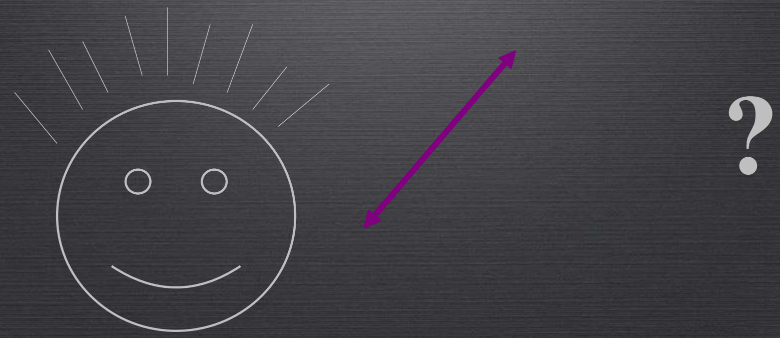
Medical Biophysics

Introduction
Prof. Judit Fidy

Faculty of General Medicine
Department of Biophysics and Radiation Biology

Medical Biophysics



Medical biophysics --- ?

- ***Biophysics – scientific field***

Medical biophysics --- ?

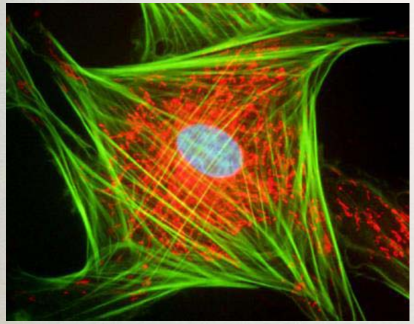
- ***Biophysics – scientific field***
  - ***physical methods (experimental and theoretical) applied to biological objects***

Examples:

Light microscopy + fluorescent dyes

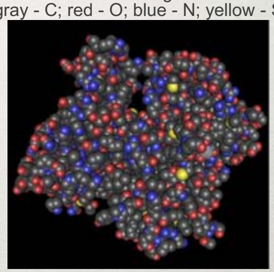
X-ray diffraction on crytals of biological macromolecules

→ Structural information about cells, molecules in atomic details

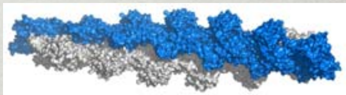


Fluorescence microscopy on cells labelled by dyes binding to actin filaments

X-ray diffraction:
Structural model of globular actin
gray - C; red - O; blue - N; yellow - S



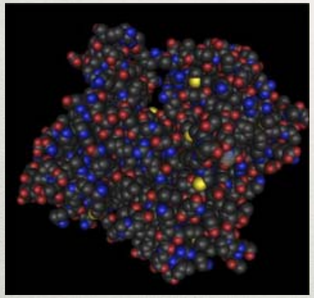
G-actin (d=5 nm)



Actin filament (d=7 nm)

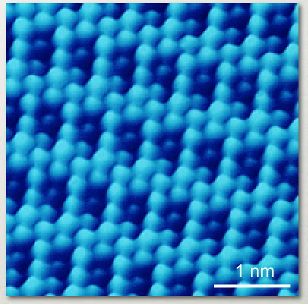
Present day resolving power of determining structural data

X-ray scattering data are collected, evaluation is by fitting a structural **model** by computer



Structural **model** of globular actin
gray - C; red - O; blue - N; yellow - S

direct measurement by sophisticated microscopy techniques

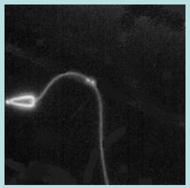


Oxygen atoms on the surface of a rhodium single crystal
(scanning probe microscopic image)

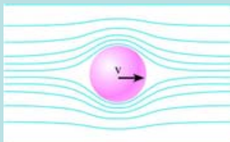
Example : Drag coefficient of a sperm cell

How much force (F) is necessary for a sperm cell to be transported in a medium?

