

Interactions of light 2.

Light absorption and scattering

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Interaction of light with matter

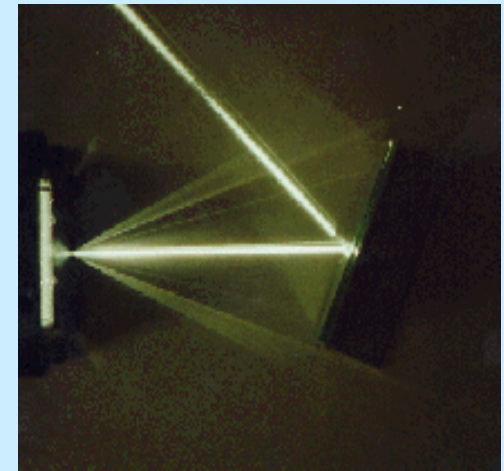
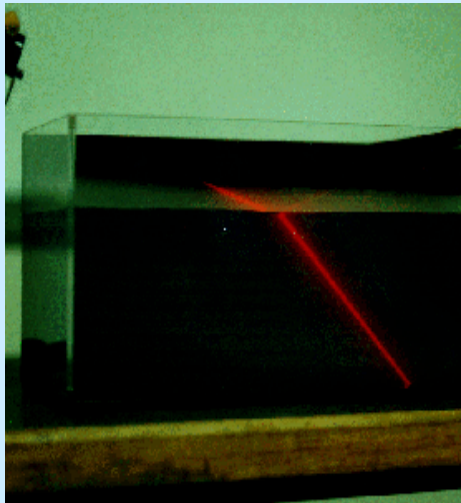
incident light

reflection

refraction

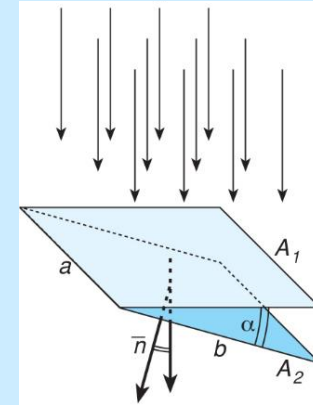
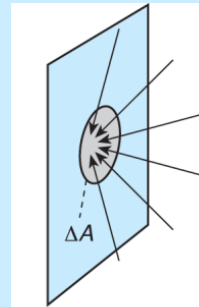
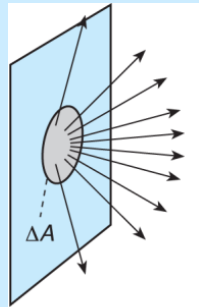
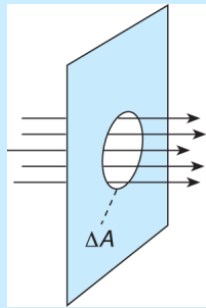
scattering

absorption



Light intensity

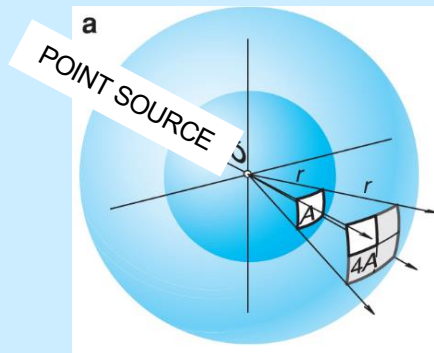
(light is a radiation transmitting energy)



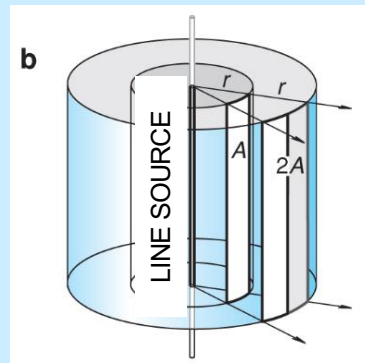
Energy flux: $I_E = \Delta E / \Delta t$ [W]

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

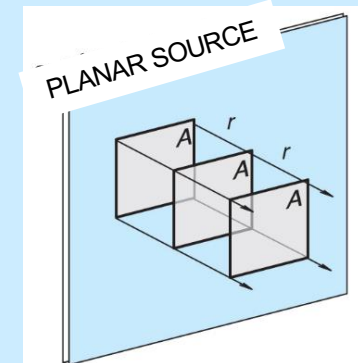
(amount of energy per unit area, per unit time, transmitted on a surface perpendicular to the direction of radiation)



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

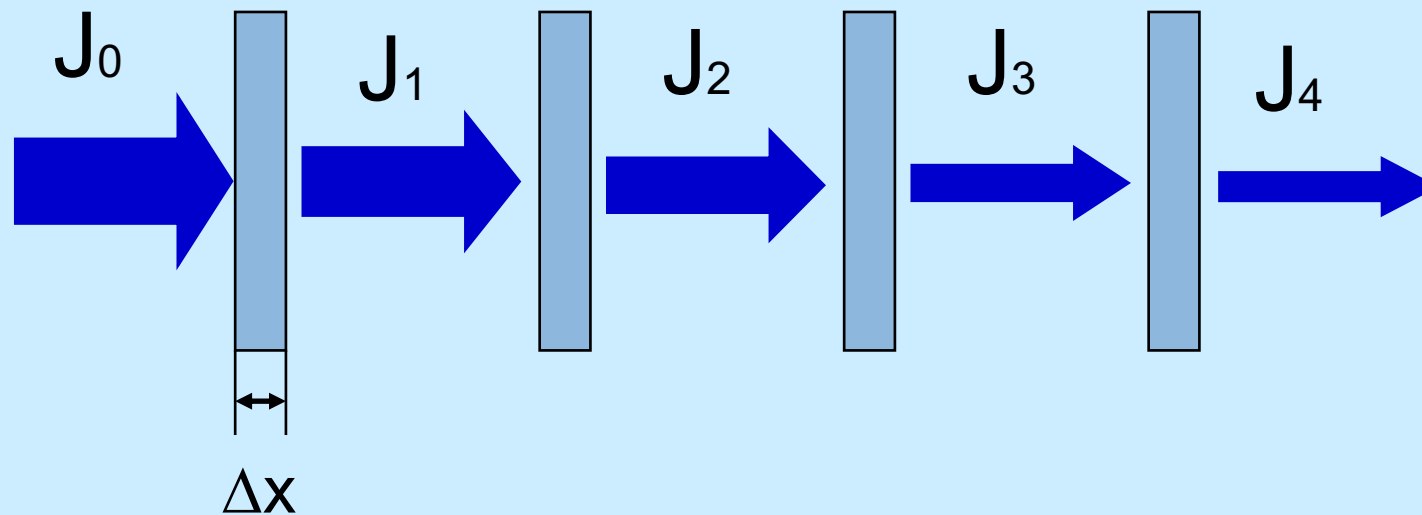
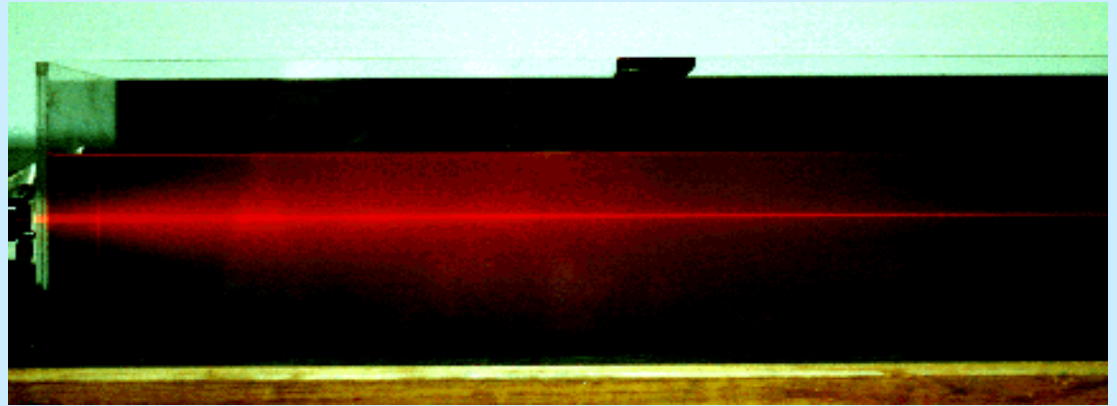


