

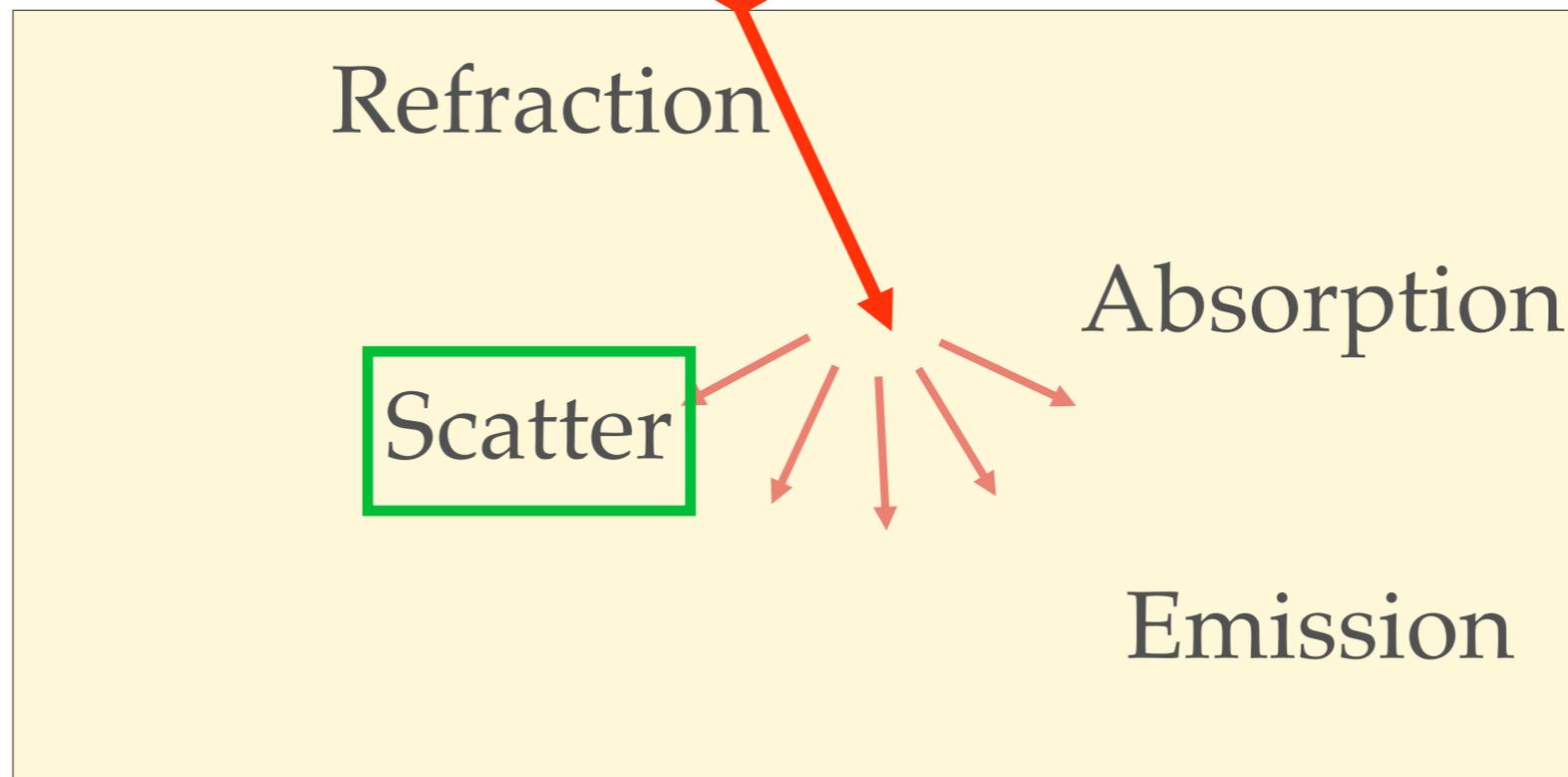
**INTERACTION OF LIGHT
WITH MATTER:
SCATTER, ABSORPTION**

MIKLÓS KELLERMAYER

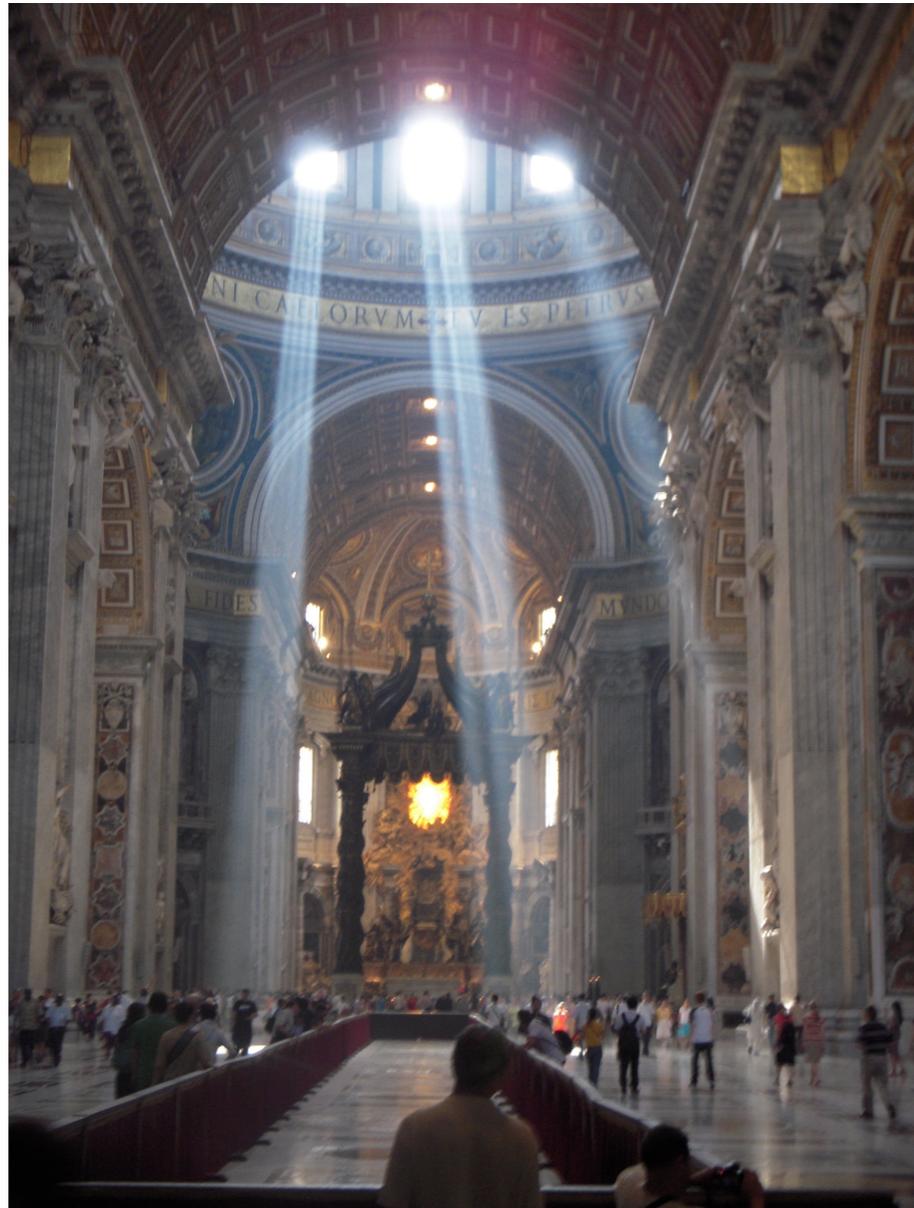
INTERACTION OF LIGHT WITH MATTER

Incident beam

Reflection



SCATTERING OF LIGHT



What are these rays?
Crepuscular rays
(St. Peter's basilica)



Why is the sky blue?

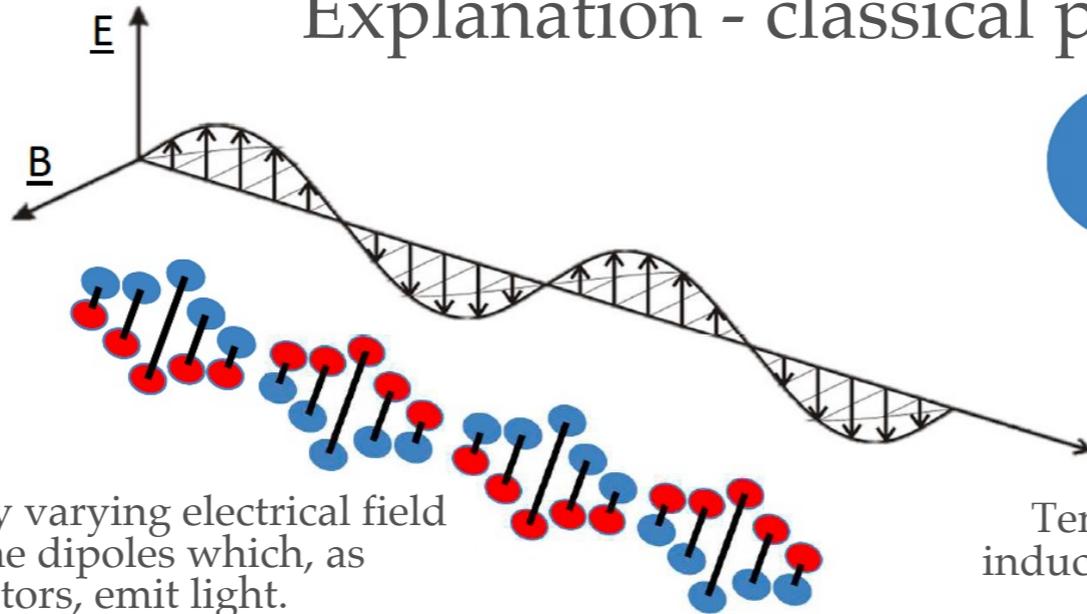


What makes the sunset red?