Simplified sperm cell model:
object with circular cross-section



Stokes' Law:



$$F = \; v = 6r \quad v$$

$$= 6r \quad = 6\times 1.6 \quad 10^{6}(m)\times \quad \times 10^{3}(Pas) = 3 \quad 10^{8}\,Ns/m$$

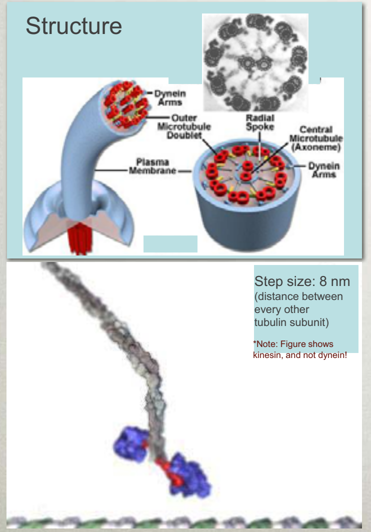
$$F = \; v = 3 \quad 10^{8}\,Ns/m \times 5 \quad 10^{5}\,m/s = 1.5 \quad 10^{12}N = 1.5\,pN$$

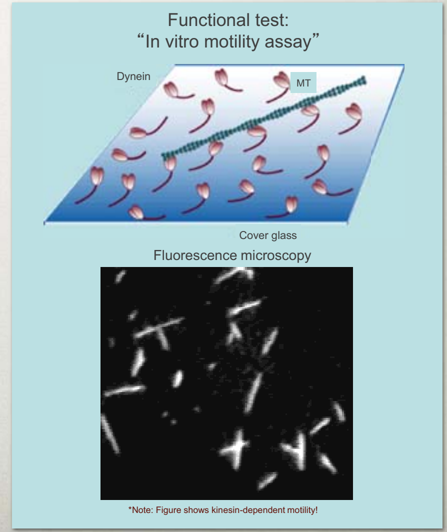
Medical biophysics --- ?

- ***Biophysics – scientific field***
  - physical methods applied to biological objects
  - ***observing biological phenomena →***
    (new physical descriptions) →
    understanding biology → learning
    → influencing

Mechanisms behind cell motility?

How does it happen (what is the exact mechanism)? Building a predictive model.





- ***Medical** biophysics*

- physical methods applied to biological objects →

*→ **diagnostics, therapy***

- observing biological phenomena → new physical descriptions → understanding biology → learning,

→ targeting of medications, nanotechnology for internal monitoring and substitution of impaired physiological functions

The course

Lectures: topics needed as foundation for medical practice - *not malpractice!*

Laboratory practices:
goal: learn how to design and peform experiments
how to evaluate the data and to draw conclusions

The course

Lectures: topics needed as foundation for medical practice

Laboratory practices:
goal: learn how to design and peform experiments
how to evaluate the data and to draw conclusions

Preparation for medical practice

Lecture topics

Semester I.

1. Length scale of biology. Atomic physics
2. Electromagnetic radiation. Dual nature of light. Matter waves
3. The atomic nucleus. Radioactivity. Nuclear radiation
4. Interaction of electromagnetic radiation with matter
5. Radioactivity in the medical practice. Dosimetry, nuclear medicine
6. Luminescence
7. Laser and its medical applications
8. X-ray
9. Multi-atom systems. The Boltzmann distribution
10. Molecular biophysics. Water, macromolecules, biopolymers
11. Nucleic acids and proteins. Folding of RNA and proteins
12. Atomic and molecular interactions. Scanning probe microscopies
13. Biomolecular structure. Diffraction, X-ray crystallography, light- and electron microscopy. Mass spectrometry, CD
14. Biomolecular structural dynamics. Fluorescence, ESR, NMR. Basics of MRI

Semester II.

1. Gas laws. Pulmonary biophysics
2. Thermodynamics. Thermodynamic system, laws
3. Equilibrium and change. Kinetics. Entropy an its microscopic interpretation
4. Irreversible thermodynamics. Transport processes. Diffusion, Brownian motion
5. Cytoskeletal system. Motor proteins. Mechanisms of biological motion
6. Biomechanics. Biomolecular and tissue elasticity
7. Fluid dynamics. Circulatory biophysics
8. Muscle biophysics. Striated muscle, smooth muscle
9. Cardiac biophysics. Work of the heart. The cardiac cycle
10. Bioelectric phenomena. Resting potential
11. Action potential. Biophysics of electrically active tissues. EKG, EMG, EEG. Principles of sensory function
12. Sound, ultrasound. Auditory biophysics
13. Optics of the eye, biophysics of vision
14. Collective processes in ensembles. Complex systems, networks

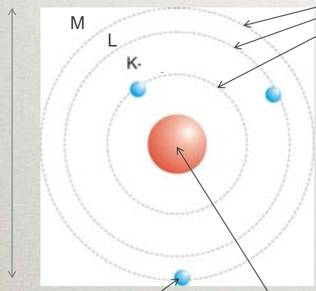
Towards complexity ?