$$J \sim 1/r$$



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

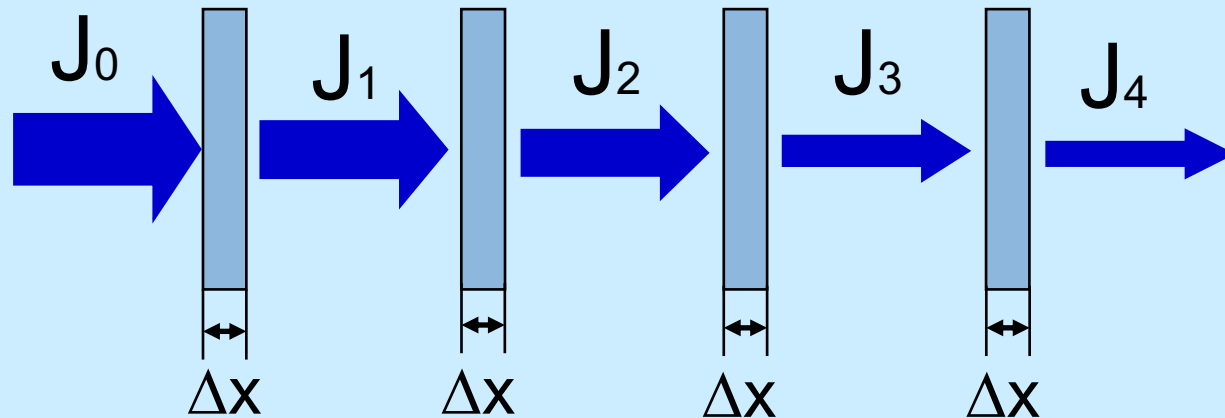
Absorption of light



Intensity of radiation is attenuated when passing through materials.

Law of attenuation

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



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

Differential form

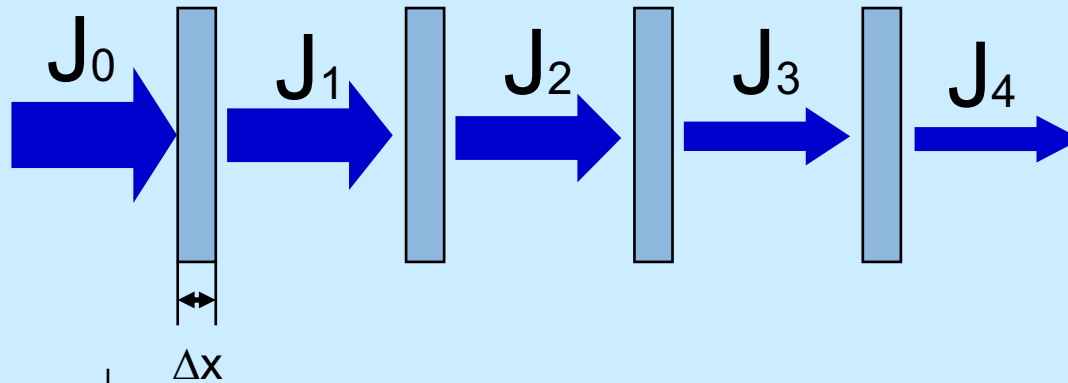
J_i : incident intensities [W/m^2]

ΔJ : change of intensity after passing through Δx thickness

μ : attenuation coefficient [$1/\text{m}$]

The decrease is proportional to the thickness of absorber Δx and J what is the initial intensity.

Law of attenuation



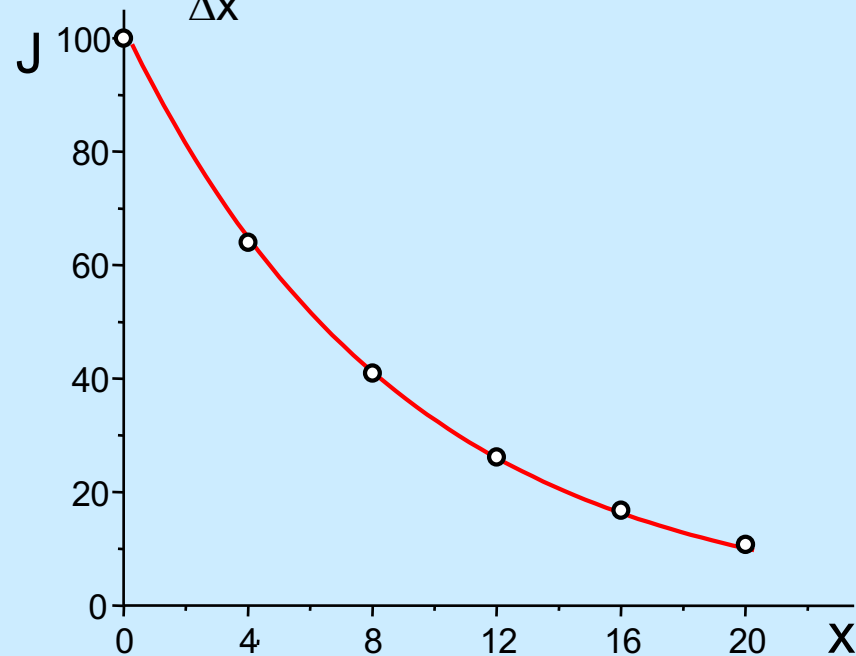
$$\frac{\Delta J}{\Delta x} = -\mu \times J$$

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 thickness of the layer.

