

Biophysics I

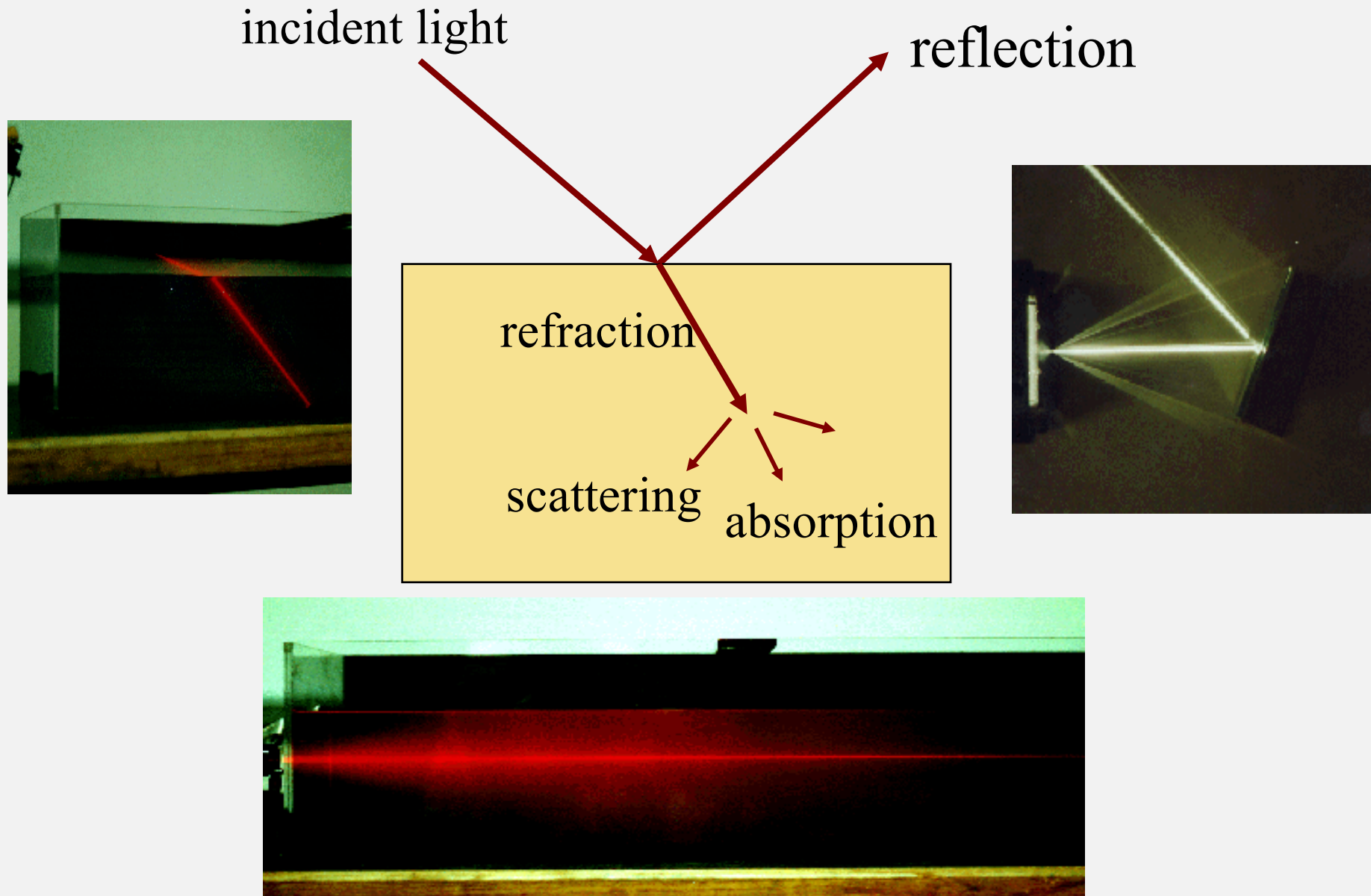
4. Interactions of light and matter: scattering, absorption, reflection, color vision

Liliom, Károly

2021. 10. 01.

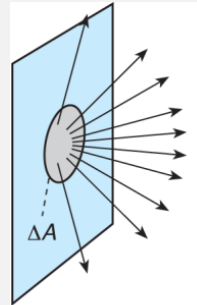
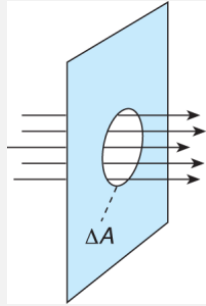
liliom.karoly@med.semmelweis-univ.hu
karoly.liliom.mta@gmail.com

Interactions of light and matter

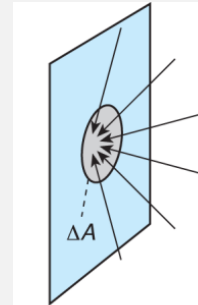


Light intensity

(light is a radiation)

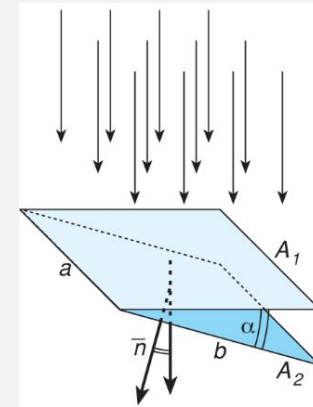


emitted



irradiated

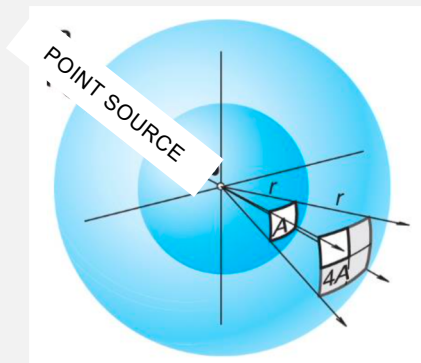
energy flux density (intensity)



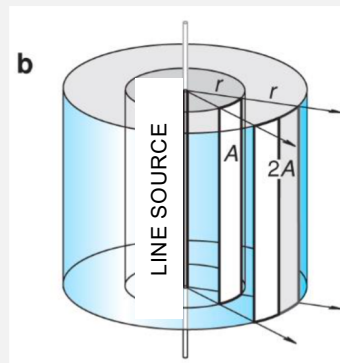
(amount of energy per unit area, per unit time, transmitted on a surface perpendicular to the direction of radiation,
 $A_1 = A_2 * \cos \alpha$)

Energy flux: $I_E = \Delta E / \Delta t$ [W]

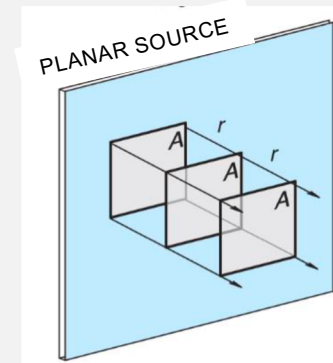
Intensity = energy flux density: $J = \Delta I_E / \Delta A$ [W/m²]