Starting from „simple" : ***the atom*** (simplification: composed of elementary particles)

„orbits" of electrons bound to the nucleus

- probability distribution functions
- each orbit means a discreat energy status of e^-
- K, L, M… labels meaning n=1,2,3..

schematics



d~10^{-10} m

Orbital electrons (-)

Atomic nucleus

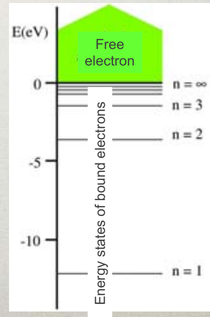
d<10^{-18} m
Free electron

Proton (+)
Neutron

d~10^{-14} m

d~10^{-15} m

Energy measured in „eV" units



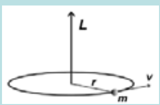
H-atom

Atomic „bound" electrons – quantum numbers

The energy and the momenta of the electron in the atom can have only well defined, discrete values

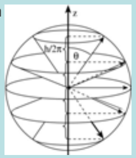
Angular momentum and spin momentum

absolute value



$L = m * v * r$

direction



both magnitude and direction are discrete

name	symbol	orbital meaning	range of values	value example
principal quantum number	n	shell	$1 \le n$	$n = 1, 2, 3...$
azimuthal quantum number (angular momentum)	ℓ	subshell	$(0 \le \ell \le n-1)$	for $n = 3$: $\ell = 0, 1, 2\,(s, p, d)$
magnetic quantum number, (projection of angular momentum)	m_ℓ	energy shift	$-\ell \le m_\ell \le \ell$	for $\ell = 2$: $m_\ell = -2, -1, 0, 1, 2$
spin projection quantum number	m_s	spin	$-\frac{1}{2}, \frac{1}{2}$	for an electron, either: $-\frac{1}{2}, \frac{1}{2}$

Quantum numbers and the periodic table

Characterization of bound atomic electronic states: with n, l, m_l, m_s quantum numbers

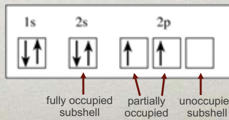
n → electron shell
n, l → electron subshell
n, l, m_l → electron orbital
s –spin state

Wolfgang Pauli (1900-1958)

Pauli's exclusion principle:
•Each quantum state can be occupied by a single electron.
•Within an atom there cannot be two electrons for which all four quantum numbers are identical.

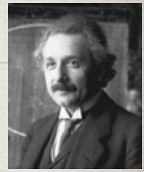
Friedrich Hermann Hund (1896-1997)

Hund principle:
•Order of filling up the quantum states.
•For a given electron configuration, the state with maximum total spin has the lowest energy.



Electron configuration of the C atom
s: "sharp", p: "principal", d: "deformed" (spectroscopic nomenclature)

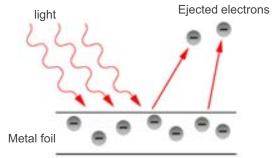
Atomic „bound” electrons – interact with photons of electromagnetic radiation



Albert Einstein
1879-1955

PHOTONS

The photoelectric effect



Observation by F.Lenard:

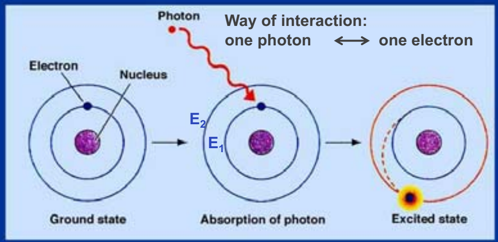
Kinetic energy of ejected electrons does not depend on the intensity of light. It depend solely on the frequency of light