J_0 : incident intensity [W/m²]

J : intensity after passing through x thickness

μ : attenuation coefficient [1/m]

The (linear) attenuation coefficient depends on:

photon energy

material composition of absorber

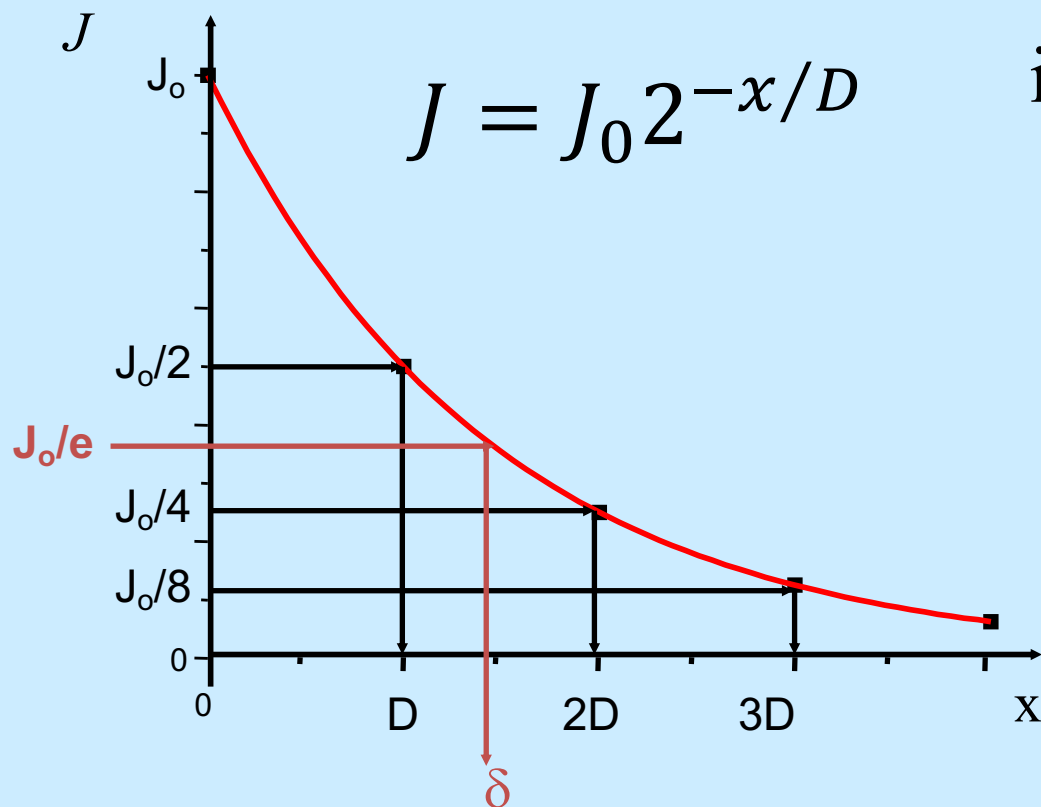
density of absorber

Graphical representation

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

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

Definition of attenuation coefficient

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

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

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

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

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

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!

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

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

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

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

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

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

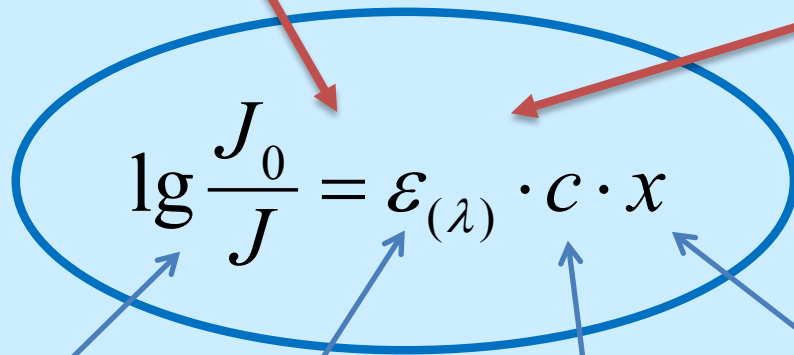
Analitical application of light absorption

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

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

In diluted solutions attenuation coefficient is proportional with 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 1 cm*)

molar concentration [mol/L]

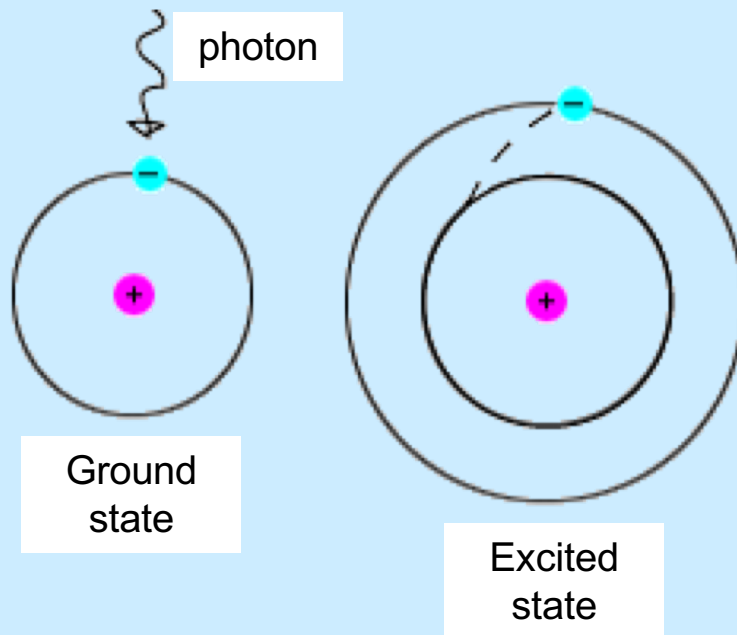
molar extinction coefficient
[L mol⁻¹cm⁻¹]

Transmittance, $T = J/J_0 \cdot 100$ [%]

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

Mechanism of light absorption

Electron potential energy is quantized in atoms and molecules:

