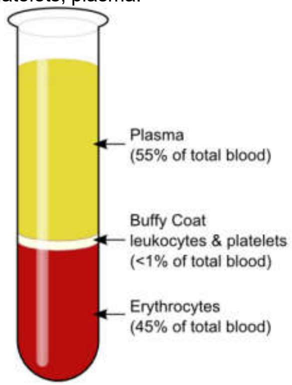


The densitiy of an object is influenced by:

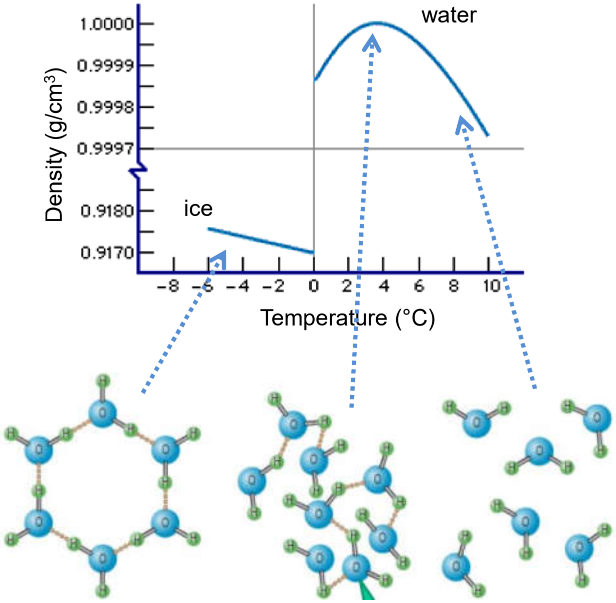
- **material**
- **pressure**
- **temperature**

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



Problem

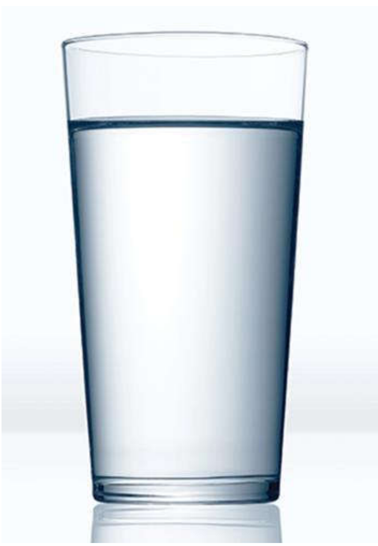
How much pressure does an 80 kg man in a standing position exert on the ground if

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)

Hydrostatic pressure



Hydrostatic pressure

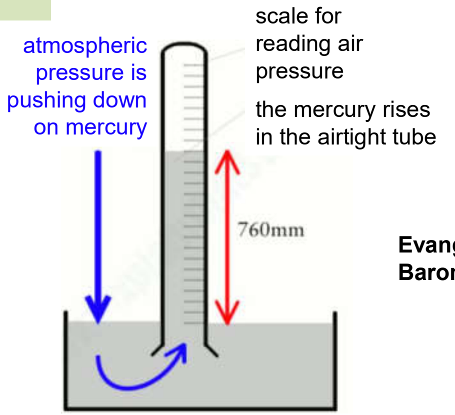
Pressure in gases and liquids due to gravity :

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

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

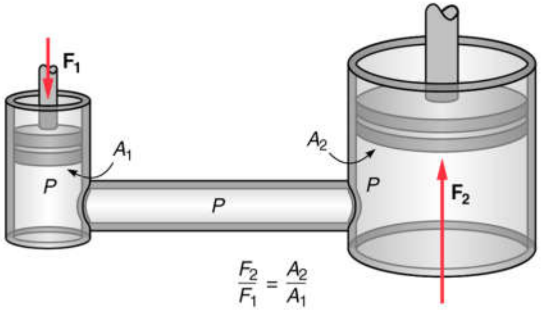
The **hydrostatic pressure** exerted by the liquid on the bottom of the vessel **depends only on the filling level** of the vessel, but **not on the shape** of the vessel and thus on the volume of liquid in it.

Pascal's principle

Blaise Pascal
(1623 –1662)

In a fluid at rest in a closed container, a pressure change in one part is transmitted without loss to every portion of the fluid and to the walls of the container.

(At all points of a fluid at rest at the same height, the pressure is the same and equal in all directions.)