$$J \sim 1/r^2$$

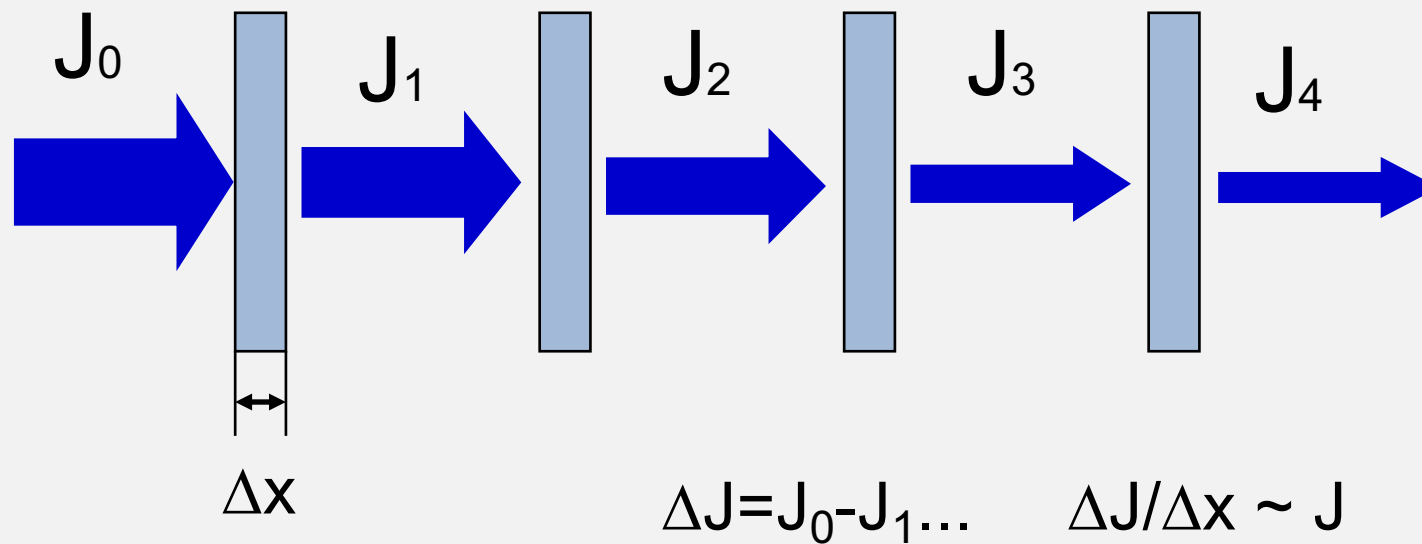
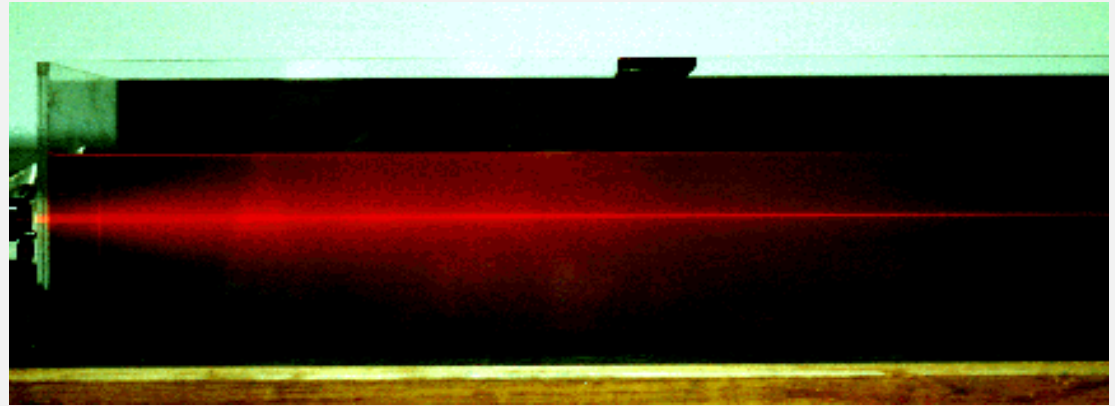


$$J \sim 1/r$$



$$J \sim \text{constant}$$

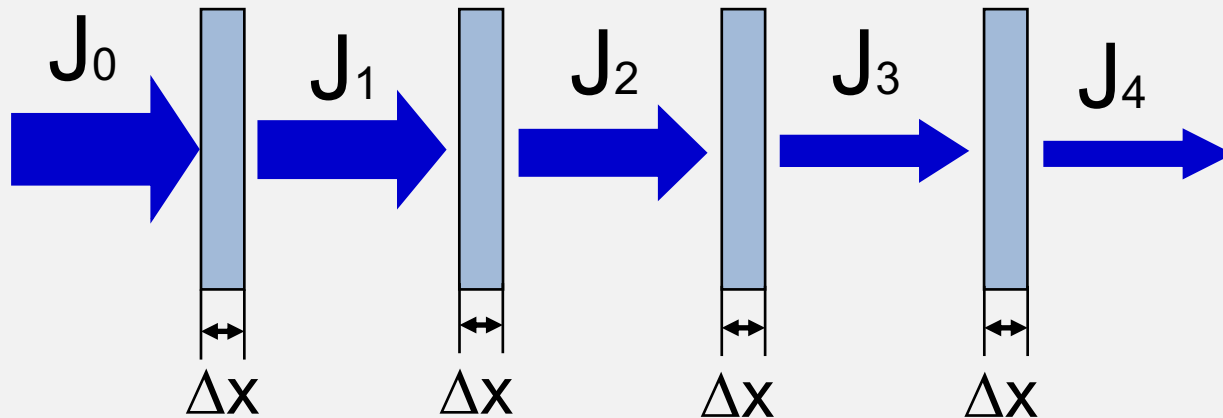
Absorption of light



Intensity of radiations passing through matter is attenuated.

Law of attenuation

$$\Delta J = J_0 - J_1 = J_1 - J_2 = \dots$$



$$\frac{\Delta J}{\Delta x} = -\mu \times J$$

Differential form

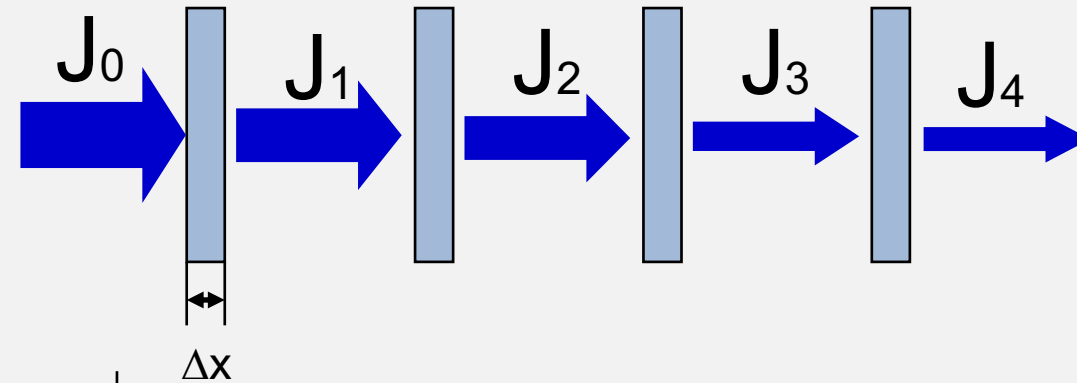
J_i : incident intensities [W/m²]

ΔJ : change of intensity when passing through Δx layer

μ : attenuation coefficient [1/m]

The decrease of intensity over a thin layer of the absorber is proportional to the intensity entering into that layer.

Law of attenuation



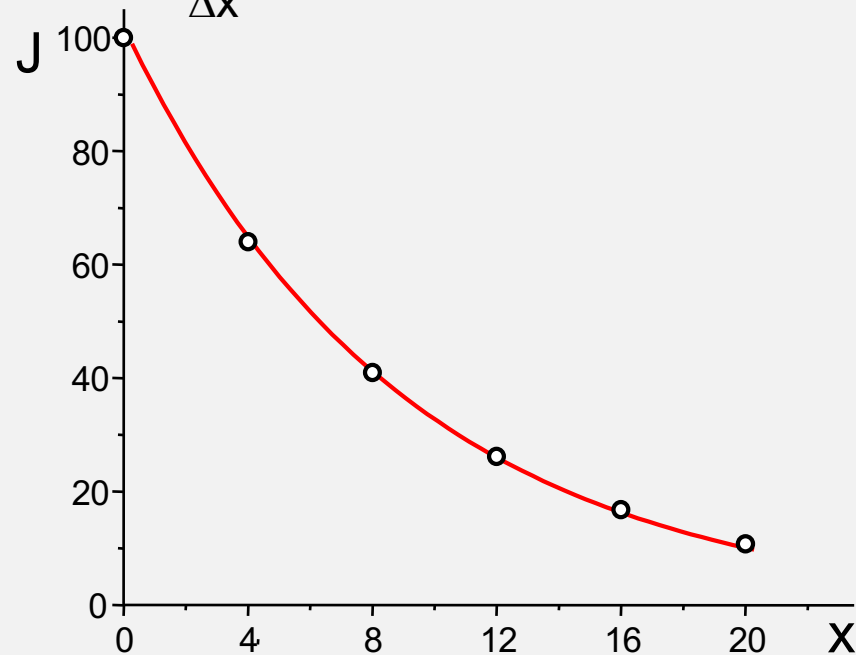
$$\frac{\Delta J}{\Delta x} = -\mu \times J$$

solution

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

Integral form

e = Euler's number = 2,71828...



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

J is an exponential function of the layer thickness.