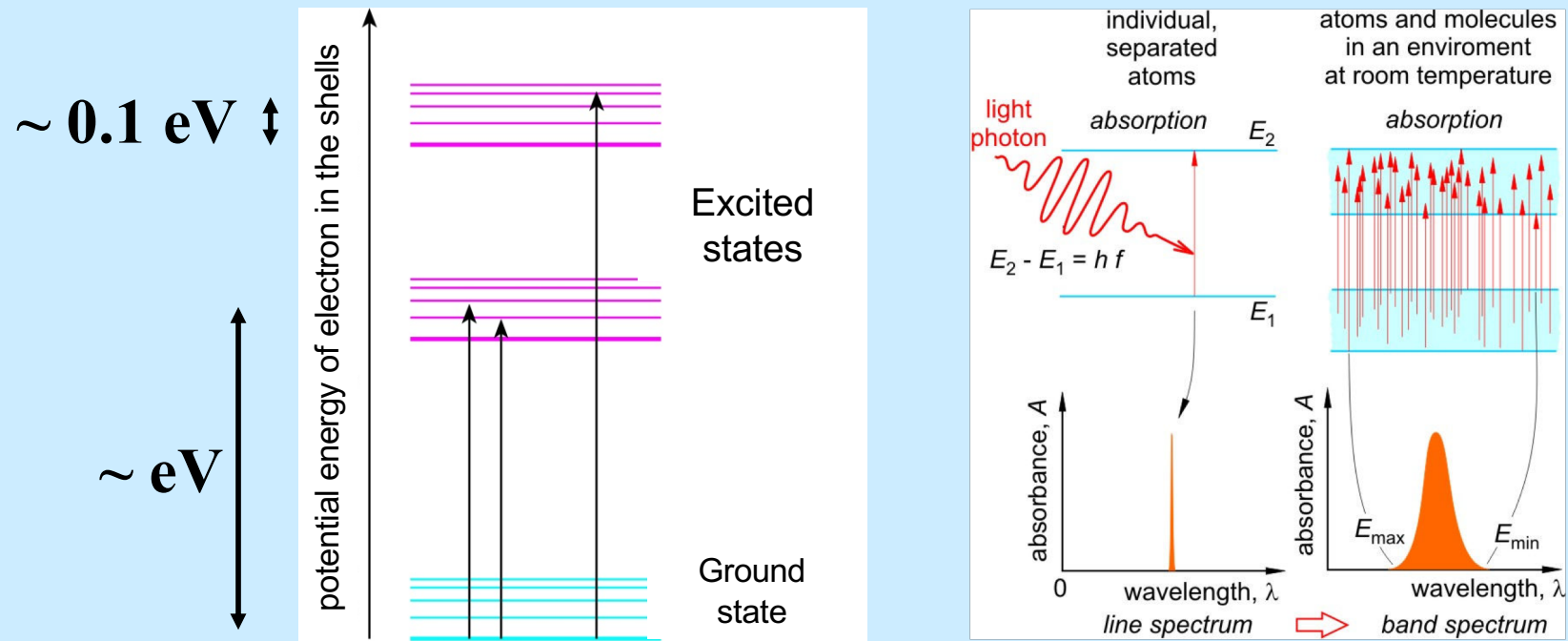


$$hf = \Delta E = E_{n+1} - E_n$$

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

→ excitation of outer shell electrons

Electronic and vibronic energy levels

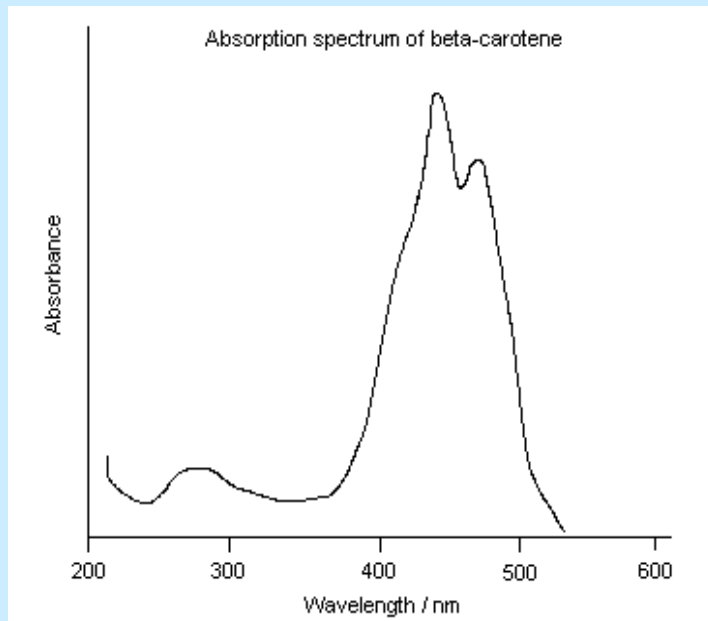
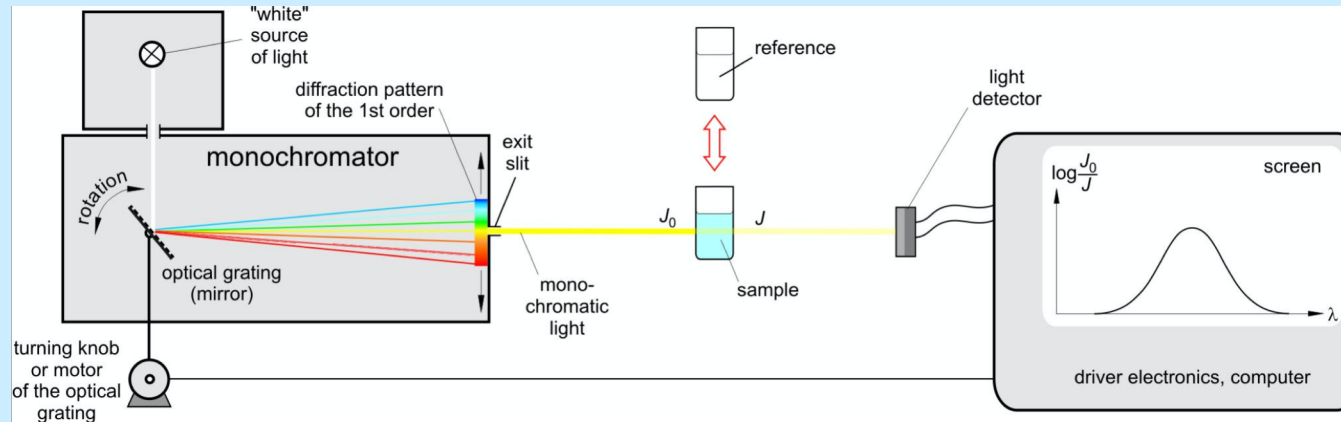