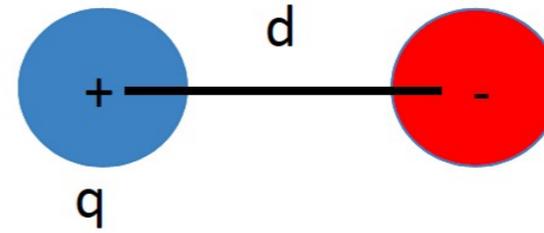
SCATTERING OF LIGHT

Explanation - classical physics

Light is an electromagnetic wave (E, B : electric and magnetic fields)



The temporally varying electrical field vibrates the dipoles which, as oscillators, emit light.



Molecule as a dipole
Dipole moment (p_0):

$$p_0 = Qd$$

Temporally varying dipole moment induced by the varying electrical field: $p = p_0 \sin \omega t$

Dimension: Qdt^{-1}

How large is the scattered ("re-radiated") light's power? (P_{scatt} ; dimension $W = Fdt^{-1}$)

N.B. - Coulomb's law:

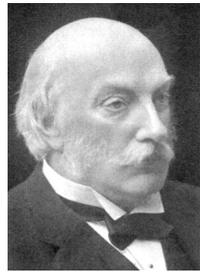
$$F \sim \frac{Q_1 Q_2}{r^2} \quad (\text{dimension } Q^2 d^{-2})$$

Dimensional derivation

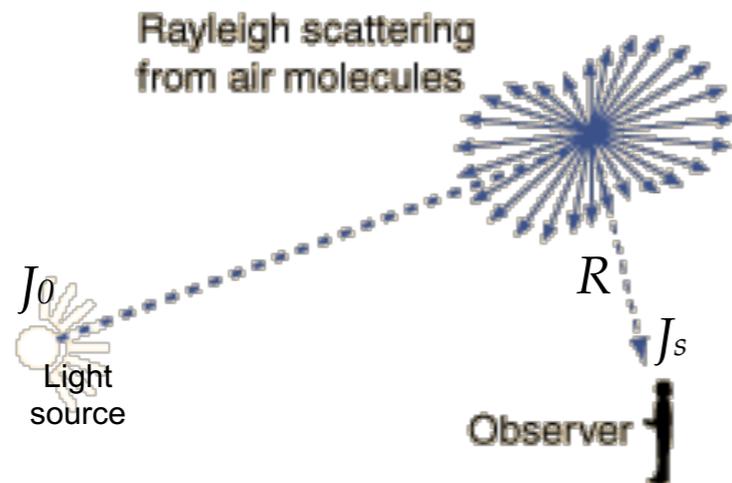
Physical parameter	Dimension	Operation
p_0^2	$Q^2 d^2$	Square
p_0^2	$Q^2 d^{-2} d^4 = Fd^4$	Expand with $d^2 d^{-2}$
p_0^2 / c^3	$Fd t^3$	Divide by c^3 ($d^3 t^{-3}$)
$(p_0^2 / c^3) \omega^4$	$Fd t^{-1} = W$	Multiply by ω^4 (t^{-4})

$$P_{scatt} = \frac{p_0^2}{c^3} \omega^4$$

LIGHT SCATTERING



Lord Rayleigh
(1842-1919)



- Elastic collision: photon energy (wavelength) does not change
- Emission by resonating dipoles
- Scattering particles far from each other

$$J_s = J_0 \frac{8\pi^4 N \alpha^2}{\lambda^4 R^2} (1 + \cos^2 \Theta)$$

J_s =intensity of scattered light
 J_0 =intensity of incident light
 N =number of scattering particles
 α =polarizability (dipole moment per electric field)
 λ =wavelength of light
 R =distance between scatterer and observer
 Θ =angle between light source and observer



Strong wavelength dependence \rightarrow enhancement of short wavelengths \rightarrow blue sky



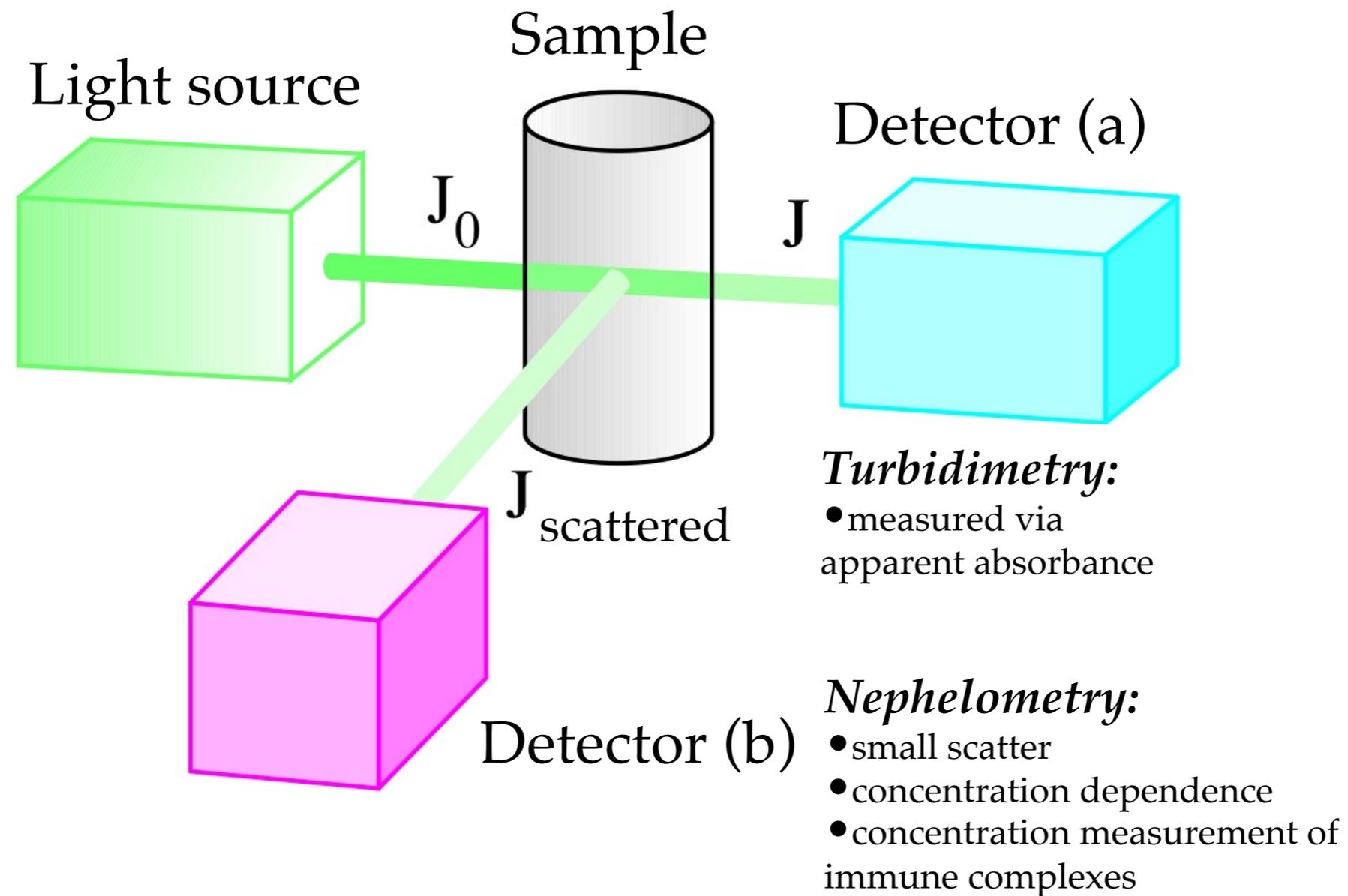
Mie scatter
($d \sim \lambda$)
(J_s λ -independent)



Gustav Mie
(1868-1957)