Explanation by A.Einstein **1905**

$$E_{photon} = hf \qquad c = \lambda f$$

$$E_{photon} = hf = W_{ionization} + E_{kinetic}$$

Photon:
energy quantum of electromegnetic radiation in interaction with matter

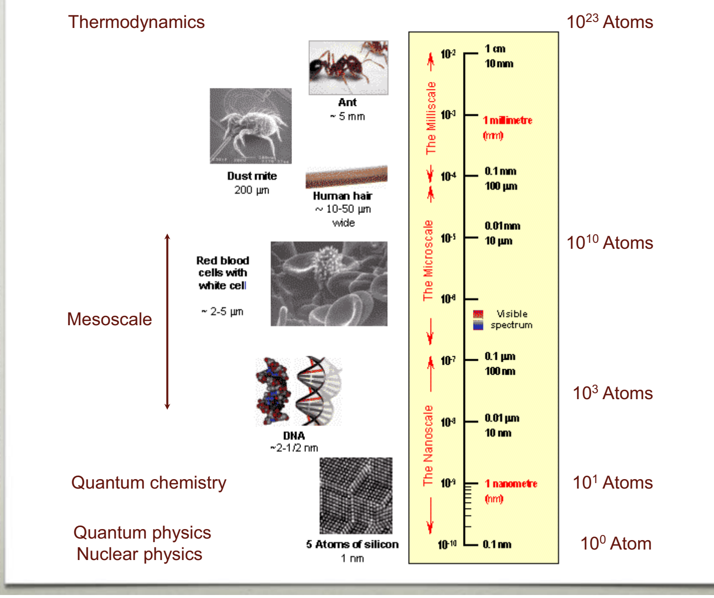


An orbital electron is able to change its energy status to another orbit by consuming/absorbing or releasing/emitting the energy difference between the two orbits in the form of a photon of electromagnetic radiation of proper frequency

$$\boxed{hf = E_2 - E_1}$$

Complexity - shown in dimensions

Stages of complexity require distinct physical models of understanding



Paying tribute to the discoverers

Democritus (460-370 BC)
Matter composed undivisible particles (atomos).

John Dalton (1766-1844).

Dalton's atom of a given element

Elements are made of extremely small particles called atoms.
Atoms of a given element are identical in size, mass, and other properties; atoms of different elements differ in size, mass, and other properties.
Atoms cannot be subdivided, created, or destroyed.
Atoms of different elements combine in simple whole-number ratios to form chemical compounds
In chemical reactions, atoms are combined, separated, or rearranged.

Joseph John Thomson
(1856-1940)

Discovery of the electron 1897.

Cathode ray (electron beam) in vacuum tube.

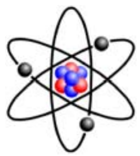
"Plum pudding" atomic model:
Electrons revolve in orbits within a positively charged jelly-like substance

Paying tribute to the discoverers

Ernest Rutherford
(1871-1937)

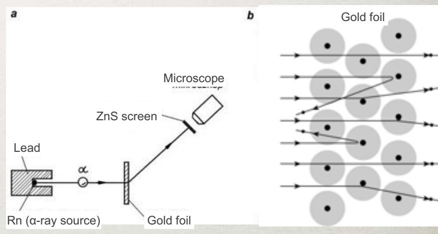
1909: discovery of the atomic nucleus

The positive charge in the atoms is not distributed like a jelly, but concentrated within a tiny volume



Rutherford's atomic model:
miniature planetary system
Gravitational force replaced by electric attraction

Rutherford's experiment



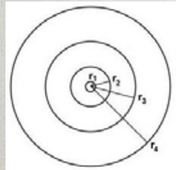
α – particle : heavy atomic nucleus 2p and 2n (2+)

Observation: most of the a particles crossed the foil undeviated from their path

interaction with positive nuclei was rare

Paying tribute to the discoverers

Niels Bohr (1885-1962)
assistant of Rutherford



Bohr model of the hydrogen atom

Rutherford – Bohr model 1911-13

1. Quantum conditions for the electron-state:
- The electrons move around on orbits of **quantized angular momentum** $L = mvr = n\dfrac{h}{2\pi}$
- On the given orbit the electron does not loose **energy – it is constant and of discrete value**
- . $E_n = \dfrac{E_1}{n^2}$ $\qquad r_n = n^2 r_1$

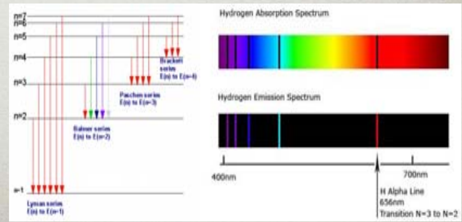
n= principal quantum number. The radii of the orbits can be calculated.. The radius of the first orbit is r_1 = 5,3 10^{-11} m ("Bohr-radius"

2. Combines e⁻-energies and the photon concept
- The atom emits radiation of „f" frequency only if the electron "jumps" from one orbit to the other.
- Energy of the radiation is the difference between the orbit energies:

$$E_{photon} = hf = E_2 - E_1 \qquad c = \lambda f$$

The orbit energies can be calculated. Energy of the first orbit is E_1=-13.6 eV. Further orbit energies are:

Energy levels in the hydrogen atom.