Molecules can absorb photons in a certain energy range

→ band spectrum

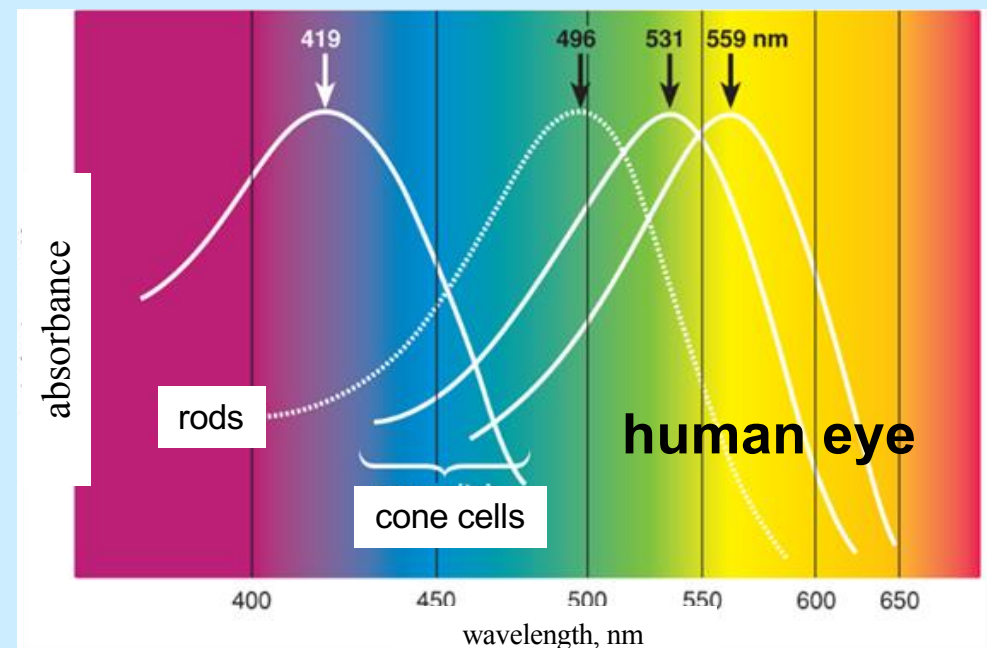
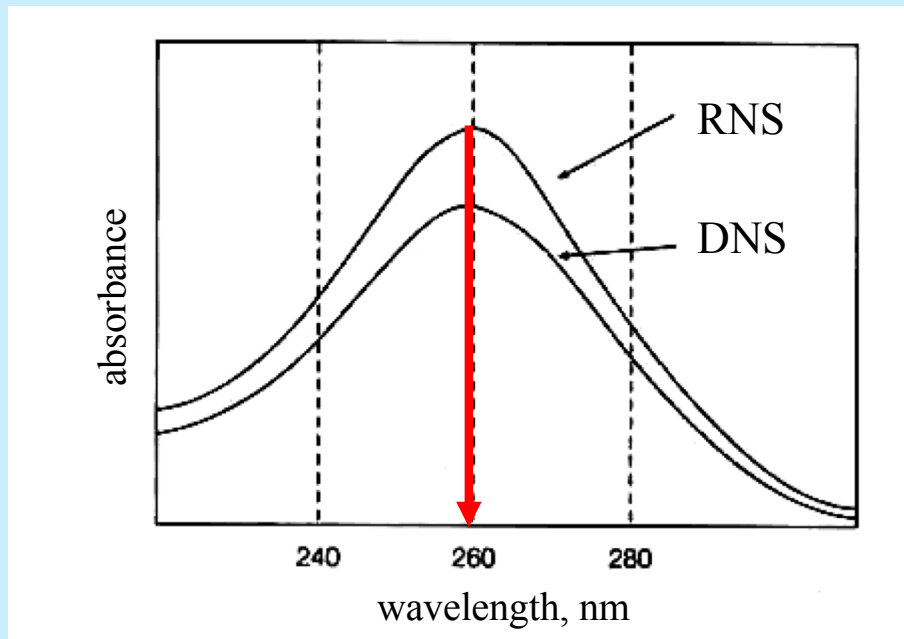
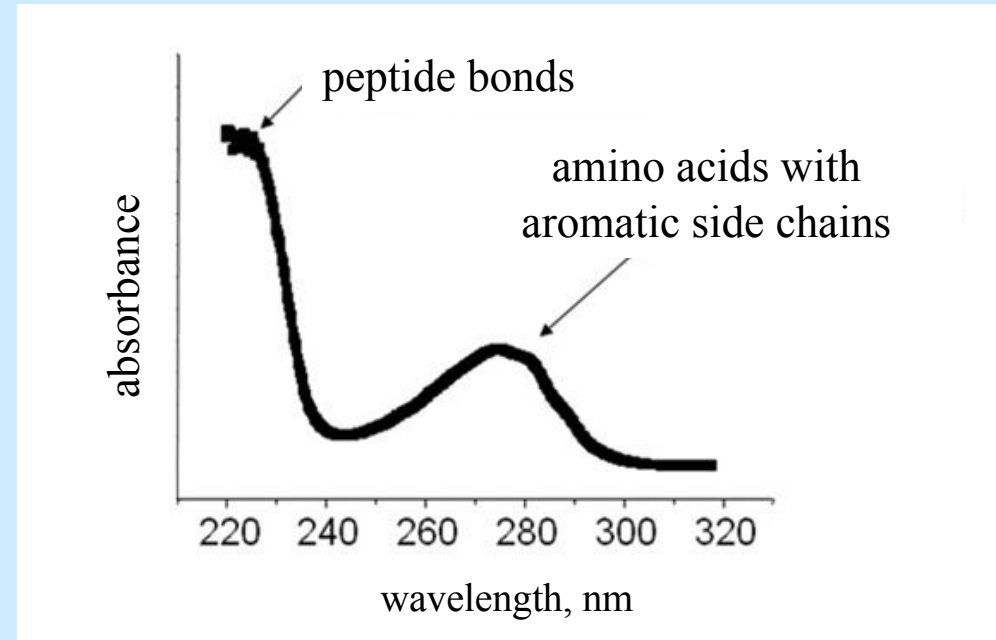
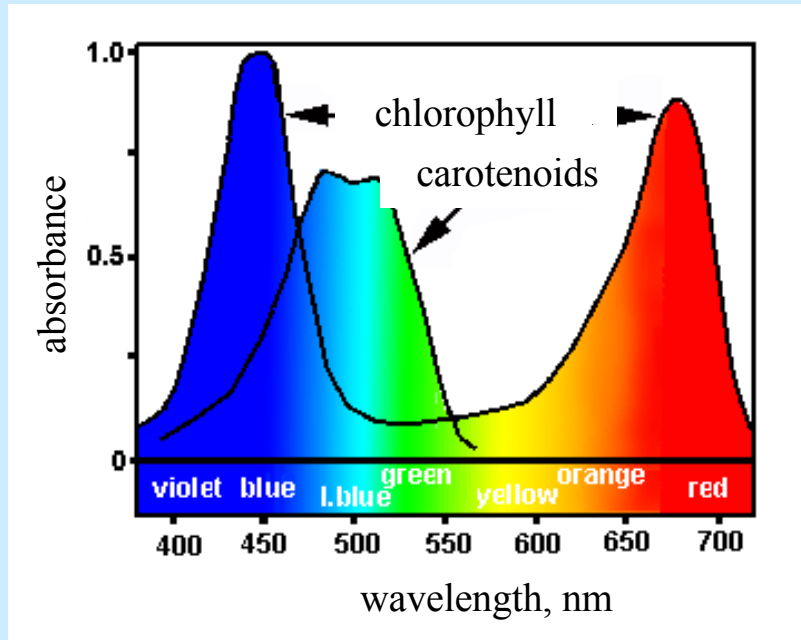
Absorption spectrum

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)

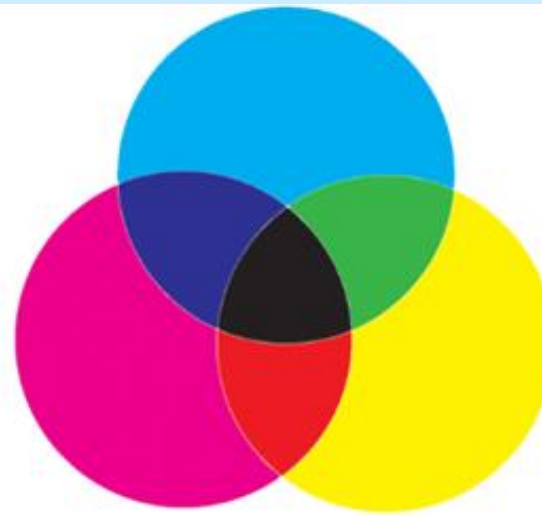
Absorption spectra of several biomolecules