J_0 : incoming intensity [W/m²]

J : intensity at x [m] layer thickness

μ : attenuation coefficient [1/m]

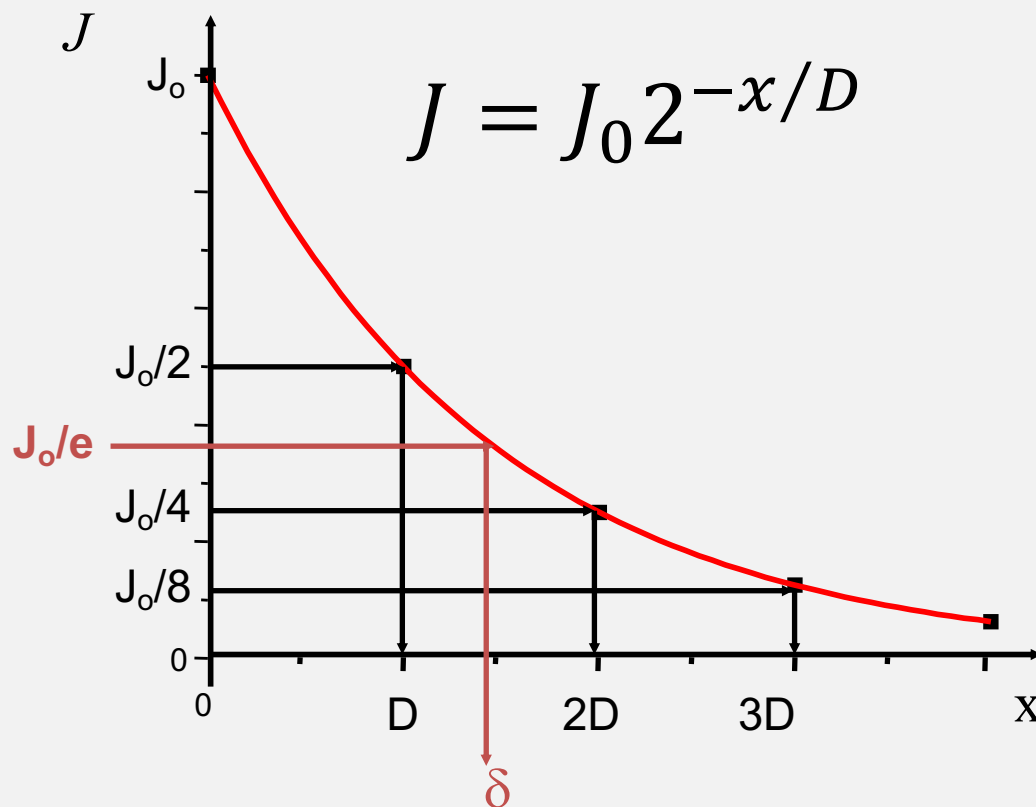
The attenuation coefficient depends on: the photon energy,
material composition of the absorber
density of the absorber

Half-value thickness

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

D: half-value thickness

δ : thickness decreasing
intensity by a factor of e



Both D and δ

– characteristic for the absorption
of light by matter

– depend on the photon energy,
the material composition and the
density of absorber

Relationships of D, δ and μ

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

If $x = D \longrightarrow J_0 / 2 = J_0 e^{-\mu D}$

$$\mu = \frac{\ln 2}{D} = \frac{0.693}{D}$$

If $x = \delta \longrightarrow J_0 / e = J_0 e^{-\mu \delta}$

$$\mu = \frac{1}{\delta}$$

An example calculation:

The attenuation coefficient of muscle is 800 cm^{-1} at the wavelength emitted by a CO_2 laser. Calculate the thickness of the muscle layer that absorbs 90 % of the energy of this laser!

$$J_0 = 100\%, \quad J = 100\% - 90\% = 10\%, \quad \mu = 800 \text{ cm}^{-1}$$

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

$$10 = 100 e^{-800x}$$

$$100/10 = e^{800x}$$

$$\lg 10 = 800x \lg e$$

$$x = 29 \text{ } \mu\text{m}$$

Analitical application of light absorption

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

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

In diluted solutions
 μ is proportional to
the concentration:

$$\mu \lg e = \varepsilon_{(\lambda)} \cdot c$$

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

Beer's law

Absorbance

layer thickness (*usually set to 1 cm*)

molar concentration [mol/l]

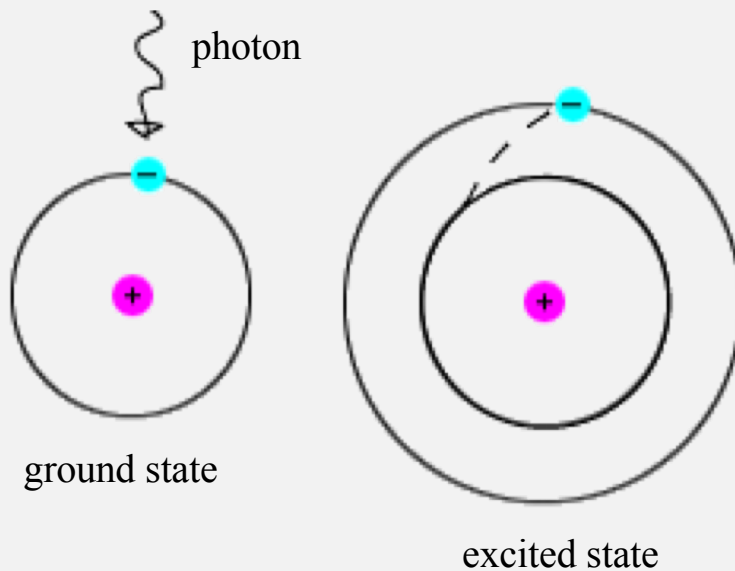
molar extinction coefficient
[l mol⁻¹cm⁻¹]

Transmittance, $T = J/J_0 \cdot 100$ (%)

Absorbance, optical density, $A = OD = \lg J_0/J$

Mechanism of light absorption

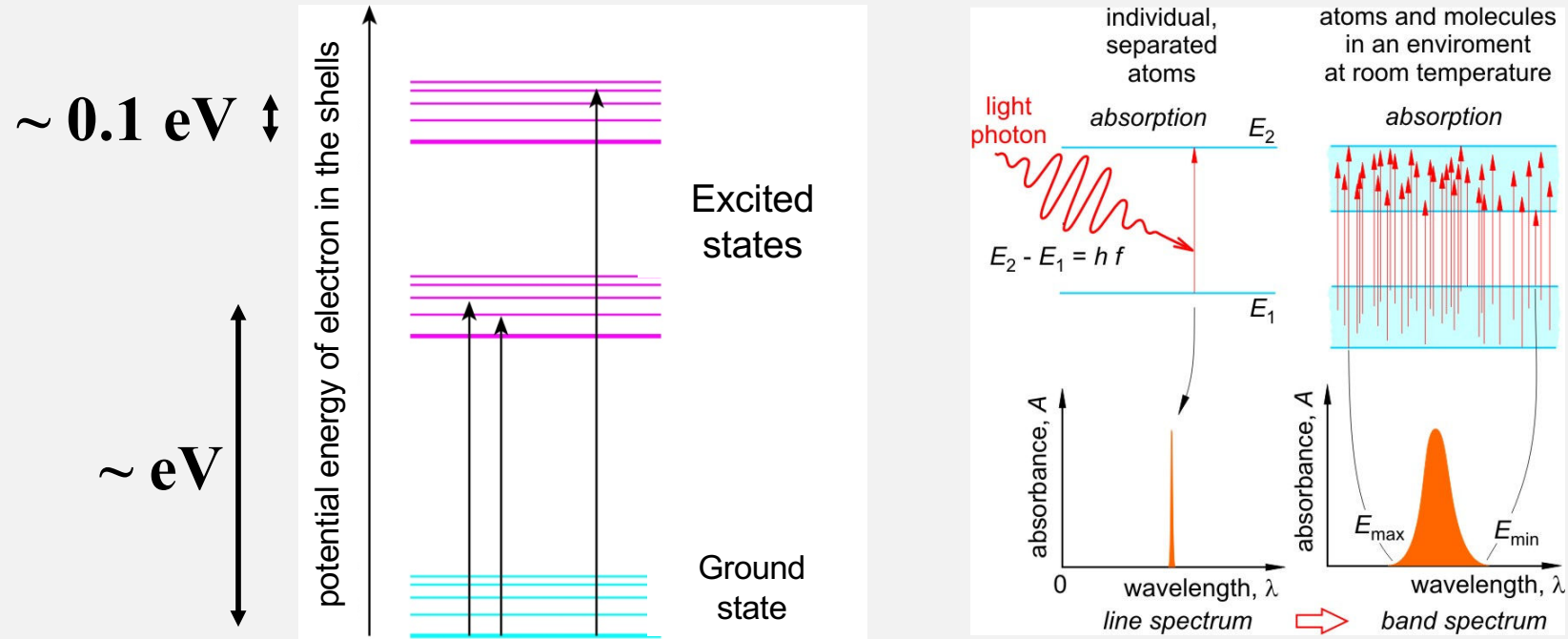
The potential energy of electrons is quantized in atoms and molecules



