Light and Photons

PHYS 4400, Principles and Varieties of Solar Energy

Instructor: Randy J. Ellingson
The University of Toledo

January 15, 2015

Light

- What is light?

- Electromagnetic wave – direction of the electric field?
- Speed of light = 299,792,458 m/s (exact)
- Relationship defines wavelength as a function of frequency: $\lambda\nu = c$
- This relation is true only in a ______________ (?)
  - *Hint – is this relationship true in water?*

- Relation true only in a vacuum: $\lambda\nu = c$.
- The general case depends on the refractive index, that slows the velocity of light: $c(n) = c/n$. And $\lambda_n = \lambda_0/n(\lambda_0)$.
- Refractive index of air: $n_{air} \approx 1.0003$
- Demonstration of a dispersive medium: http://www.rpi.edu/dept/phys/Dept2/APPhys1/optics/optics/node7.html

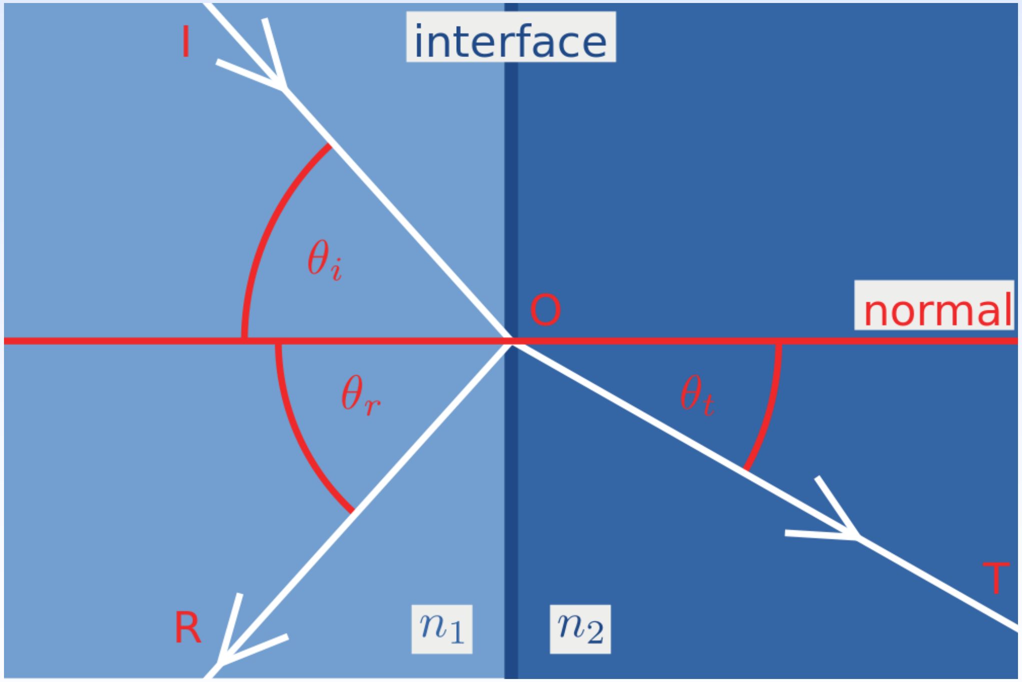
- Polarization: direction of the E-field. Simple cases are random, or linear (e.g., vertical or horizontal)

Side note on refractive index

Note that in general, the refractive index is a complex quantity: $\tilde{n} = n + ik$
The real part, *n*, refers to the phase speed of the light, and *k* depends on light absorption in the medium.

Reflection and Refraction of Light

Refraction refers to an interaction that results in a deviation of a beam or ray of light at an interface between two media of differing refractive indices; the effect does not occur for rays incident perpendicular to the interface.