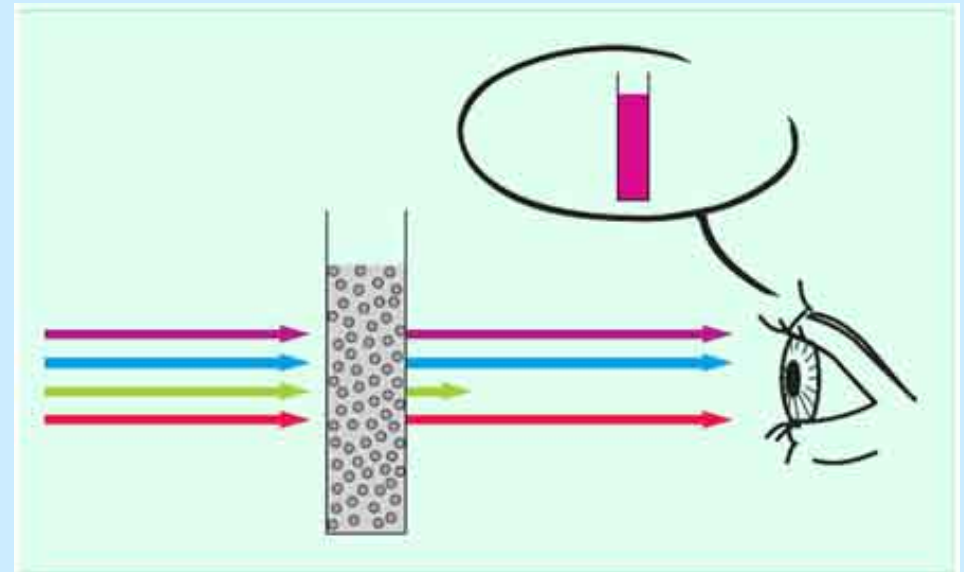
Absorption and color - complementary colors



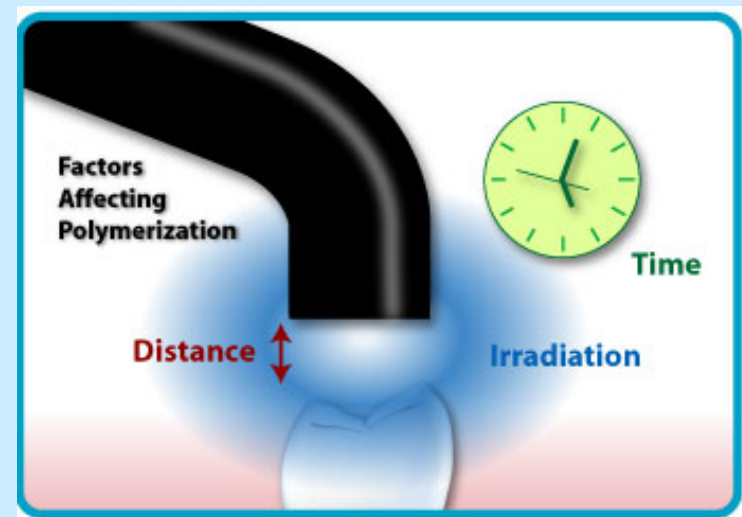
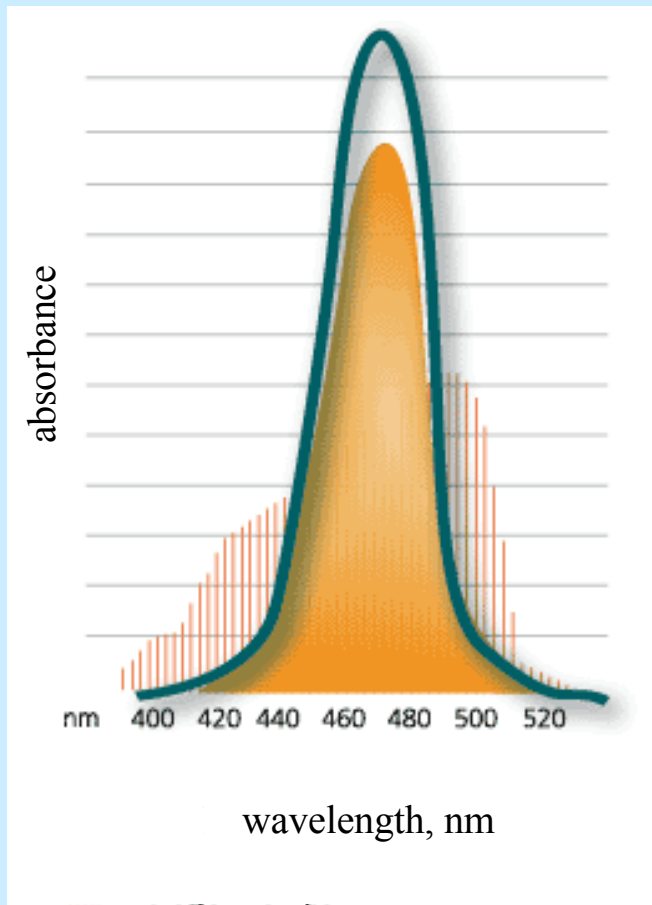
additive color mixing



subtractive color mixing



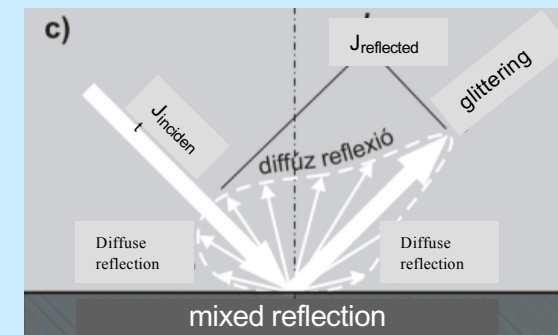
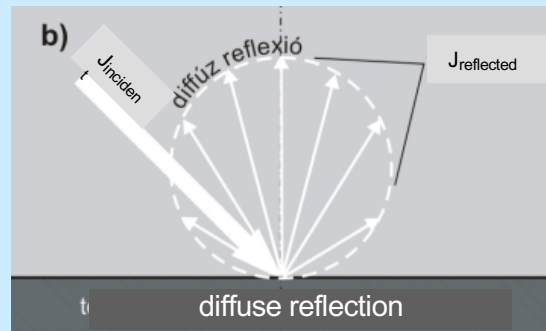
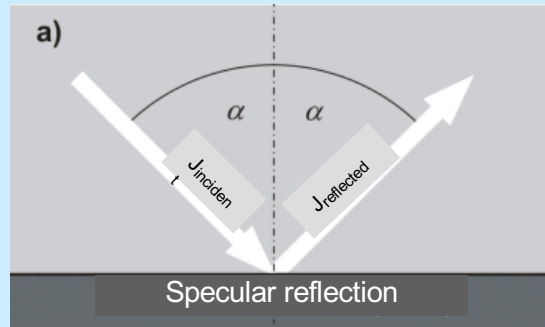
Application in Dentistry



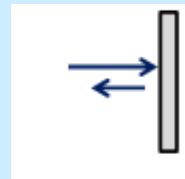
Camphor chinone
dental composite polimerizes due to light absorption