$$hf = \Delta E = E_{n+1} - E_n$$

$$E_{\text{VIS}} = hf = 1.6 - 3.1 \text{ eV}$$

Mechanism of light absorption

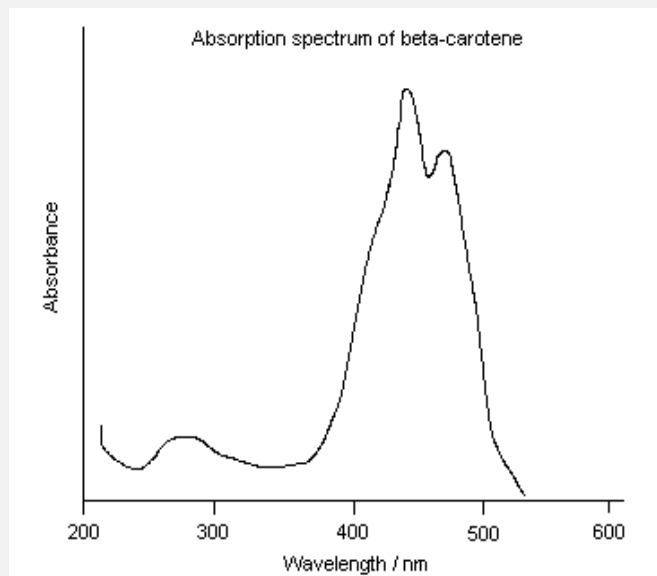
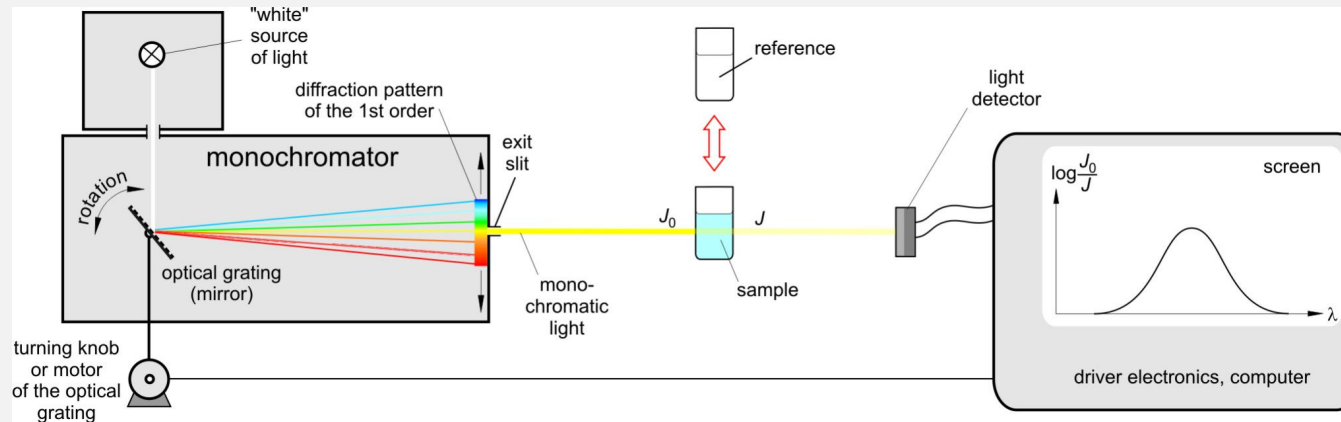


Molecules can absorb photons in a certain energy range

→ band spectrum

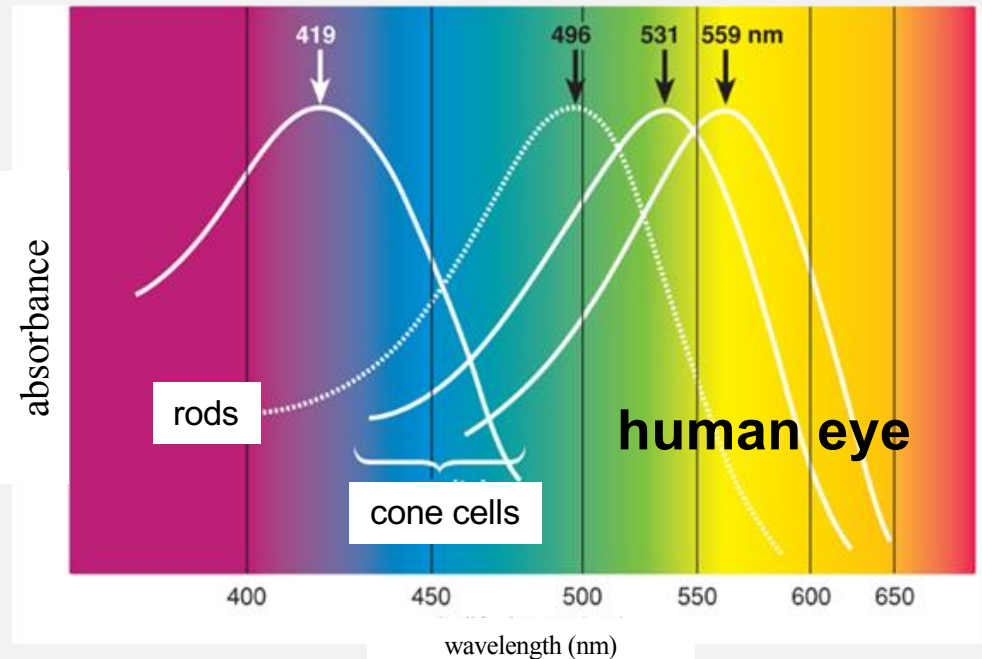
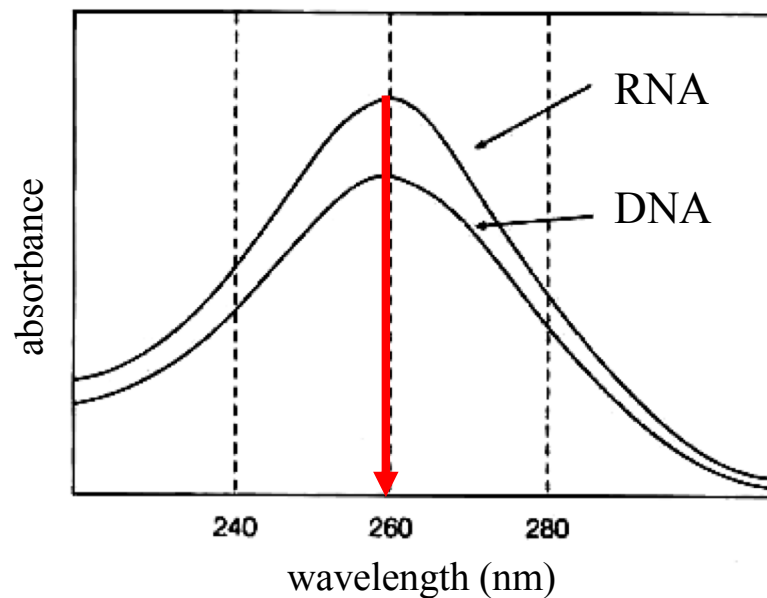
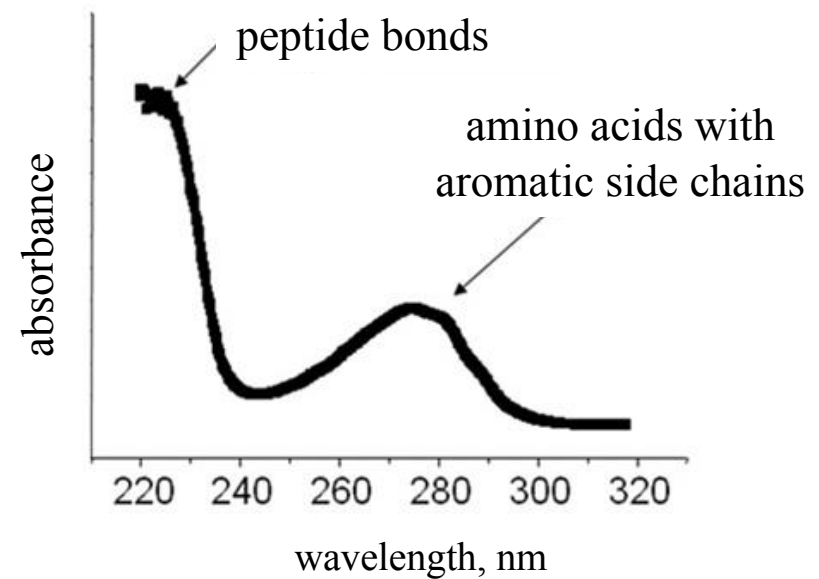
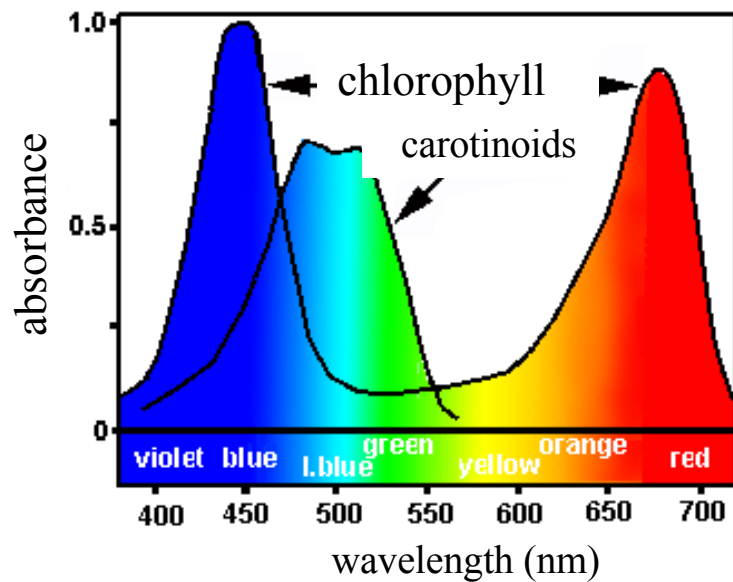
Absorption spectrum