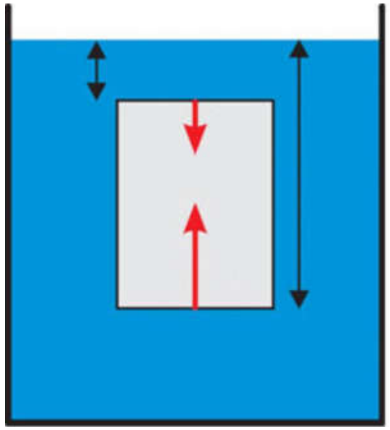


$$\frac{F_2}{F_1} = \frac{A_2}{A_1}$$

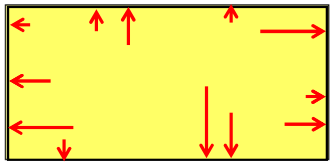
Archimedes' law and buoyancy

Every body immersed in a liquid or gas is subjected to a buoyancy equal to the weight of the liquid or gas displaced by the body. *Every body immersed in water loses as much weight as the weight of water it displacesa.*

<u>Bouyancy:</u>



Pressure of gases



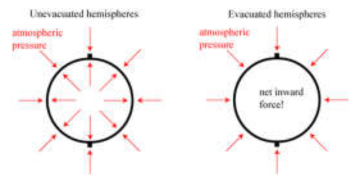
later:

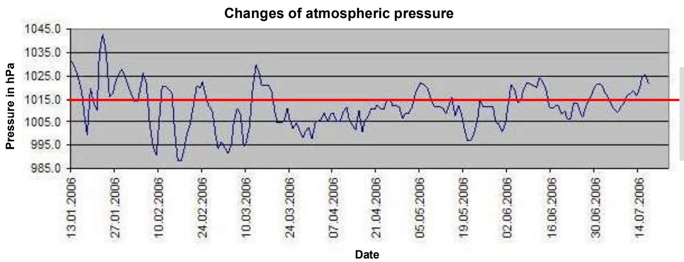
$$pV = NkT$$

- 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 ~ 6·10^{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":

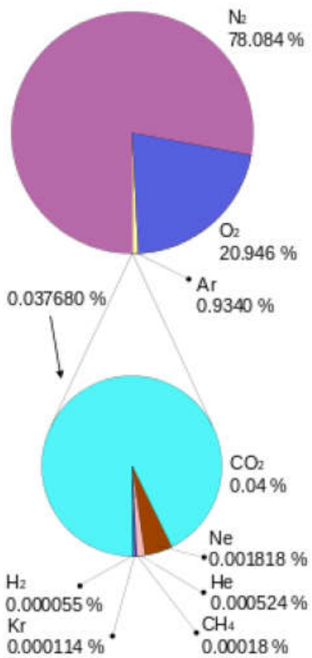




Normal atmospheric pressure= 101 kPa = 1010 hPa

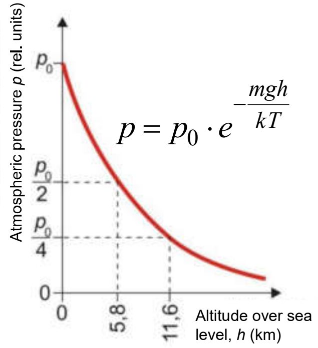
Partial pressure

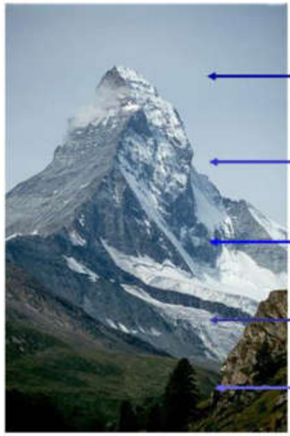
- A concept for gas mixtures.
- Air is a mixture of gases (nitrogen, oxygen, carbon dioxide,…)
- Each component of the gas mixture contributes to the total gas pressure.
- The **partial pressure** corresponds to the pressure that one of the components of the gas mixture would exert if it filled the total 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

High altitude air and „hypoxia"



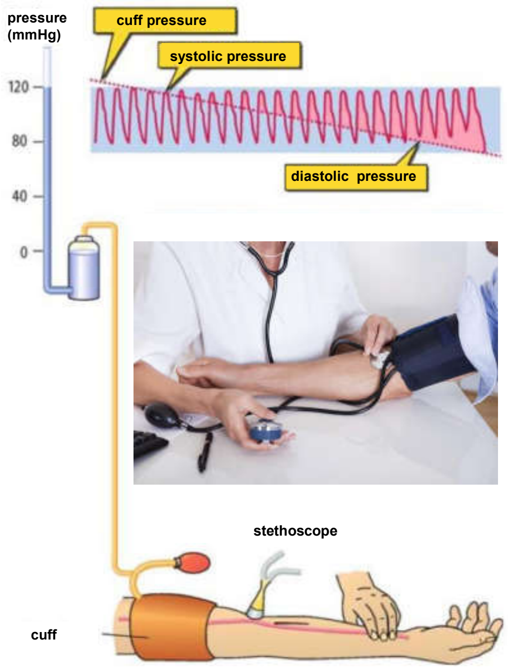


altitude (m)	p air (hPa)	p O_2 (hPa)	O_2 (%)
4.000	616	129	20,9
3.000	701	147	20,9
2.000	795	166	20,9
1.000	898	188	20,9
NN	1.013	212	20,9