Achievements

The model explained the spectra of the hydrogen atom.
Quantum-concept included for electron and for radiation

Problems:

Orbiting electrons should radiate according to classical mechanics – orbital energy should not be constant
The orbiting electrons should have measurable magnetic moments

*N.B.: postulate: fundamental requirement, condition

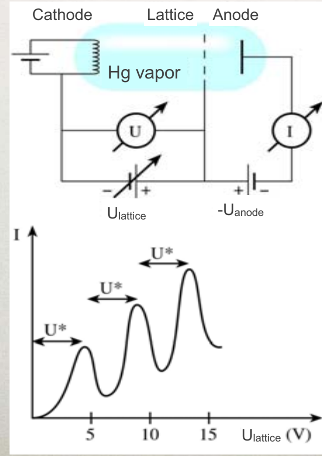
Paying tribute to the discoverers

Experimental verification of the quantized energy states of bound electrons

Franck-Hertz experiment (1914)

James Franck (1882-1964)

Gustav Ludwig Hertz (1887-1975)



The electrons accelerated by the lattice voltage ($U_{lattice}$), upon inelastic collision with the Hg atoms, loose their energy in discrete packages ("quantum" - sing., "quanta" - pl.).

Paying tribute to the discoverers

Louis V. de Broglie (1892-1978)

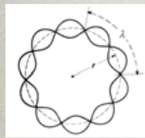
1923: wave – particle duality concept

The electron as a wave

$$\lambda = \frac{h}{p} = \frac{h}{m_e v}$$

Clinton Joseph Davisson (1881-1958)
Lester Herbert Germer (1892-1968)

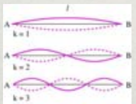
Atomic electrons are considered as standing waves instead of orbiting particles



Quantum condition
for standing waves on an orbit:

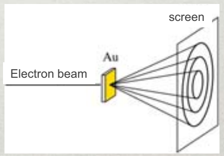
$$2\pi r = n\lambda = n\frac{h}{mv}$$

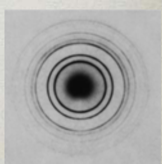
Quantized behavior in the stationary waves of a stretched string



$$l = k\frac{\lambda}{2}$$

1927: diffraction pattern with electrons: wave behavior verified





Paying tribute to the discoverers

Erwin Schrödinger
(1887-1961)

„Schrödinger equation" ~ 1930

electron wave functions to describe the state of the electron in the atom

Discrete energies of orbitals corresponding to wave functions

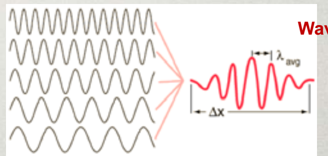
Ψ(x,t) wavefunction:
- [Ψ(x,t)]: gives the amplitude of the electron wave as a function of position (x) and time (t).
- Ψ^2: gives the probability of finding the electron or electron charge density. functions
- Ψ^2: integrated across the entire space = 1 (i.e., the electron can be found somewhere).
- Ψ: with the help of Schrödinger's equation, allows calculation of electron energies.
- For a free electron Ψ is a sine wave: momentum is precisely known (p=h/λ), but position (x) entirely unknown (uncertainty principle!)

Imagine a photon or an electron as a wave

Werner Heisenberg (1901-1976)

$$\Delta x \cdot \Delta p \geq \frac{h}{2\pi}$$

Uncertainty principle



Wave packet view

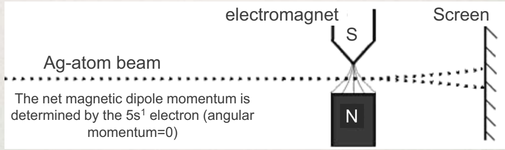
If the position of the electron is defined (Δx is small) then the wavelength (p→λ) will vary within a large scale :

Paying tribute to the discoverers

Stern-Gerlach experiment (1922) – experimental proof for the spin states of the electron