Absorbance depends on the wavelength: $A = \varepsilon_{(\lambda)} \cdot c \cdot x$



Absorbance as a function of wavelength is characteristic to the absorber (depends on the electronic structure of the material)

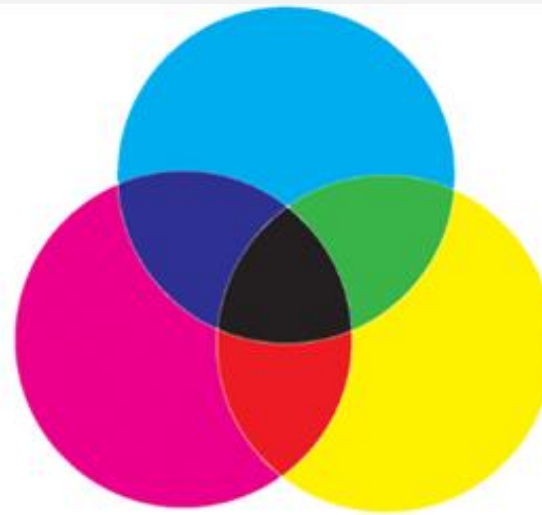
Absorption spectrums of several biomolecules



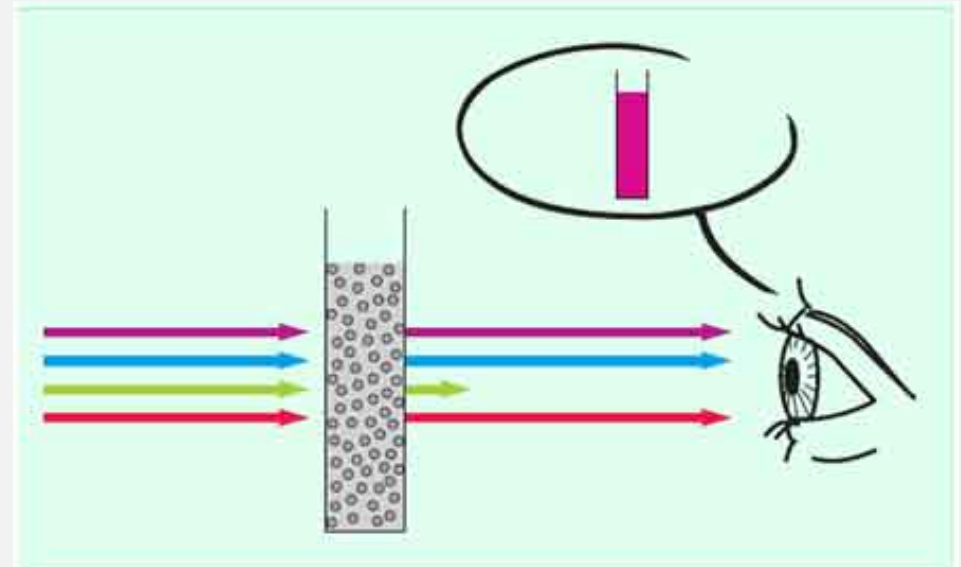
Absorption and colors – complementary colors



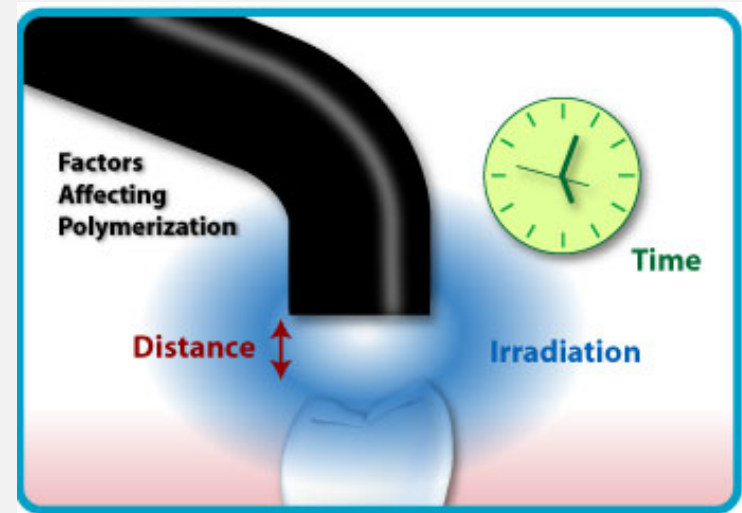
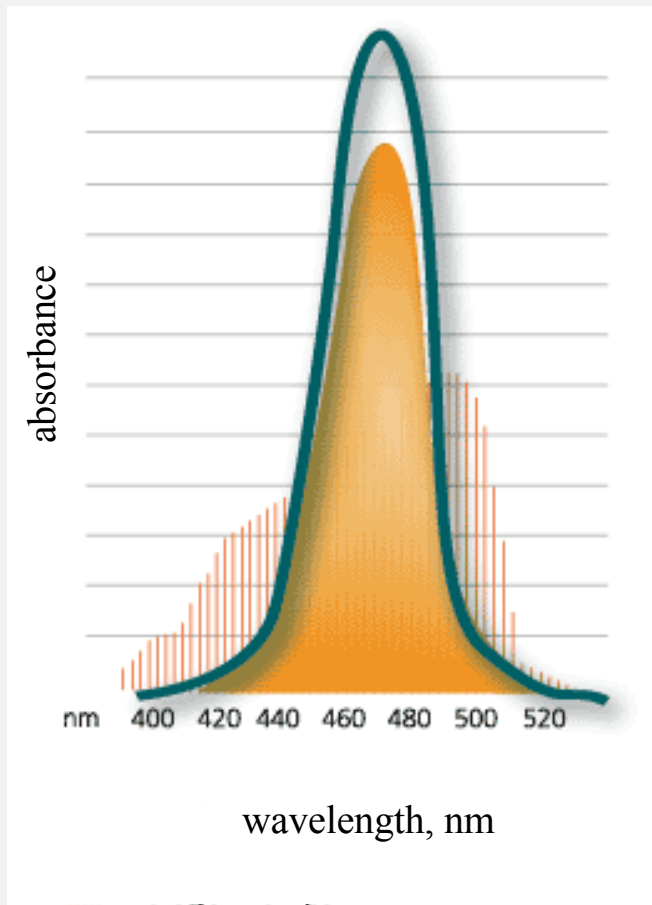
additive color mixing