- 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

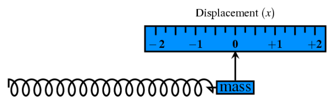
Blood pressure and its measurement

- 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).

Mechanics – Oscillations



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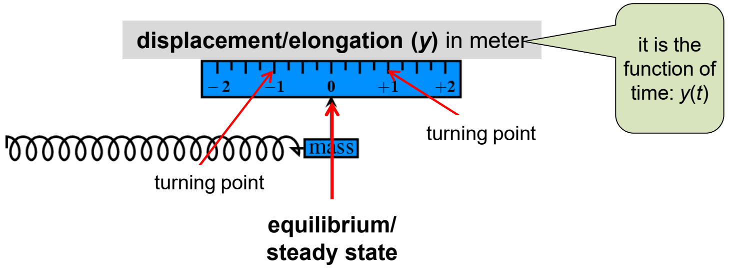
3. Harmonic oscillations
4. Restoring force
5. Free oscillation and eigenfrequency
6. Mass-spring oscillator
7. Driven oscillation
8. Resonance

Basic concepts of oscillations

Oscillator: a physical system capable of oscillation(e.g. mass attached to a spring or pendulum).
Oscillation (mechanical): a periodic (repetitive) motion about a point of equilibrium.



Amplitude (A): maximal displacement

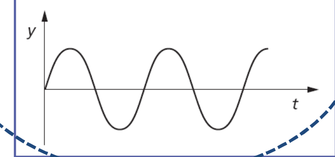
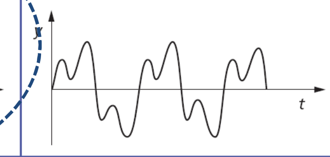
Reminder:

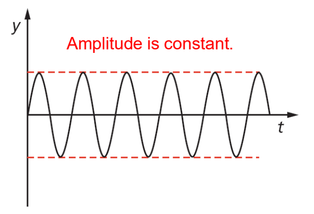
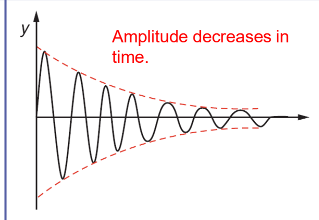
- **Period** (*T*): duration of one cycle in a repeating event; its base unit is the second (s).
- **Frequency** (*f*): number of cycles per unit time. The reciprocal of period:

$$f = \frac{1}{T} \qquad \left(\frac{1}{\mathrm{s}} = \mathrm{Hz}\right)$$

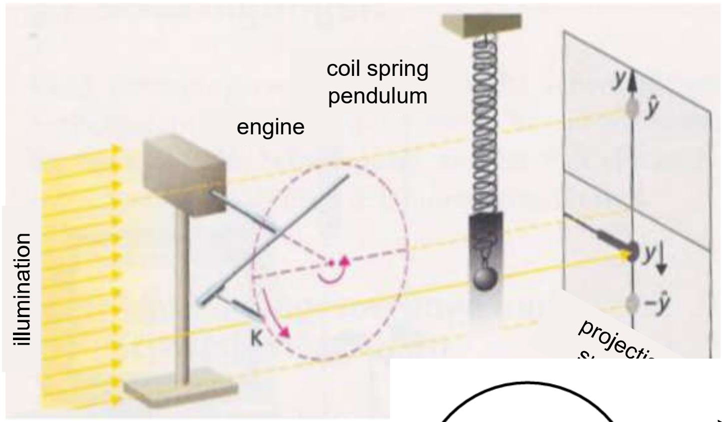
- **Angular frequency** (ω): the number of cycles in 2π. 2π times the frequency : $\omega = 2\pi f$