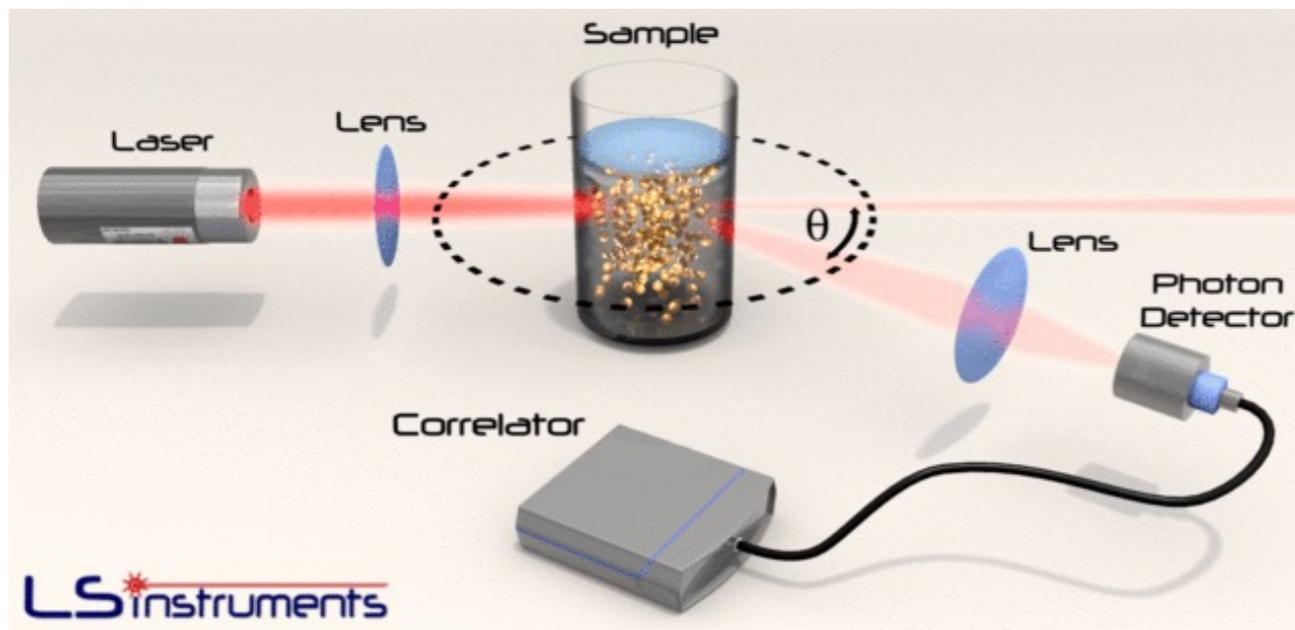
If scatterers are interacting particles the the overall size of which is comparable to the wavelength \rightarrow interference, cancellation \rightarrow gray clouds

BIOMEDICAL APPLICATIONS OF LIGHT SCATTERING

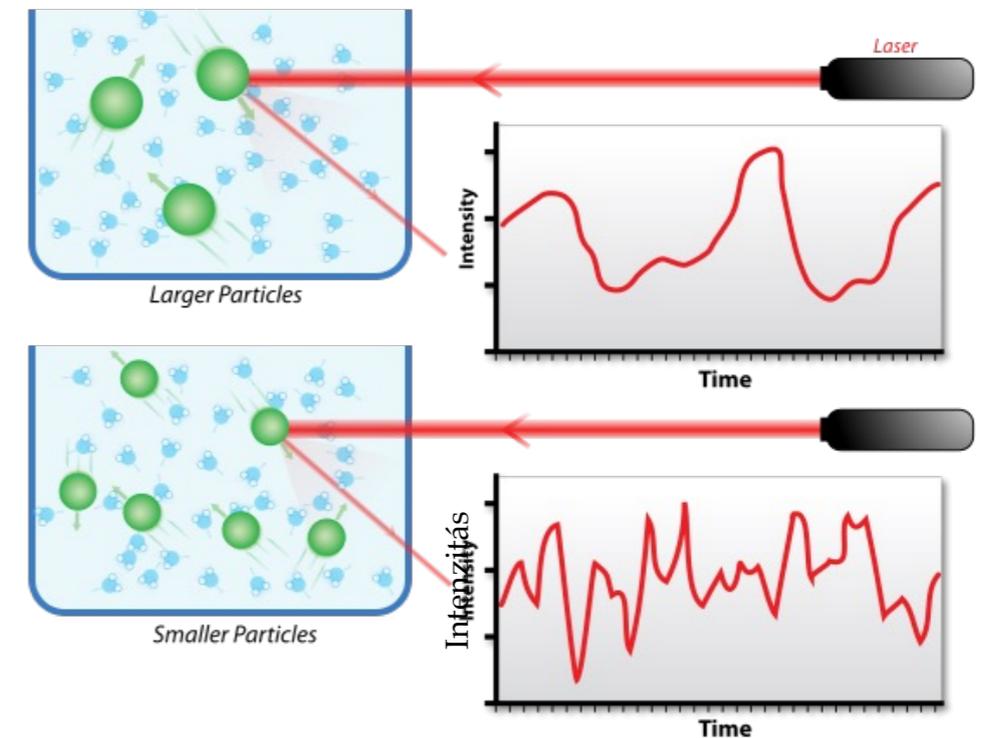


DYNAMIC LIGHT SCATTERING (DLS)

Diffusing nm-scale particles



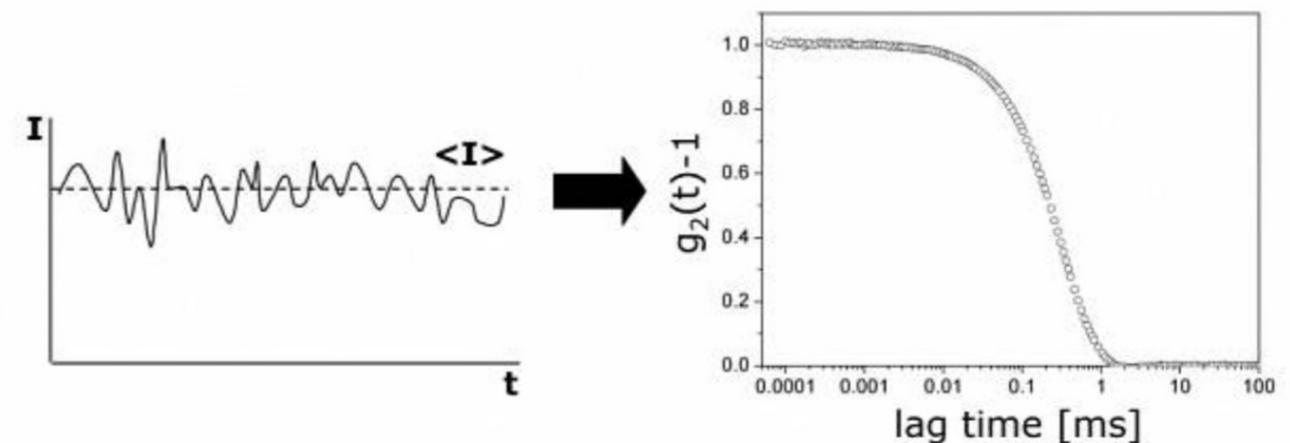
Intensity of scattered light fluctuates in time



Fluctuation rate depends on particle size

- From the autocorrelation function (“self-similarity”) of temporal intensity fluctuation the diffusion constant (D) can be calculated.
- From the diffusion constant the radius (r) of the spherical particle can be calculated (Stokes-Einstein):