Reflection of light

Diffuse reflection

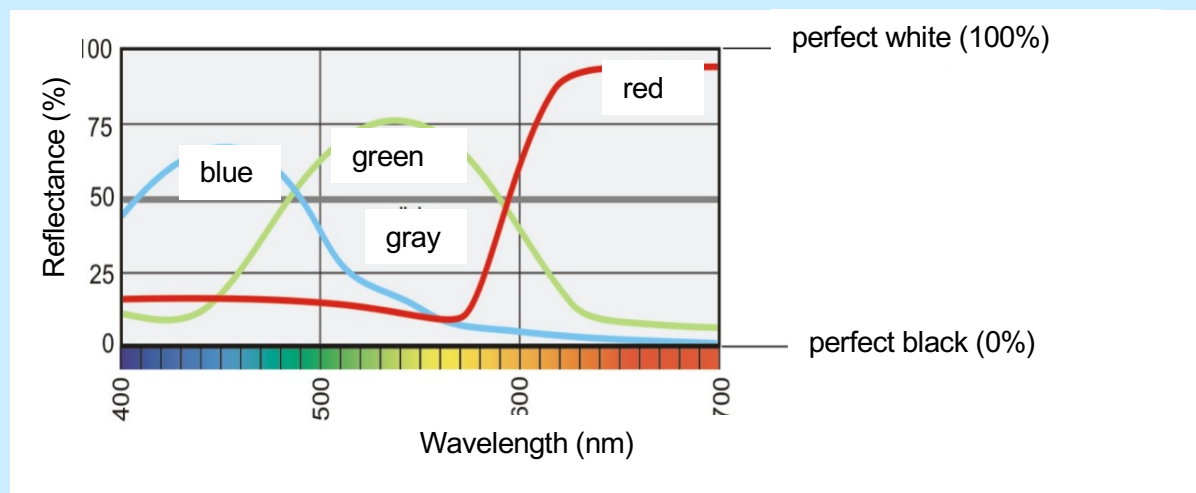


spectral reflectance



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

Spectrum of reflectance



Light scattering



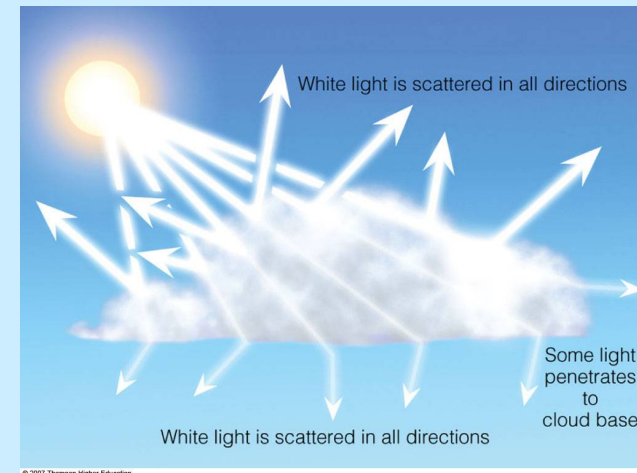
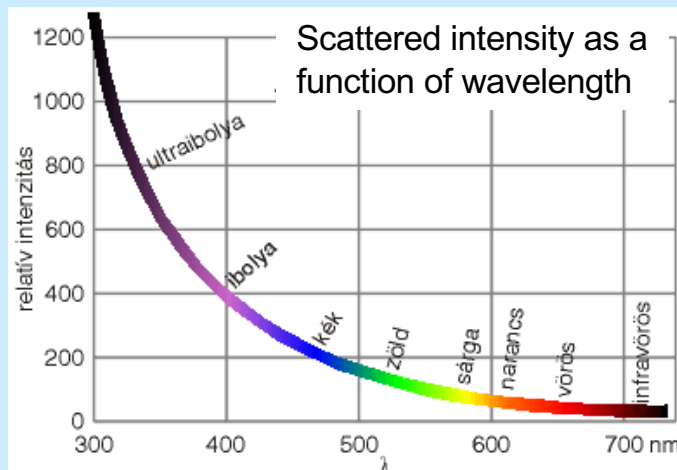
Scattering coefficient:
$$\sigma(\lambda) = \frac{J_{\text{scattered}}}{J_{\text{incident}}}$$

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

$d \ll \lambda$
Rayleigh scattering

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

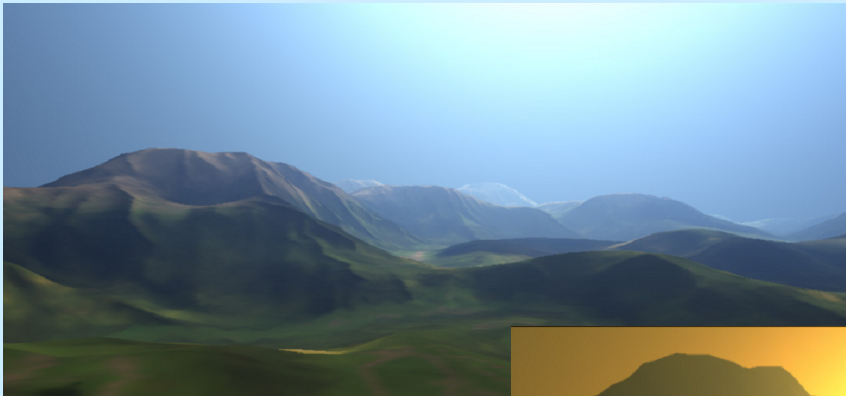
$d \geq \lambda$
Mie scattering
 σ weakly depends on λ



Light scattering

Rayleigh scattering

$$d \ll \lambda$$



Mie scattering

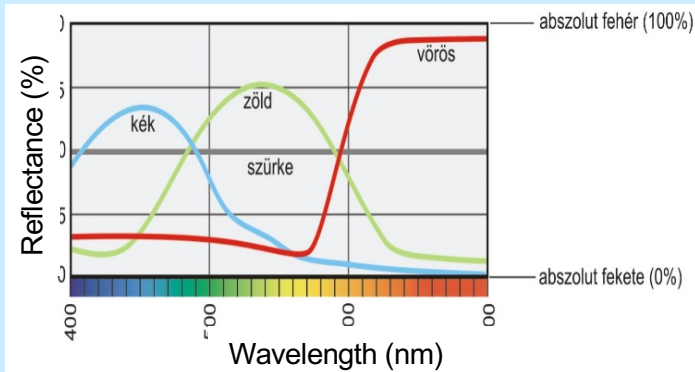
$$d \geq \lambda$$



What factors determine the color of objects?