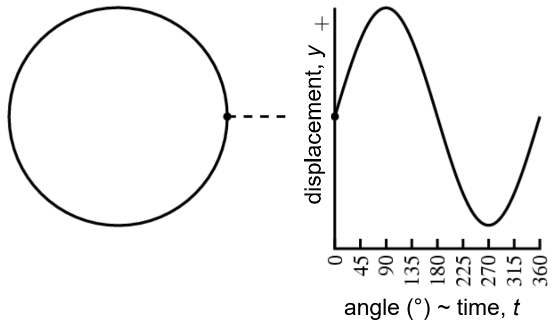
Types of oscillations

Harmonic oscillation (sinusoidal oscillation)	**Non-harmonic oscillation (non-sinusoidal oscillation)**
	
pendulum clock, spring pendulum - spring oscillator	oscillations of the human vocal cord shock absorbers in cars

Free oscillation	**Dampeded oscillation**
	
speaker diaphragm during a sound at a given volume	Pendulum which is left to itself, vibration damper

Uniform circular motion– harmonic oscillation





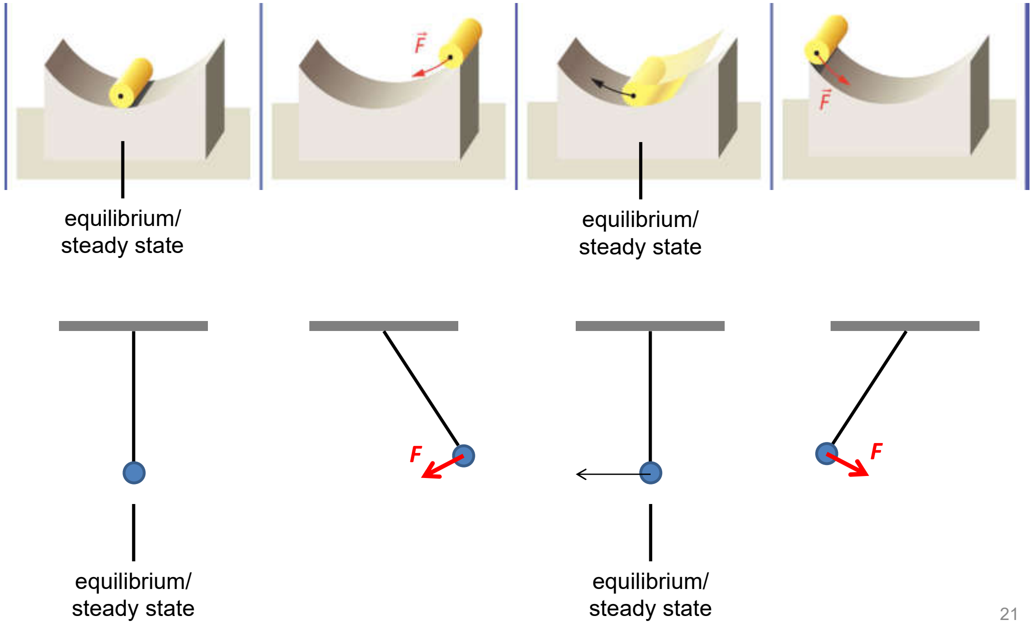
The general form of the displacement-time function:

$$y = A \cdot \sin(\omega t + \varphi_0)$$

Displacement, velocity, acceleration, force

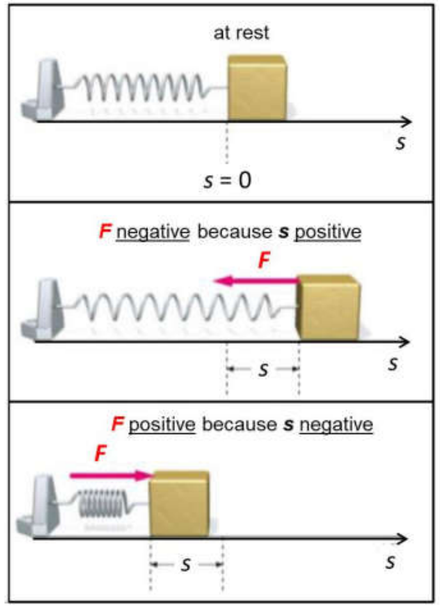
Restoring force

What force do we need for harmonic oscillations?



Restoring force

$$F = -D \cdot s$$



The restoring force is:

- Always pointing to the direction of the equilibrium.
- Proportional to the displacement but points in the opposite direction (negative)

Free oscillation

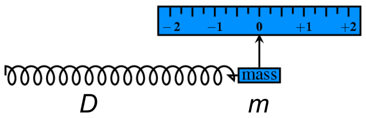
Prerequisite:
We displace the system and and release it, creating an oscillation.

Free oscillation: oscillation that proceed on its own without external influence.

Eigenfrequency (natural frequency): frequency of a free oscillation.

It is determined by the properties of the oscillator (mass, geometric quantities, material properties, etc.).