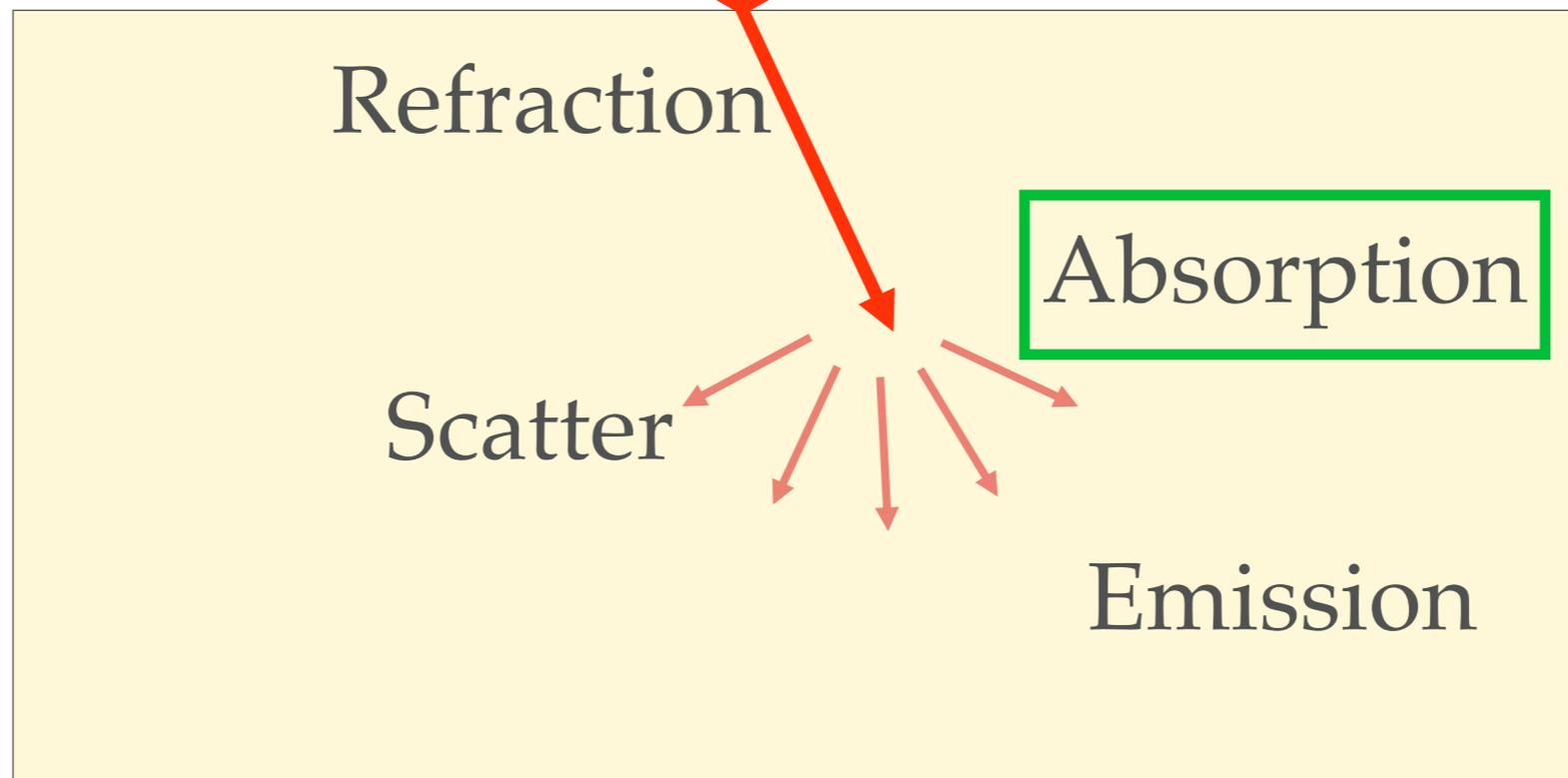
$$D = \frac{k_B T}{6\pi\eta r}$$



INTERACTION OF LIGHT WITH MATTER

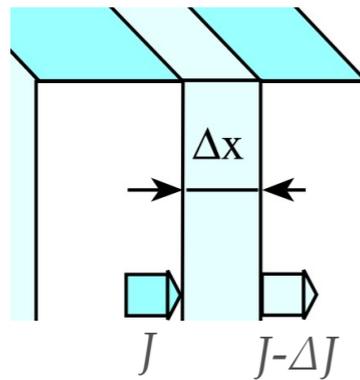
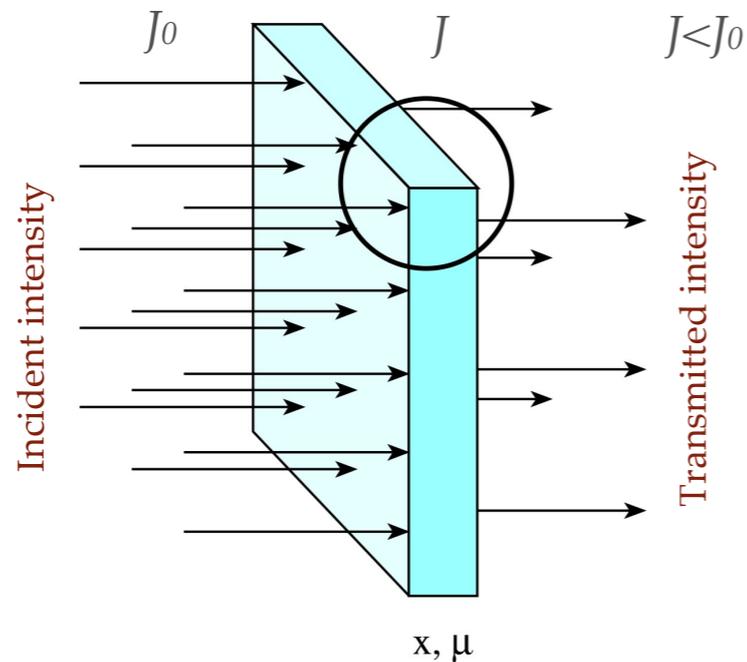
Incident beam

Reflection



Absorption - *absorbere, lat., swallow*

GENERAL ABSORPTION (ATTENUATION) LAW



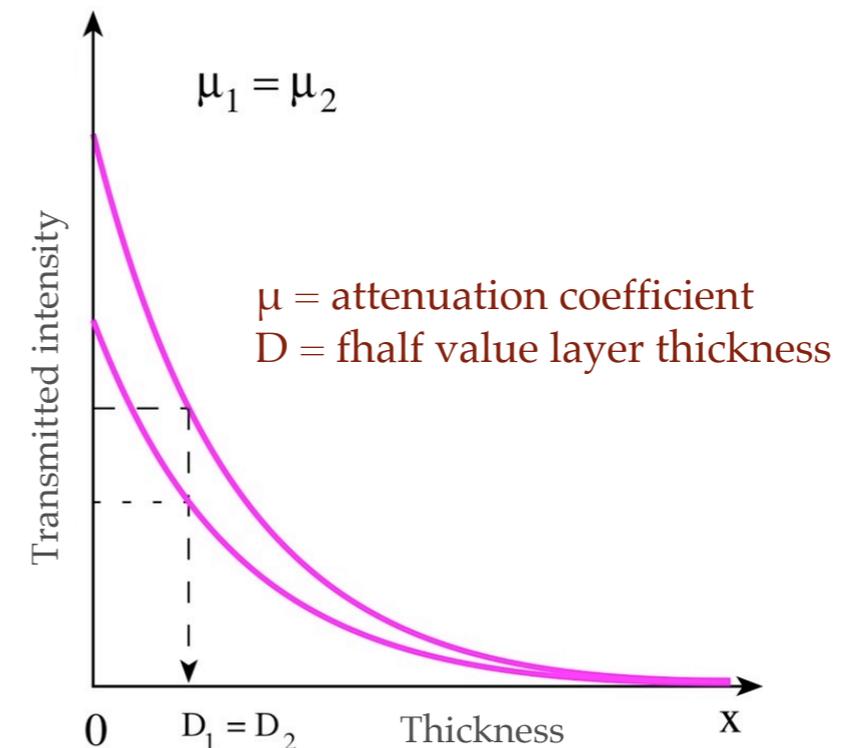
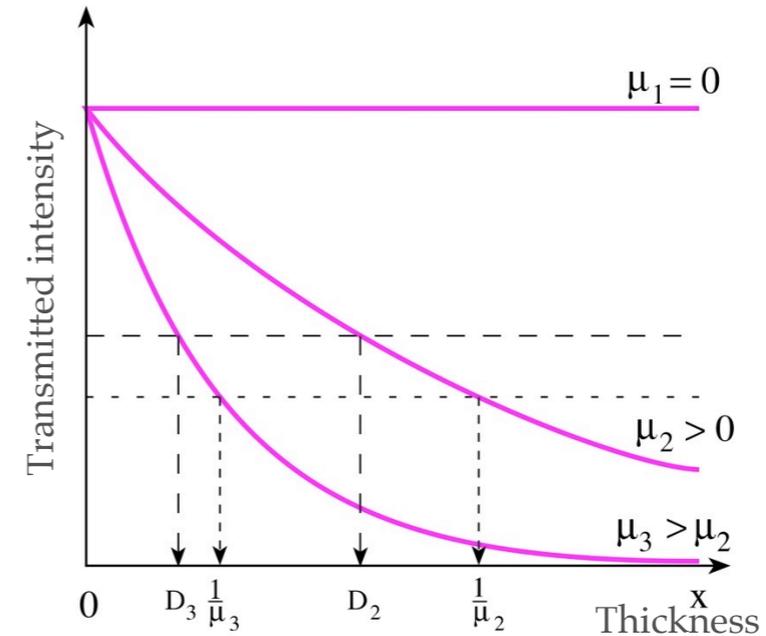
A given quantity (J) and its change (ΔJ) are proportional:

$$\Delta J = -\mu \Delta x J$$



Exponential function:

$$J = J_0 e^{-\mu x}$$

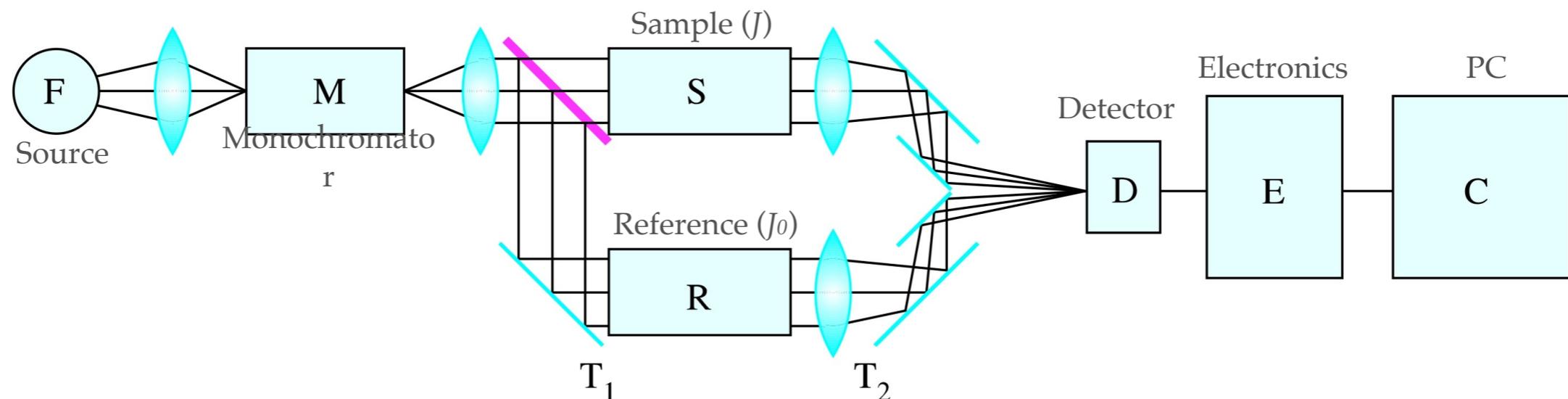


PARAMETERS AND MEASUREMENT OF ABSORPTION

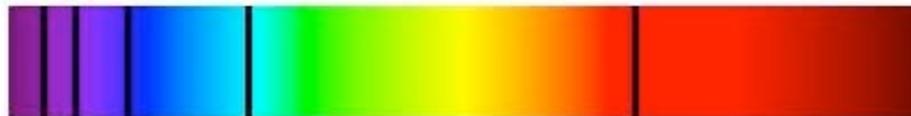
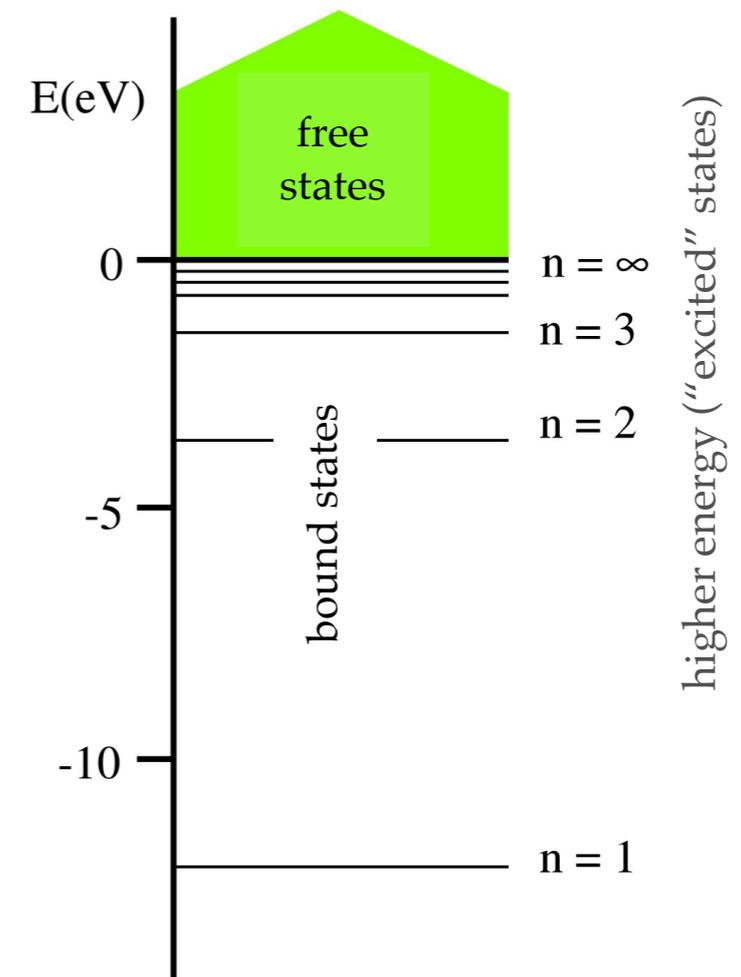
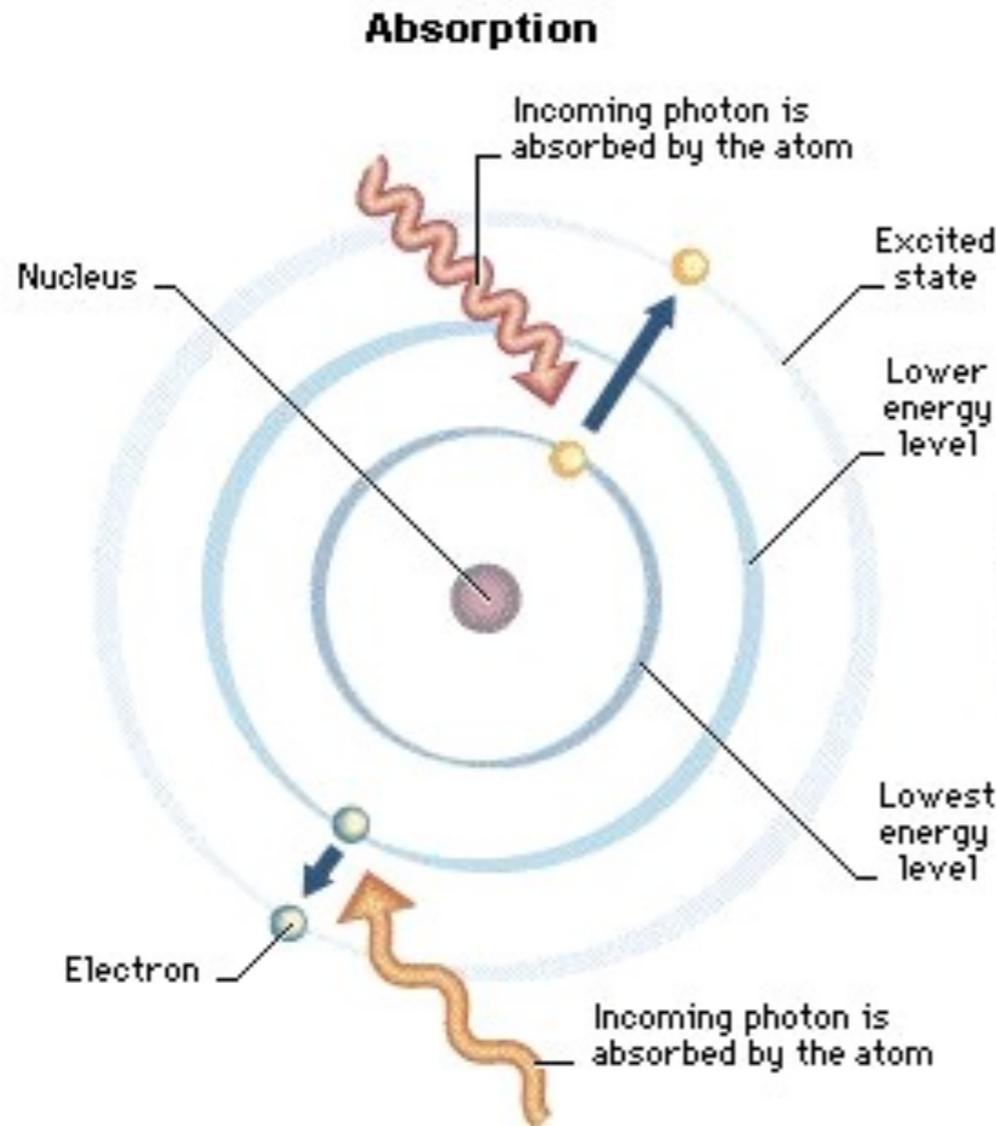
Absorbance (A): $A = \lg \frac{J_0}{J} = \lg e \cdot \mu \cdot x$ Dimensionless number
Synonyms: extinction, optical density (OD)

Transmittance (T): $T = \frac{J}{J_0} \cdot 100$ Expressed in percent (%)
Synonym: transmission coefficient

Photometry
("measurement of light"):



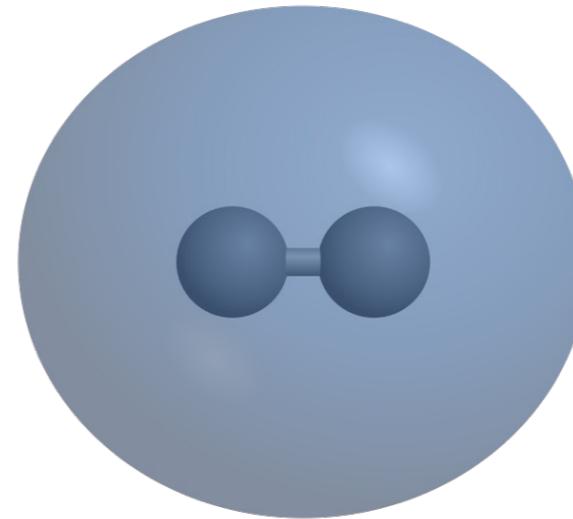
LIGHT ABSORPTION BY AN ATOM



Absorption line spectrum

STATE OF A MOLECULE IS AFFECTED BY ITS MOTIONAL MODES

Molecule: atoms connected by
chemical bonds
Simplest case: diatomic molecule
(e.g., hydrogen molecule)

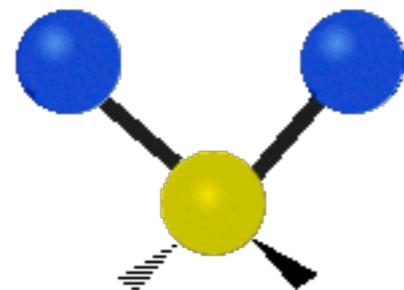


Molecules *vibrate* and *rotate*!