subtractive color mixing

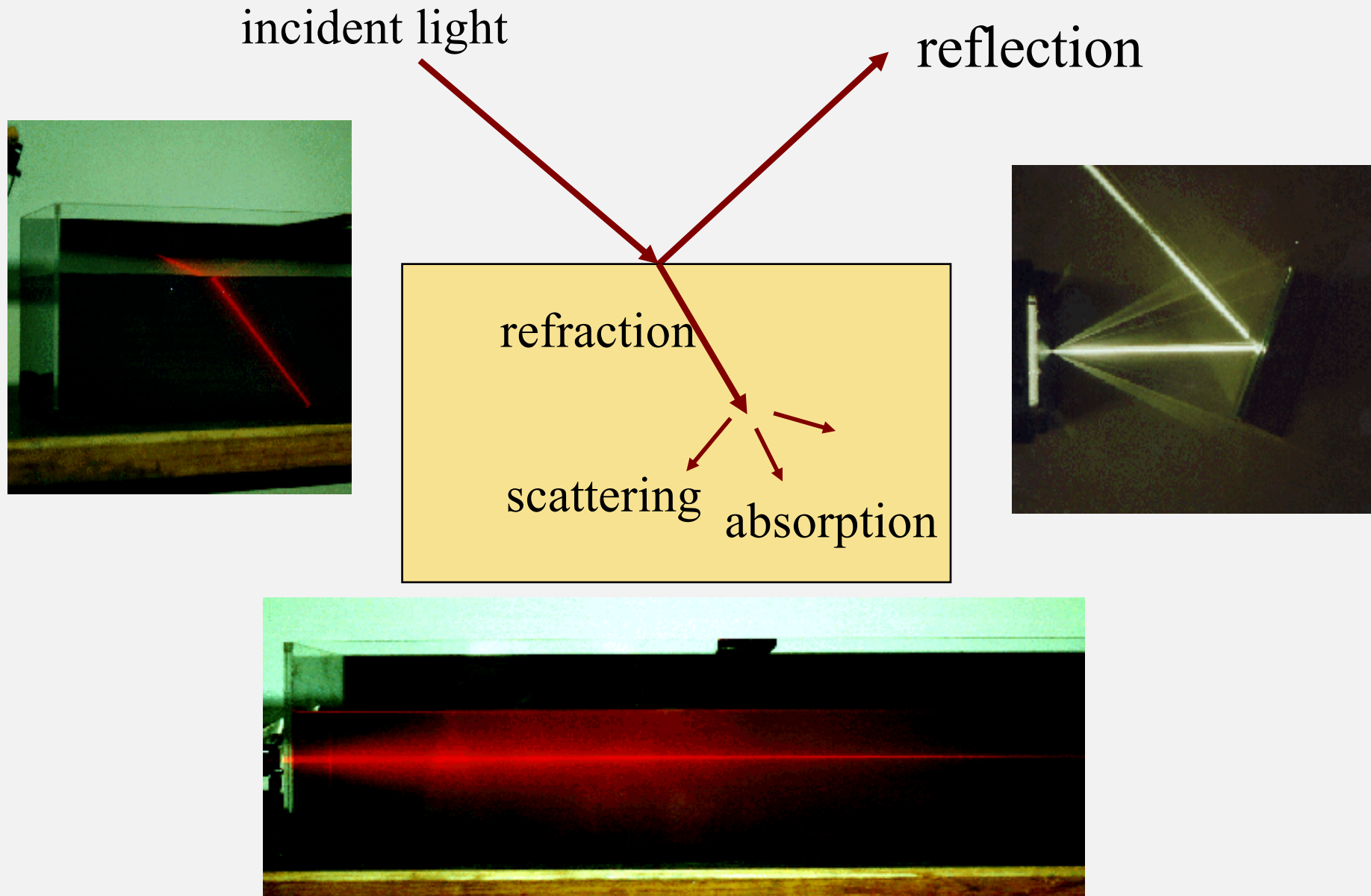


Application in Dentistry

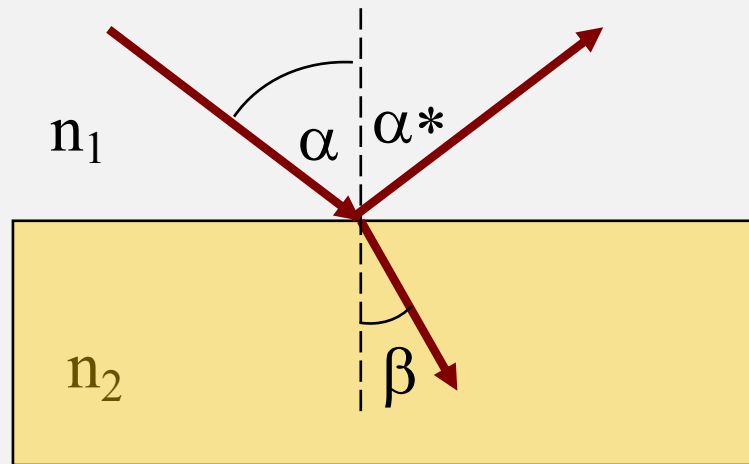


Camphor chinone
dental composite polimerizes due to light absorption

Interactions of light and matter



Refraction and reflection



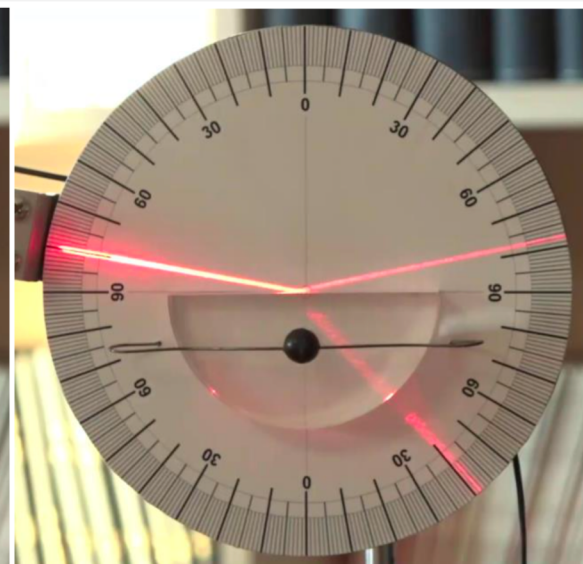
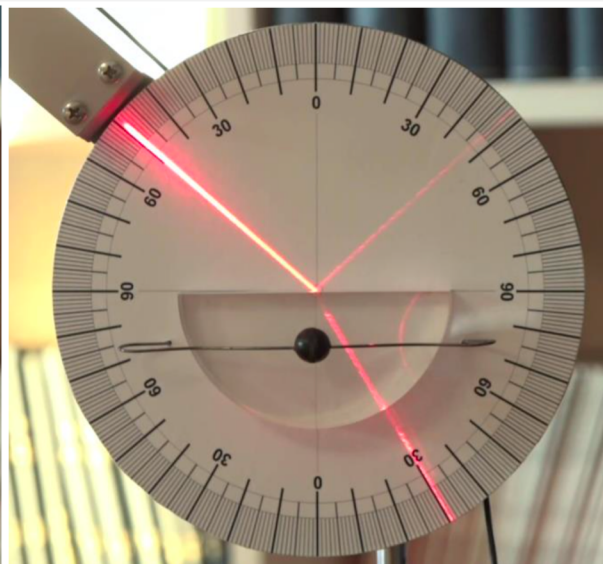
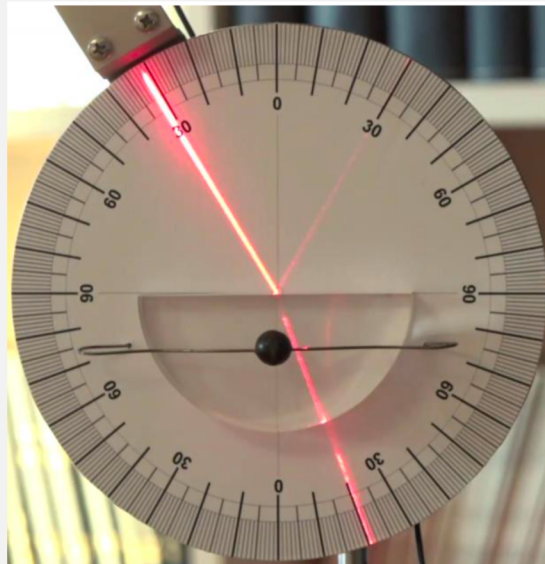
$$n_1 < n_2$$