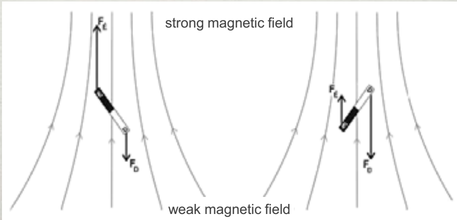
Otto Stern (1888-1969)

Walther Gerlach (1889-1979)



Silver beam splits in two

In an inhomogenous magnetic field, in addition to torque, net force arises on the magnetic dipoles: deviates the beam



The spin magnetic moment may have two values (+1/2, -1/2)

Summary: properties of the atom

(that will be emphasized in the course)

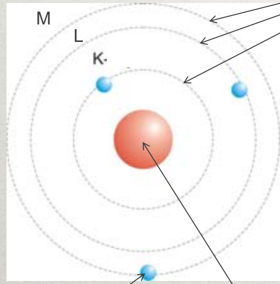
Starting from „simple" : ***the atom*** (simplification: composed of elementary particles)

„orbits" of electrons bound to the nucleus

- average distance of probability distribution functions
- each orbit means a discreat energy status of e^-
- K, L, M… labels meaning n=1,2,3..

schematics

d~10^{-10} m



Orbital electrons (-)

d<10^{-18} m

Free electron

Atomic nucleus

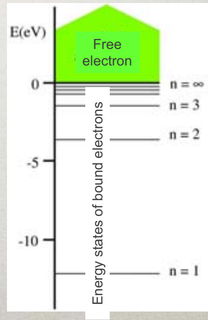
Proton (+)

Neutron

d~10^{-14} m

d~10^{-15} m

Energy measured in „eV" units

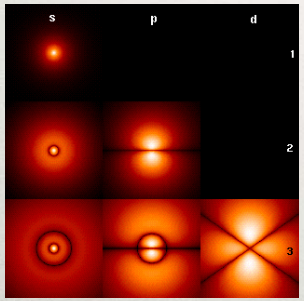


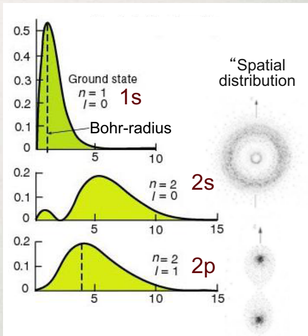
H-atom

Atomic orbitals as charge distribution functions → →Chemistry

Schrödinger's probality functions/charge distribution functions

X – Z plane





Charge density versus distance from the nucleus

Good luck!

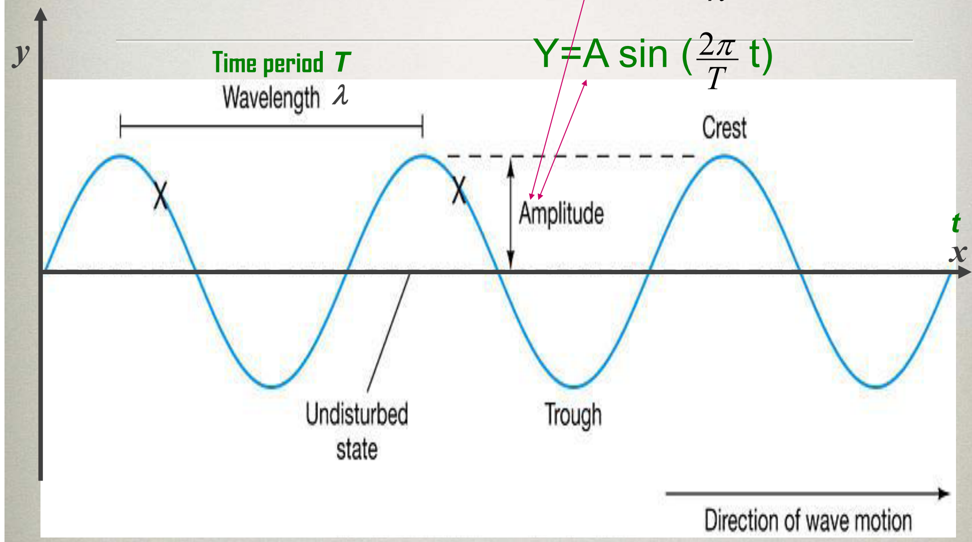
Thank you for your attention!