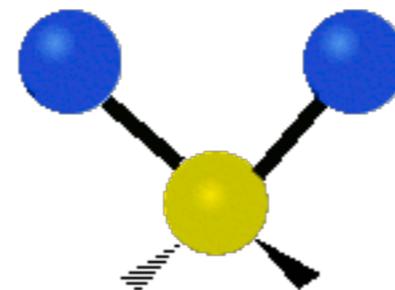
Vibration: periodic motion *along* the axis of the covalent bond

Rotation: periodic motion *around* the axis of the covalent bond

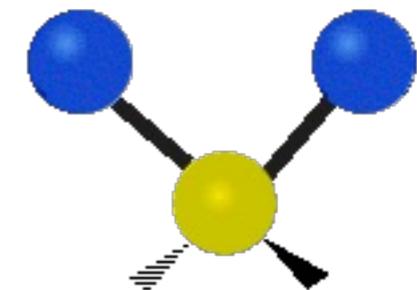
Examples of vibrational
motion in the triatomic
methylene group (-CH₂-):



Asymmetric stretching



Symmetric stretching



Scissoring

ENERGY OF A MOLECULE



Max Born
(1882-1970)



J. Robert Oppenheimer
(1904-1967)

Born-Oppenheimer approximation:

$$E_{total} = E_e + E_v + E_r$$

Important notions:

Types of energy states are independent (not coupled)

Energy states are non-continuous, but discrete

Transition between states involves packets (quanta) of energy

Scales of transition energies between different states are different:

$$E_e \stackrel{\sim 100\times}{>} E_v \stackrel{\sim 100\times}{>} E_r$$

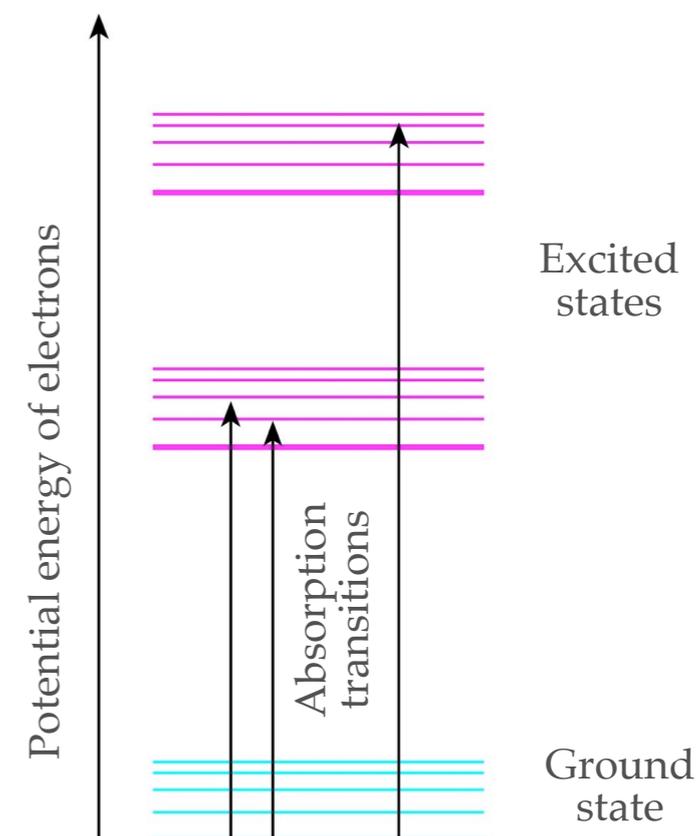
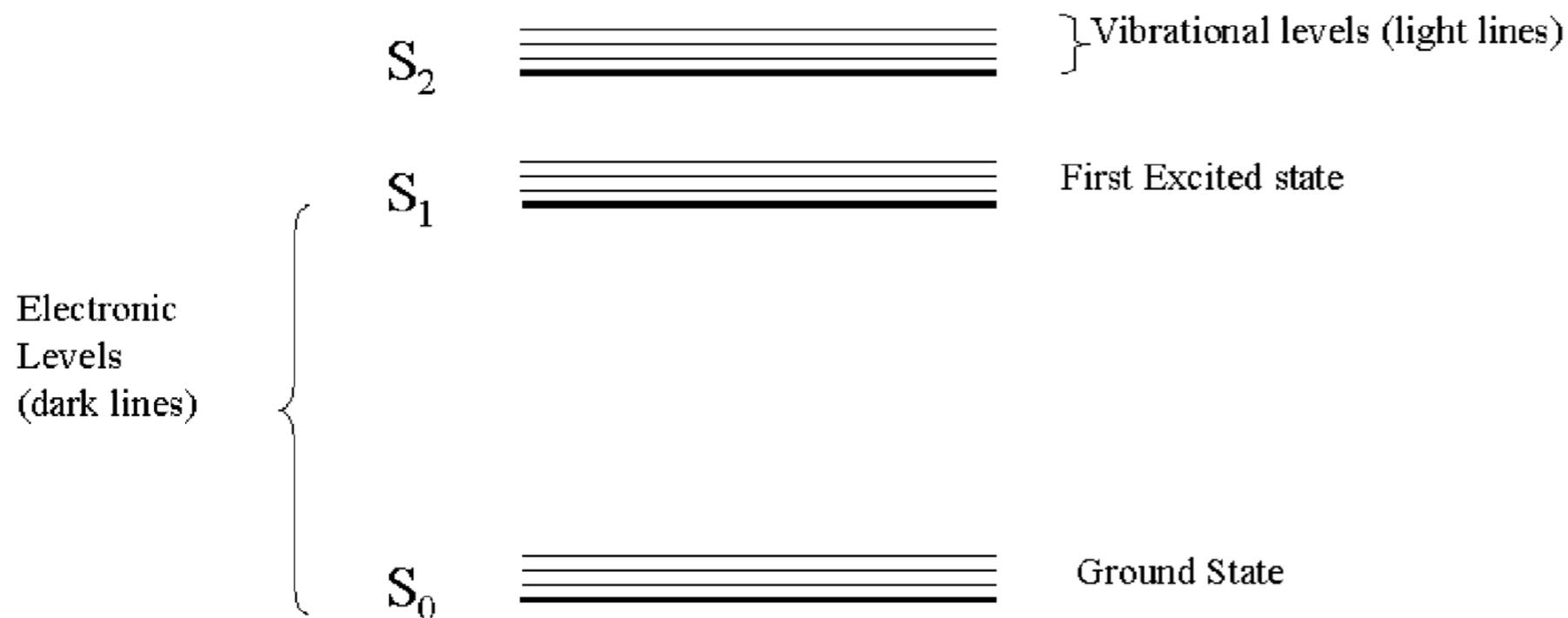
$$\sim 3 \times 10^{-19} \text{ J } (\sim 2 \text{ eV}) > \sim 3 \times 10^{-21} \text{ J } > \sim 3 \times 10^{-23} \text{ J}$$

REPRESENTATION OF ENERGY STATES

Jabłoński diagram:
illustrates the electronic states of a molecule and the transitions between them (with arrows)

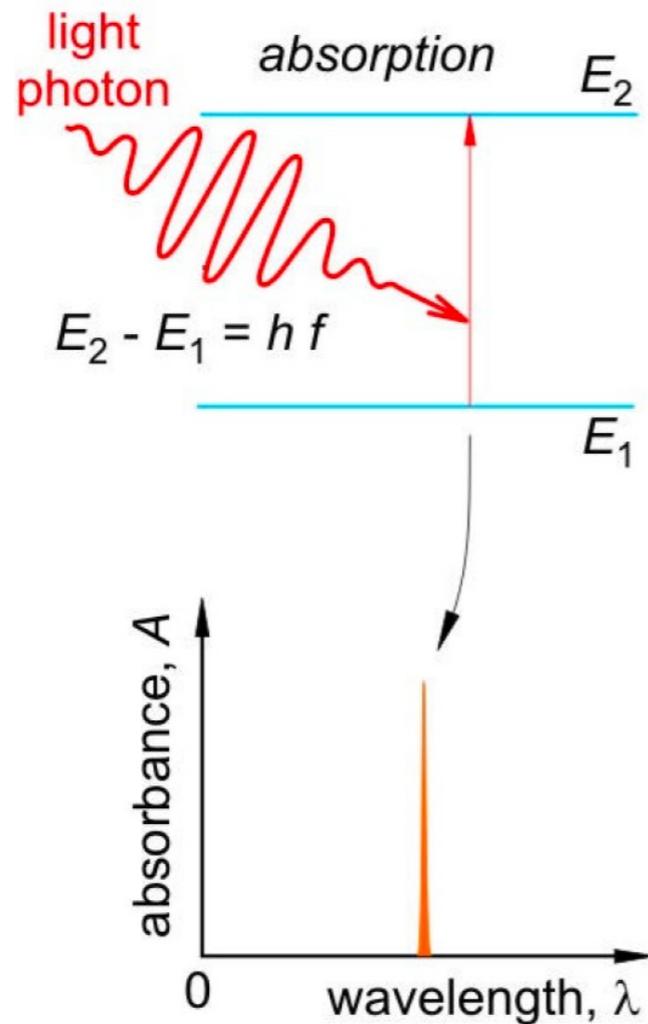


Alexander Jabłoński
(1898-1980)

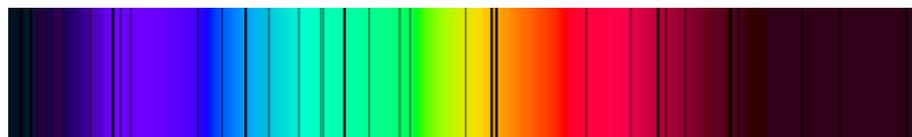


ORIGIN OF THE BAND SPECTRUM

Individual atoms

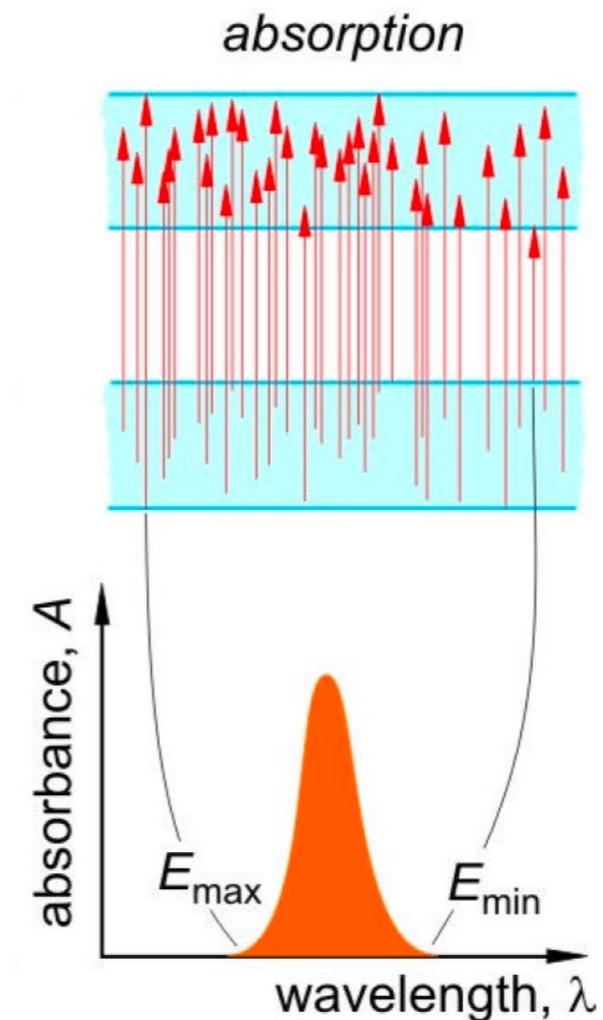


Line absorption spectrum



Narrow black lines ("missing colors") appear in the spectrum of the light source: absorption lines