$$\alpha > \beta$$

$$\alpha > \alpha^*$$

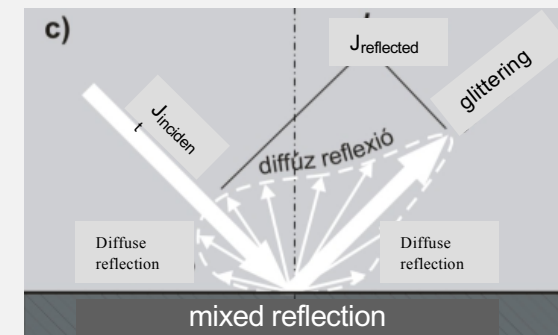
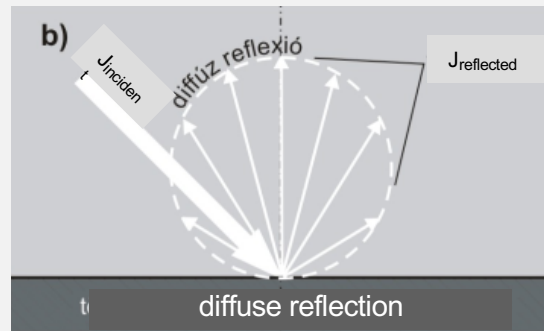
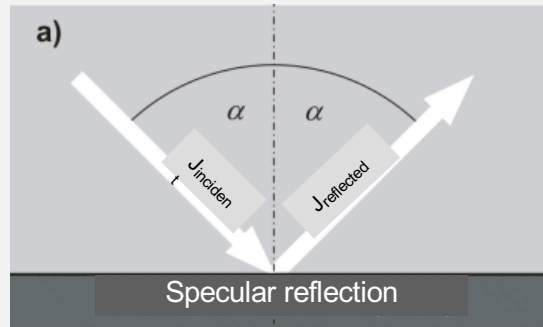
Snell's law:

$$\frac{\sin \alpha}{\sin \beta} = \frac{c_1}{c_2} = \frac{n_2}{n_1} = n_{21}$$

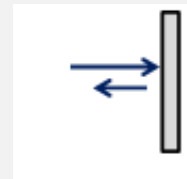


Reflection of light

Diffuse reflection

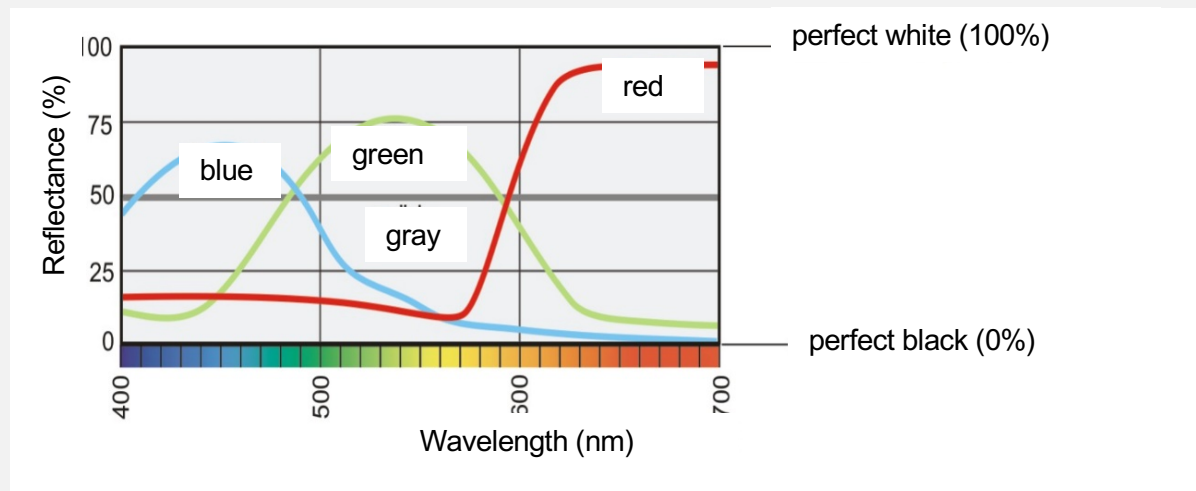


spectral reflectance



$$\rho(\lambda) = \frac{J_{\text{reflected}}}{J_{\text{incident}}} \quad \rho = \left(\frac{n_2 - n_1}{n_2 + n_1} \right)^2$$

Spectrum of reflectance



Scattering of light



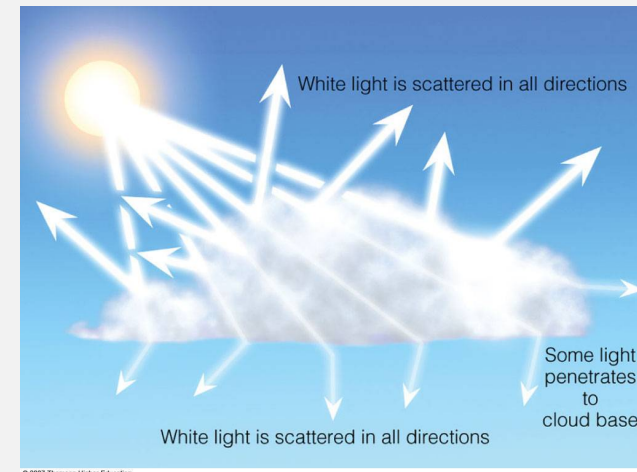
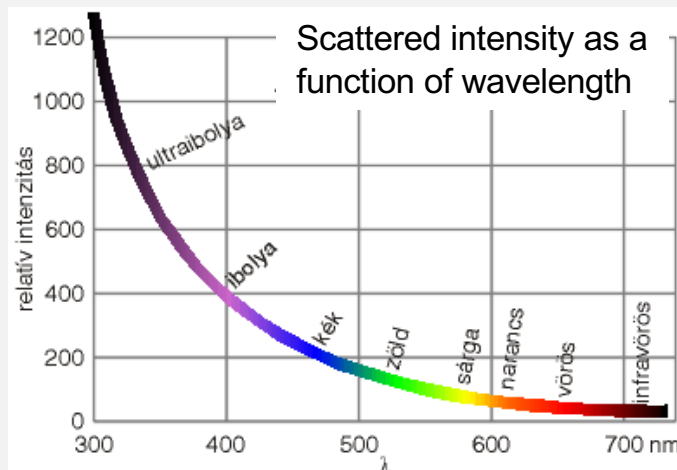
Scattering coefficient:
$$\sigma(\lambda) = \frac{J_{\text{scattered}}}{J_{\text{incident}}}$$

Elastic scattering: no energy change $\rightarrow f, \lambda$ are constant

$d \ll \lambda$
Rayleigh scattering

$$\sigma(\lambda) \sim \frac{d^6}{\lambda^4}$$

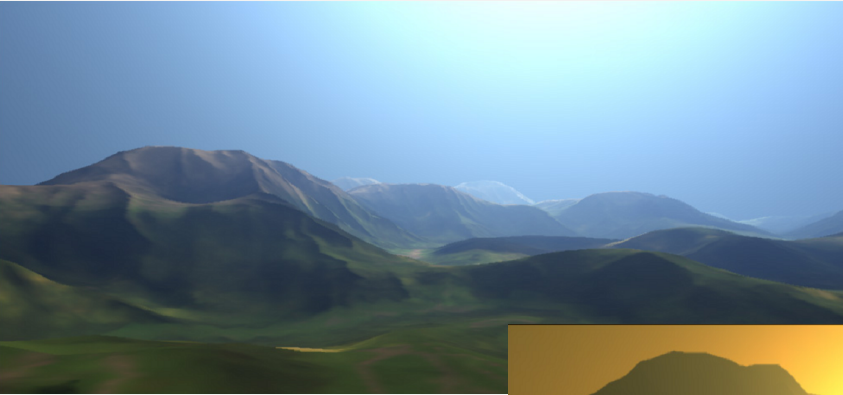
$d \geq \lambda$
Mie scattering
 σ weakly depends on λ