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

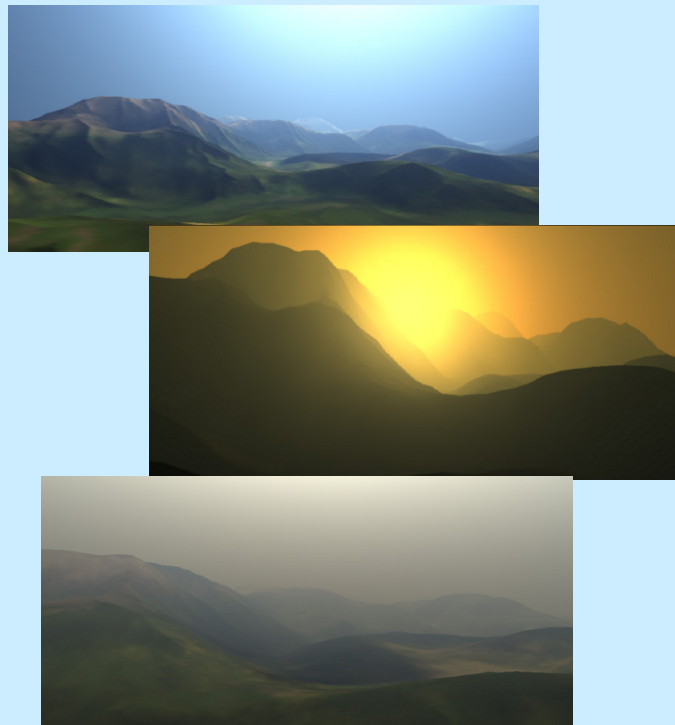
reflectance



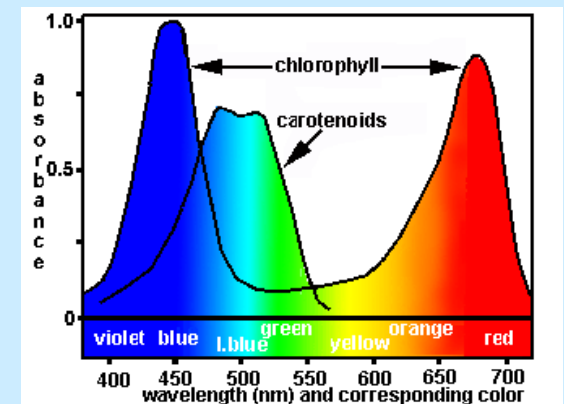
reflection of red

↓
red

scattering



absorption



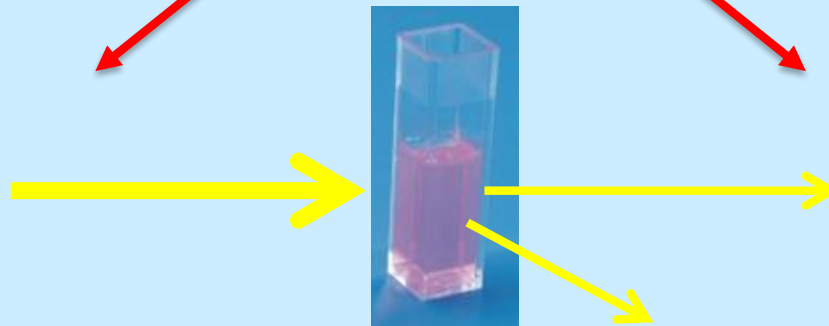
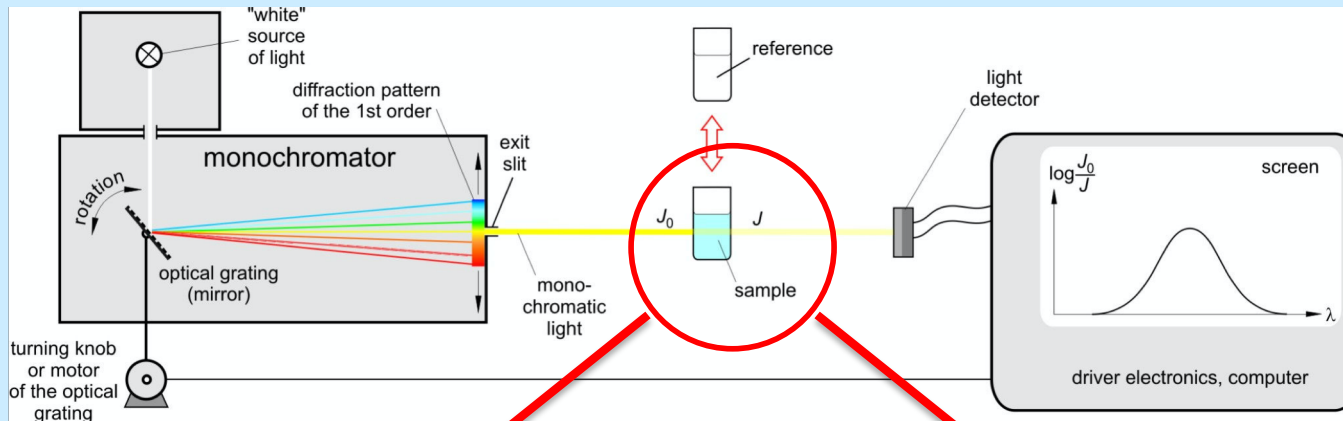
absorption of red

↓
green

Extinction

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

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

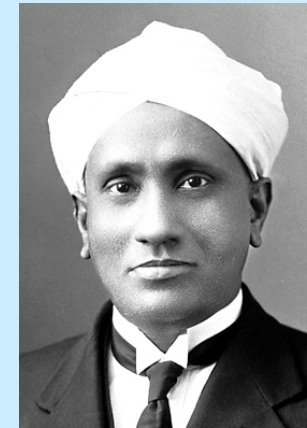
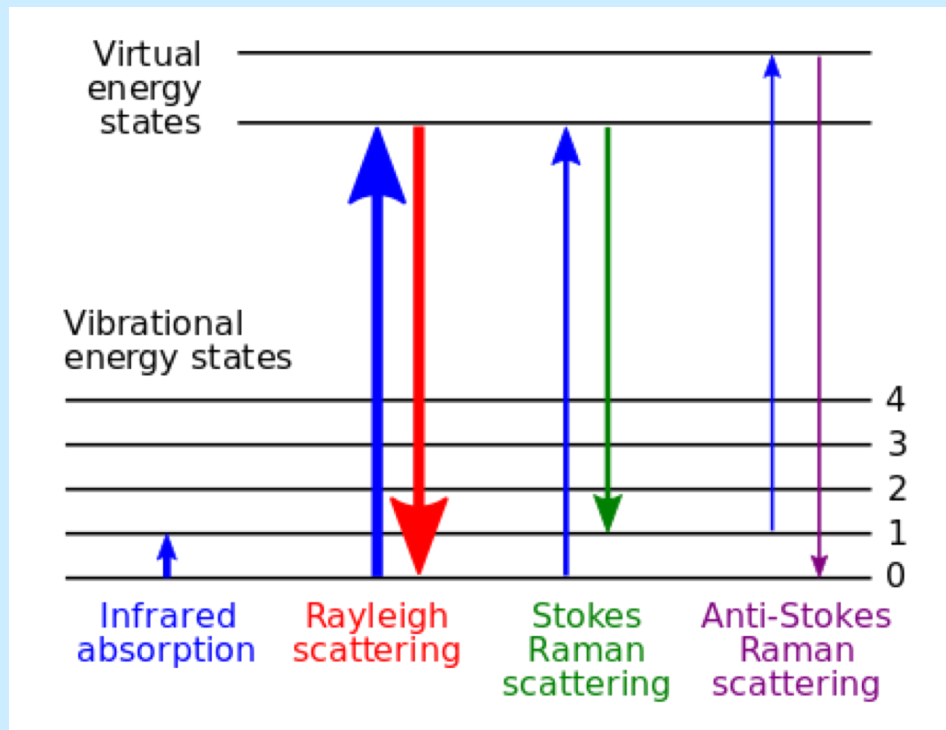


Extinction: attenuation by absorption and scattering together

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