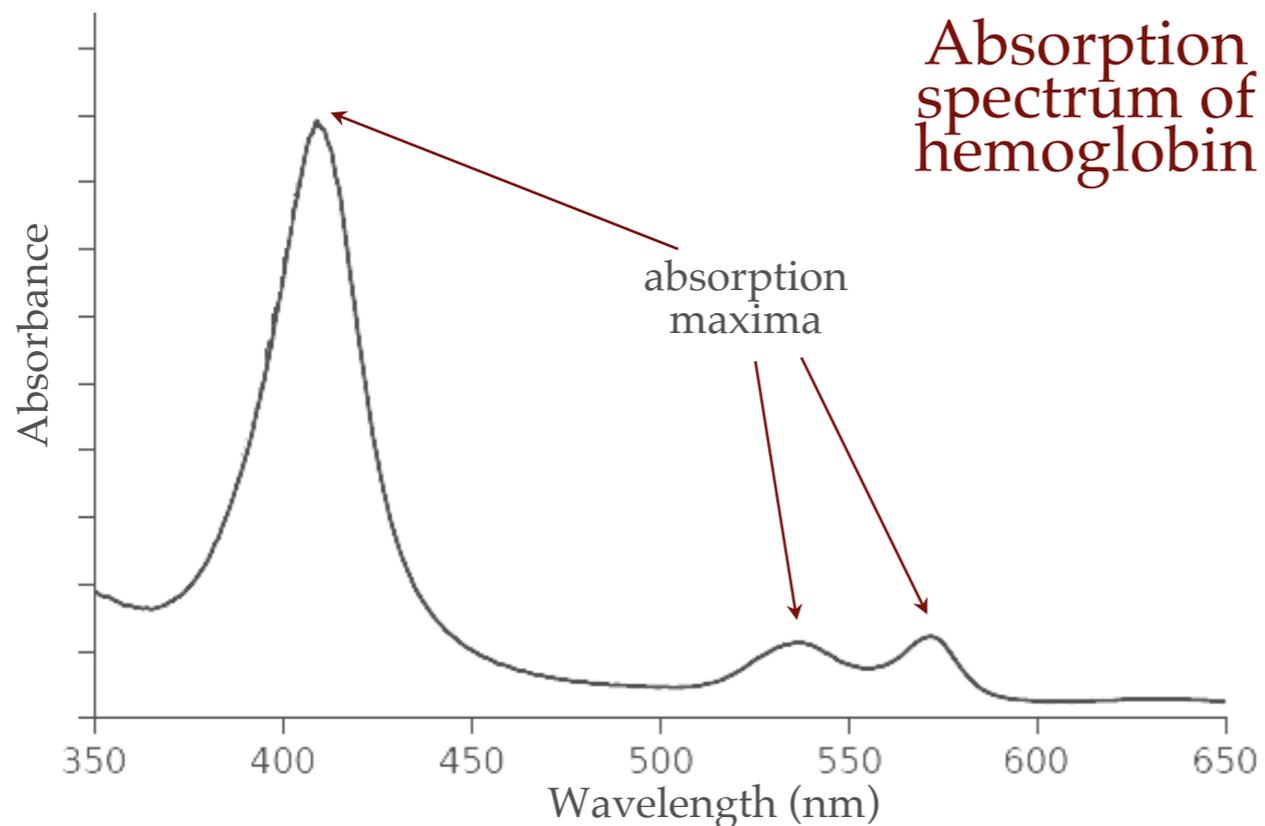
Molecules



Band spectrum - origin:

- chemically identical molecules are in different energy states
- thermal motion
- solvent conditions

MOLECULES HAVE BAND ABSORPTION SPECTRA



General attenuation law:

$$A = \lg \frac{J_0}{J} = \lg e \cdot \mu \cdot x$$

For dilute solutions - Lambert-Beer law:

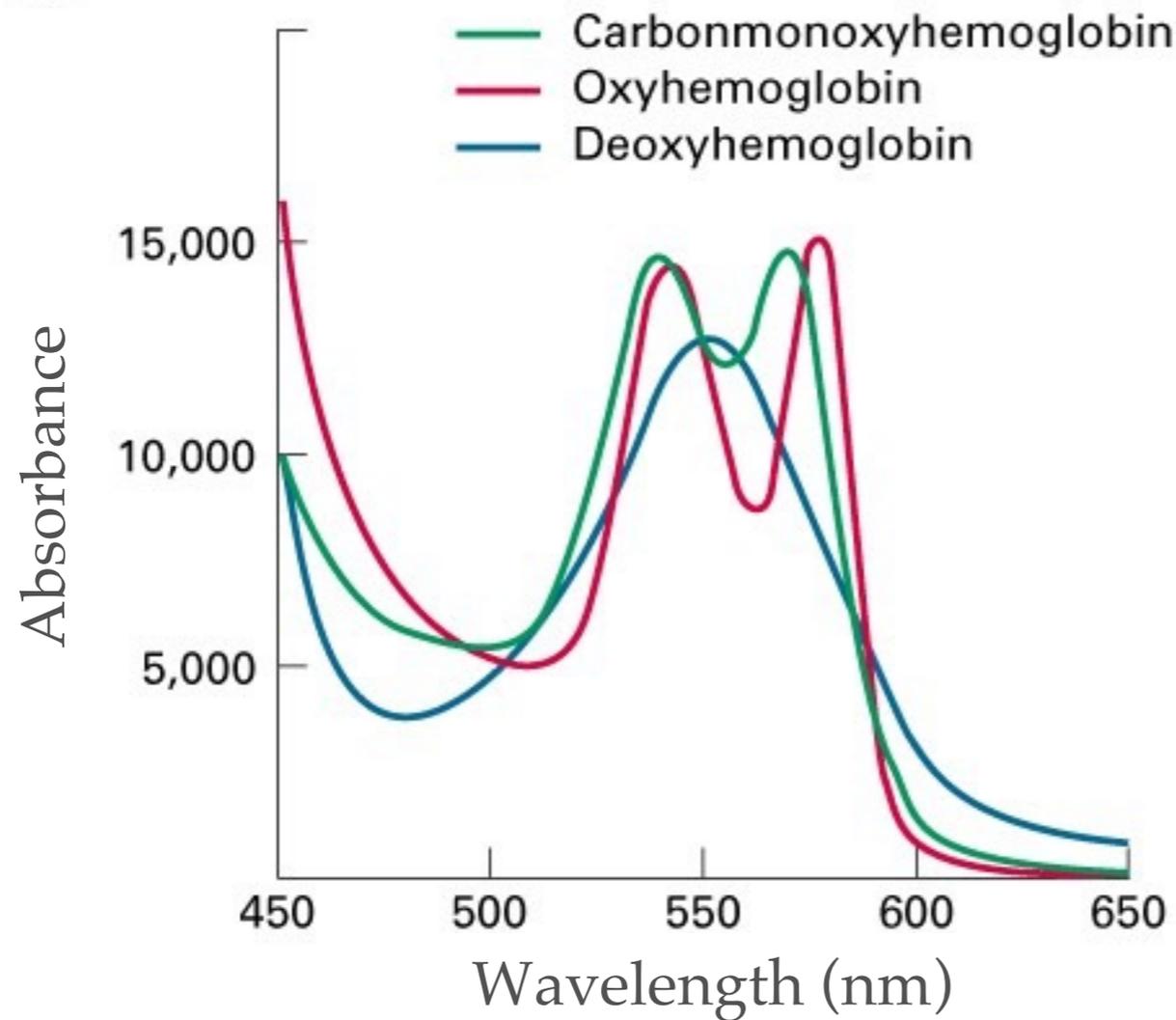
$$A_\lambda = \lg \frac{J_0}{J} = \varepsilon_\lambda \cdot c \cdot x$$