Rayleigh-scattering

$$d \ll \lambda$$

Light scattering



Mie-scattering

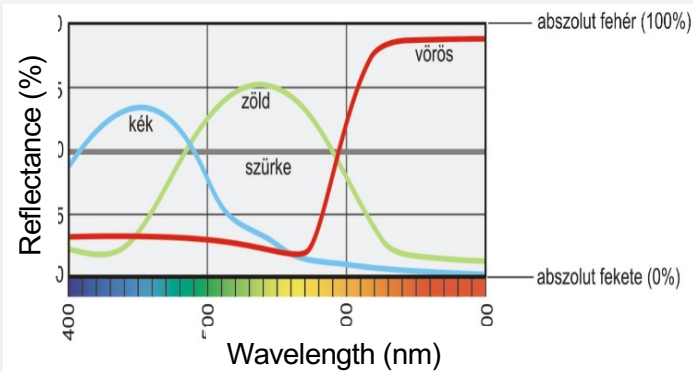
$$d \geq \lambda$$



Factors affecting the color of objects

$$\rho(\lambda) + \sigma(\lambda) + \alpha(\lambda) = 1$$

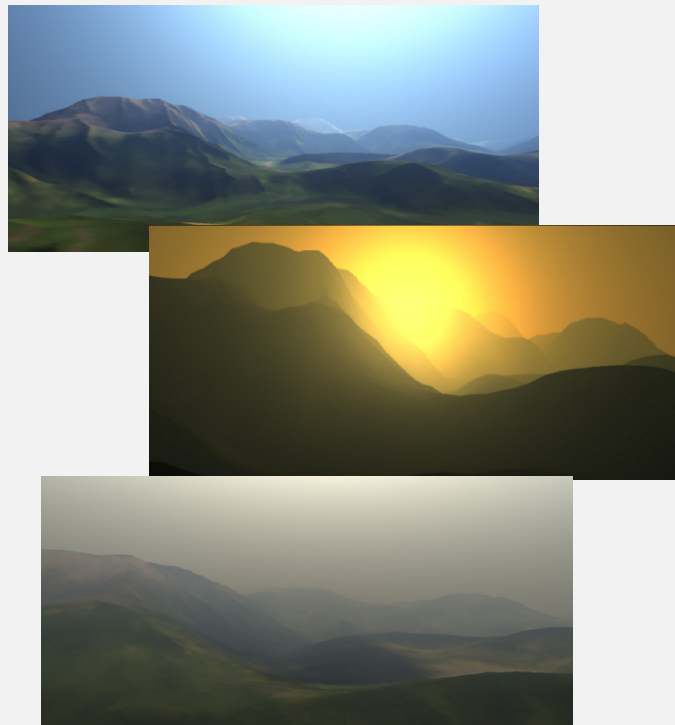
reflectance



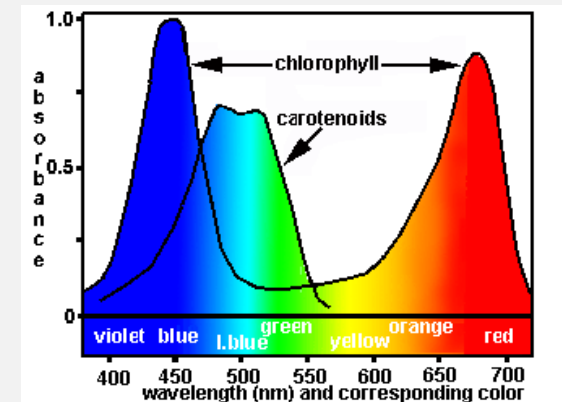
reflection of red

↓
red

scattering



absorption



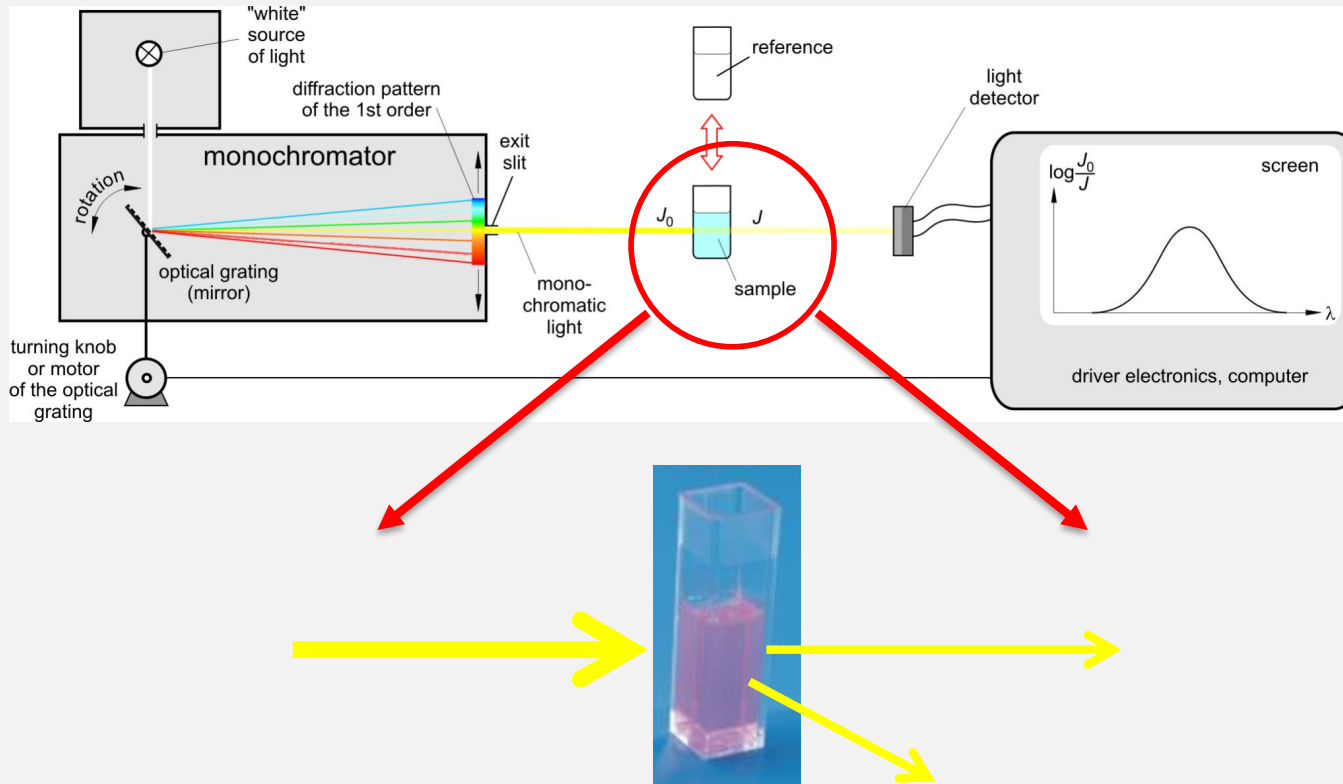
absorption of red

↓
green

Extinction

$$A = \epsilon_{(\lambda)} \cdot c \cdot x$$

$\epsilon_{(\lambda)}$: molar **extinction** coefficient
?

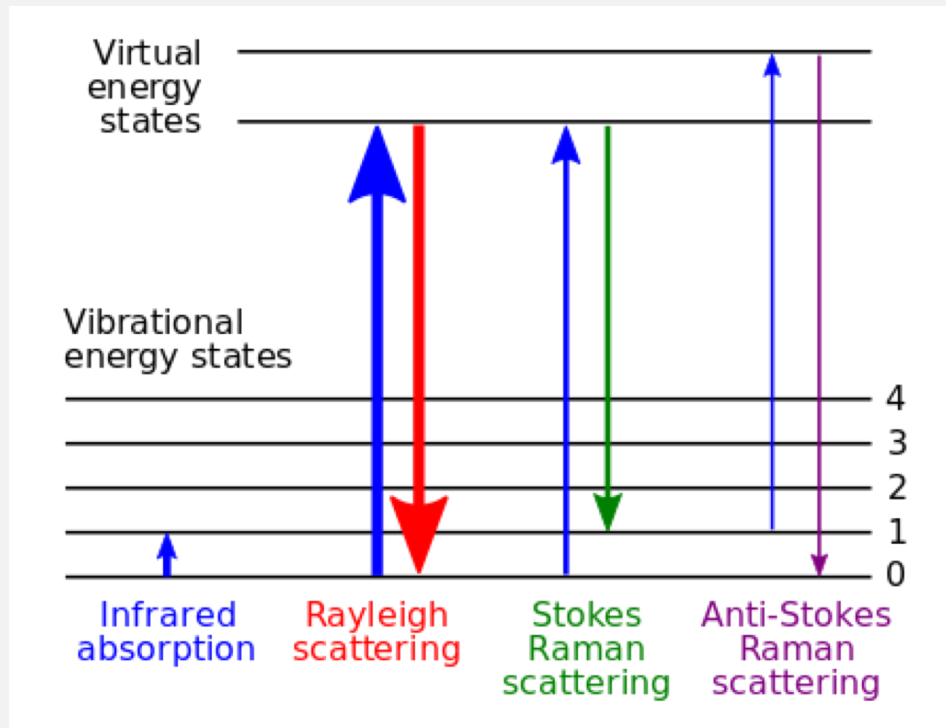


Extinction: attenuation by absorption and scattering together

Raman scattering

Energy transition between light and matter:

→ inelastic scattering: λ , f are not constant



Sir Chandrasekhara Venkata Raman

Nobel Prize in physics, 1930

"for his work on the scattering of light and for the discovery of the effect named after him"

Checklist

law of attenuation – integral form, differential form

attenuation coefficient – definition, unit, factors influencing its value

mechanism of light absorption

Beer's law

absorbance

absorption spectrum

measuring techniques

reflection of light

types of light scattering

Related chapters in

Damjanovich, Fidy, Szöllősi: Medical Biophysics

II. 1.1.

1.1.1

1.1.3

II. 2. 1.

2.1.1

2.1.2

2.1.3

2.1.4

2.1.5

2.1.8

VI.3

3.1.1

3.1.2