Mass-on-spring oscillator



$$f_{\text{natural}} = \frac{1}{2\pi}\sqrt{\frac{D}{m}}$$

Comment:
The equation is only valid in the ideal case, i.e. the oscillation is harmonic (not damped). In fact, there is always a loss of energy (friction, air resistance,…), so the oscillation is damped.

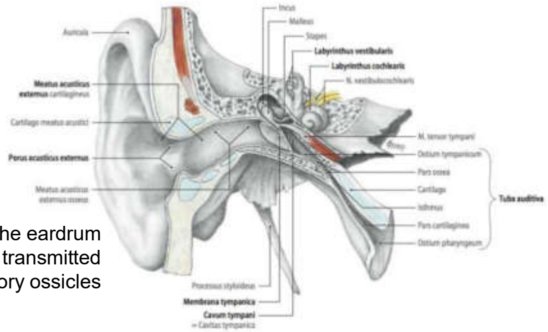
Problem

Body weight is determined in space using a spring oscillator. The oscillator used for the measurement weighs 6.5 kg and has a period of 0.75 s. Together with the astronaut, the period increased to 2.7 s. Calculate the astronaut's mass!

Driven oscillation

Oscillation caused by a periodic external force.

If one of the tuning forks is hit, the resulting air pressure fluctuations will also cause the other tuning fork to vibrate (provided that both forks are tuned to the same pitch).

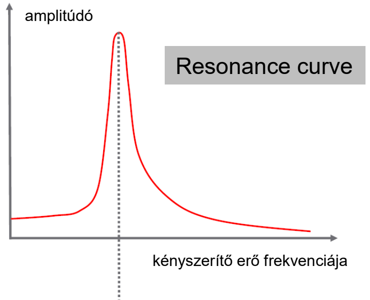


Air pressure fluctuations vibrate the eardrum and then these vibrations are transmitted through the auditory ossicles

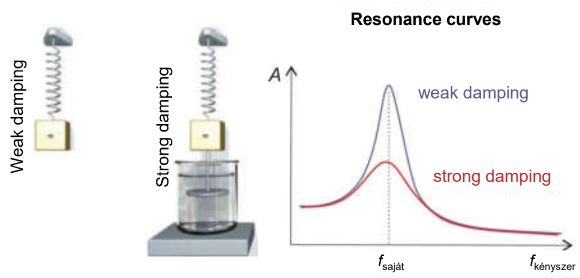
- During a driven oscillation, we can maintain the harmonic oscillation with a constant amplitude with the driving force, despite the energy losses.
- The oscillationg system takes up the frequency of the driving oscillation.

Resonance

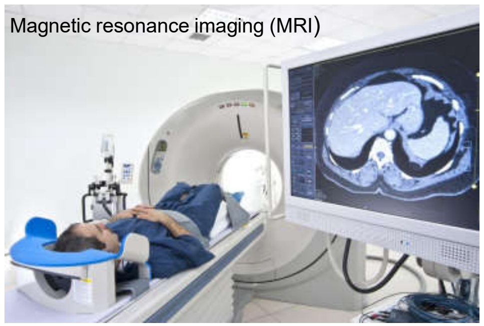
- If energy is periodically transmitted to a oscillating system by means of an external driving system, driven oscillation will develop after a certain settling time.
- Depending on the frequency of the driven oscillation, oscillations of different amplitudes are generated.
- If the frequency of the driven oscillation coincides with the natural frequency of the system, a particularly strong, high-amplitude driven oscillation is generated.
- A particularly high-amplitude oscillation at a given frequency is called a **resonance**, and a frequency characteristic of a phenomenon is called a **resonance frequency**.

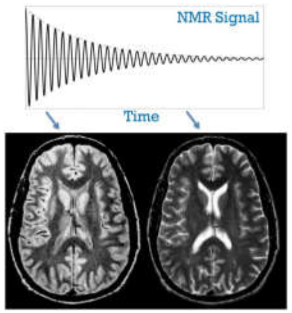


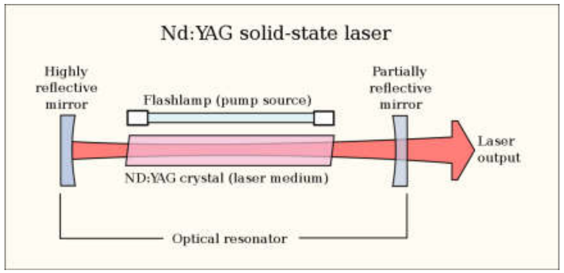
resonance frequency = Natural frequency of the oscillator



Comment:
The phenomenon of resonance is used in several technical devices (eg nuclear magnetic resonance spectroscopy and imaging, laser, ...)







Homework: Chapter 6 and 7