ε_λ = molar extinction coefficient
 c = concentration

- SI unit of molar extinction coefficient (ε_λ): $\text{m}^2\text{mol}^{-1}$
- Method ideal for concentration measurement
- Based on the wavelength (at maximum) the transition energy may be calculated:

$$E_2 - E_1 = E_{\text{foton}} = h \cdot f = h \cdot \frac{c}{\lambda}$$

ABSORPTION SPECTROSCOPY

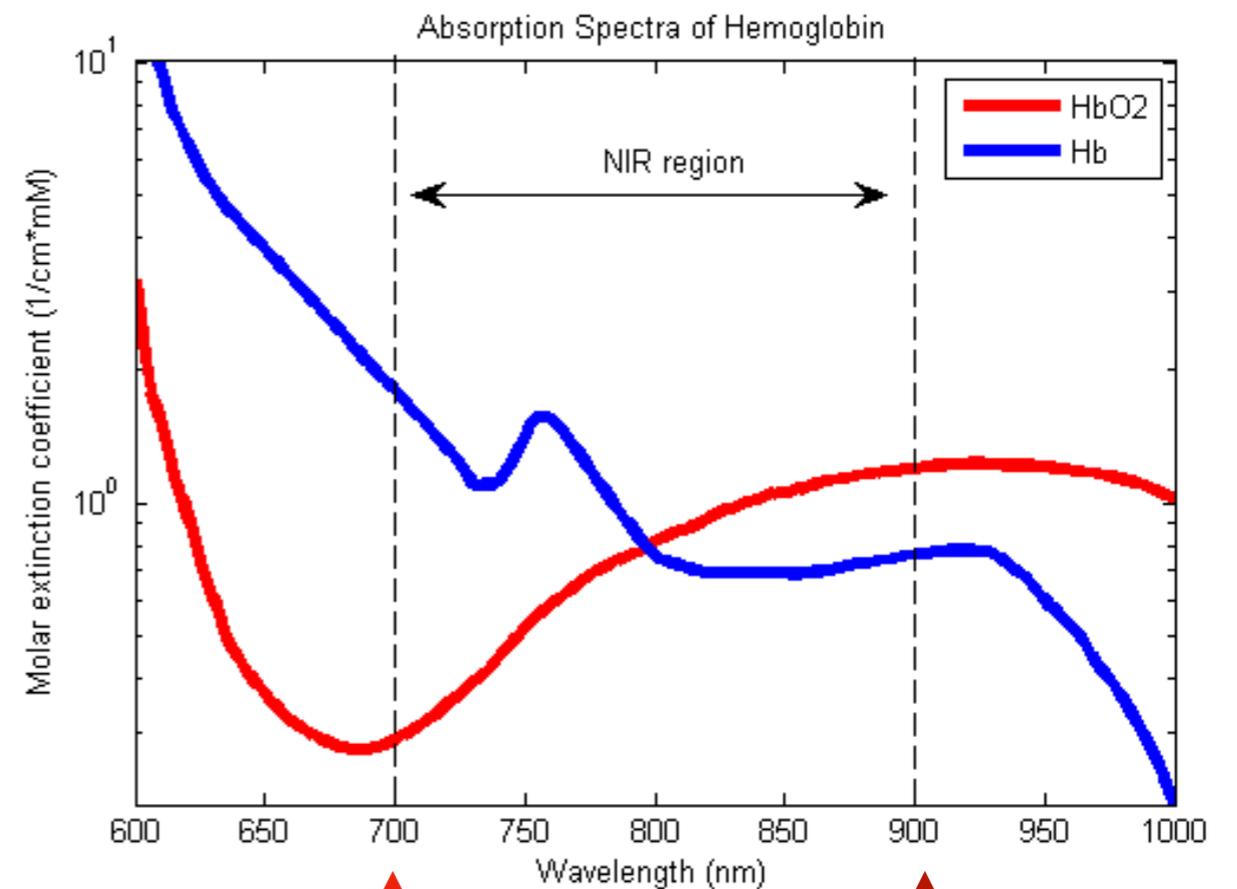
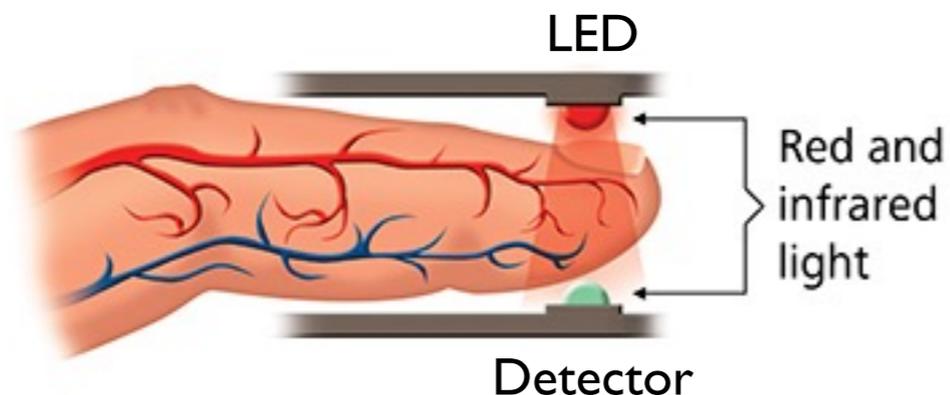


- *Spectrum*: intensity (or its derived units, e.g., OD) as a function of photon energy (or its derived units, e.g., frequency, wavelength).
- *Spectroscopy*: qualitative analysis of the spectrum.
- *Spectrometry, spectrophotometry*: quantitative analysis of the spectrum.
- *Applications*: analysis of chemical structure, concentration measurement, etc.

PULSE OXYMETRY

Non-invasive measurement of oxygen saturation (SO_2)

- % of HgB that carries O_2 is measured
- Arterial oxygen saturation (SaO_2) is estimated from the peripheral (SpO_2)
- Normal value: 95-99%
- Ratio measurement is carried out (red / IR)



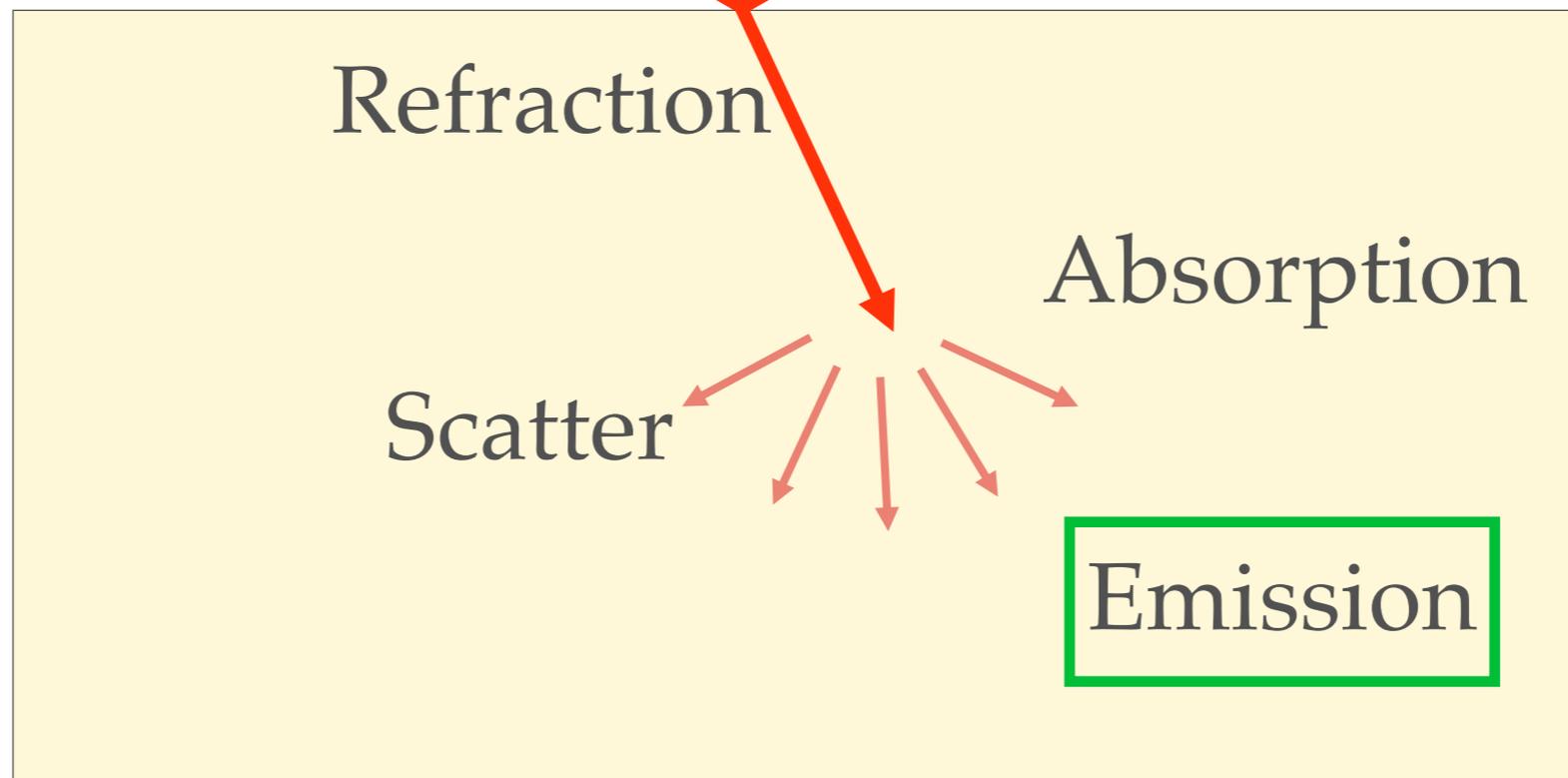
Red light:
660-700 nm

Infrared light:
900-940 nm

INTERACTION OF LIGHT WITH MATTER

Incident beam

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Feedback



<https://feedback.semmelweis.hu/feedback/pre-show-qr.php?type=feedback&qr=P8KZ8MT8H9H8MWVN>