Appendix:
Reminder: what a wave function is

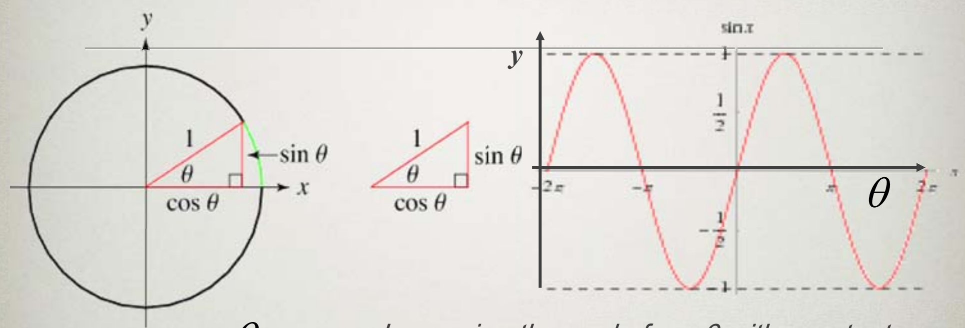
Reminder: The
sine/cosine function

$$Y = A \sin\left(\frac{2\pi}{\lambda}x\right)$$

$$Y = A \sin\left(\frac{2\pi}{T}t\right)$$



Reminder: Sinusoidal/Sine function



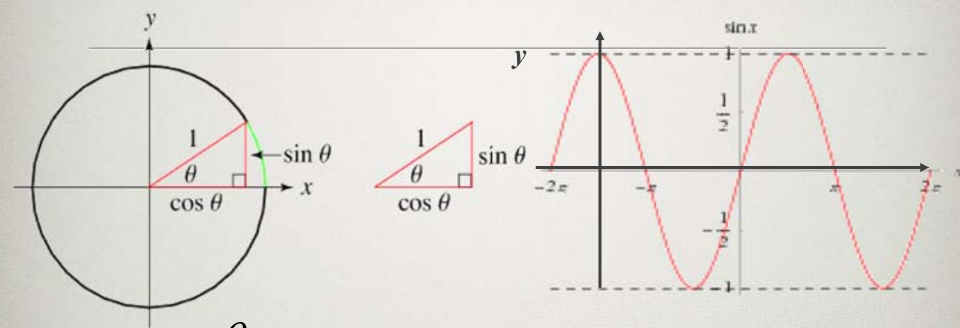
$\theta = \omega t$ *Increasing the angle from 0 with constant speed*
t=time

$$\text{one round} \quad \theta = 2\pi,\ t = T \ \text{time period}$$

$$\Rightarrow \omega = \frac{2\pi}{T} = 2\pi \cdot \frac{1}{T} = 2\pi \cdot f$$

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

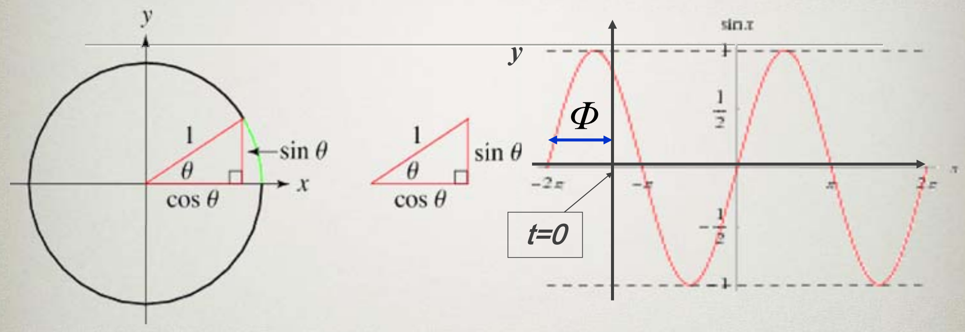
Reminder: Cosine function



$\theta = \omega t$ *Increasing the angle from 0 with constant speed*

$$y = A \cdot \cos(\omega t) = A \cdot \sin\left(\omega t + \frac{\pi}{2}\right)$$

The phase angle



$$\theta = \omega t + \Phi$$

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

General form of a „wave function”: sine-function of two variables:
t –time and ***x*** - space coordinates

$$\boxed{y = A \cdot \sin(2\pi \frac{t}{T} + 2\pi \frac{x}{\lambda} + \varphi)}$$

Frequency (f):
f = 1/T (cycles/s, Hz) f (or ν)

Speed (c) of energy propagation
c = f·λ (m/s)
or c = λ/T

A – amplitude
Maximum of $|y|$