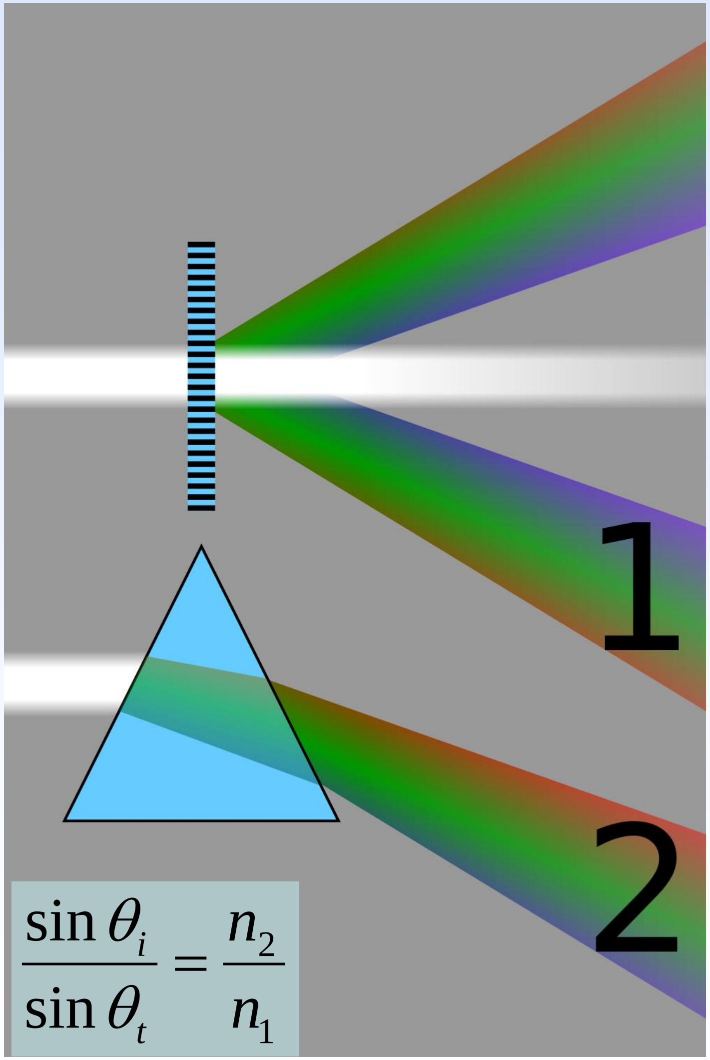
Reflection: $\theta_i = \theta_r$

Refraction: $$\frac{\sin \theta_i}{\sin \theta_t} = \frac{n_2}{n_1}$$

Refraction of Light: $n = n(\lambda)$

Diffraction occurs when a wave encounters an object. In the case of a diffraction grating, a wavelength-dependent effect results such that specific wavelength interfere constructively (and destructively) at specific positions on a screen, depending on the relative distances between grating slits and the pathlengths to the screen.

<u>Refraction</u> refers to an interaction that results in a deviation of a beam or ray of light at an interface between two media of differing refractive indices. In the case of a prism, since the refractive index of glass varies with color (wavelength), the angular deviation of colors shows up as wavelength dispersion in the beam.



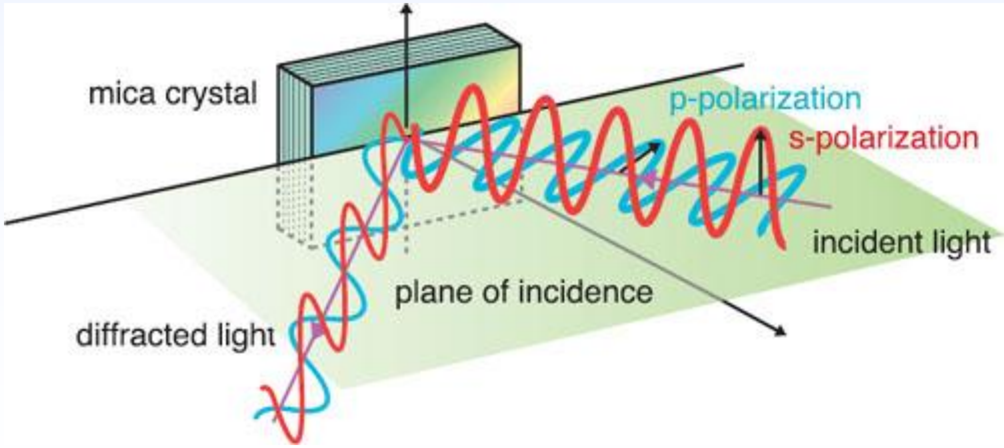
$$\frac{\sin\theta_i}{\sin\theta_t} = \frac{n_2}{n_1}$$

Polarization

Polarization refers to the direction of the electric field within a light beam.

Two polarization states are especially useful when considering reflection and transmission:

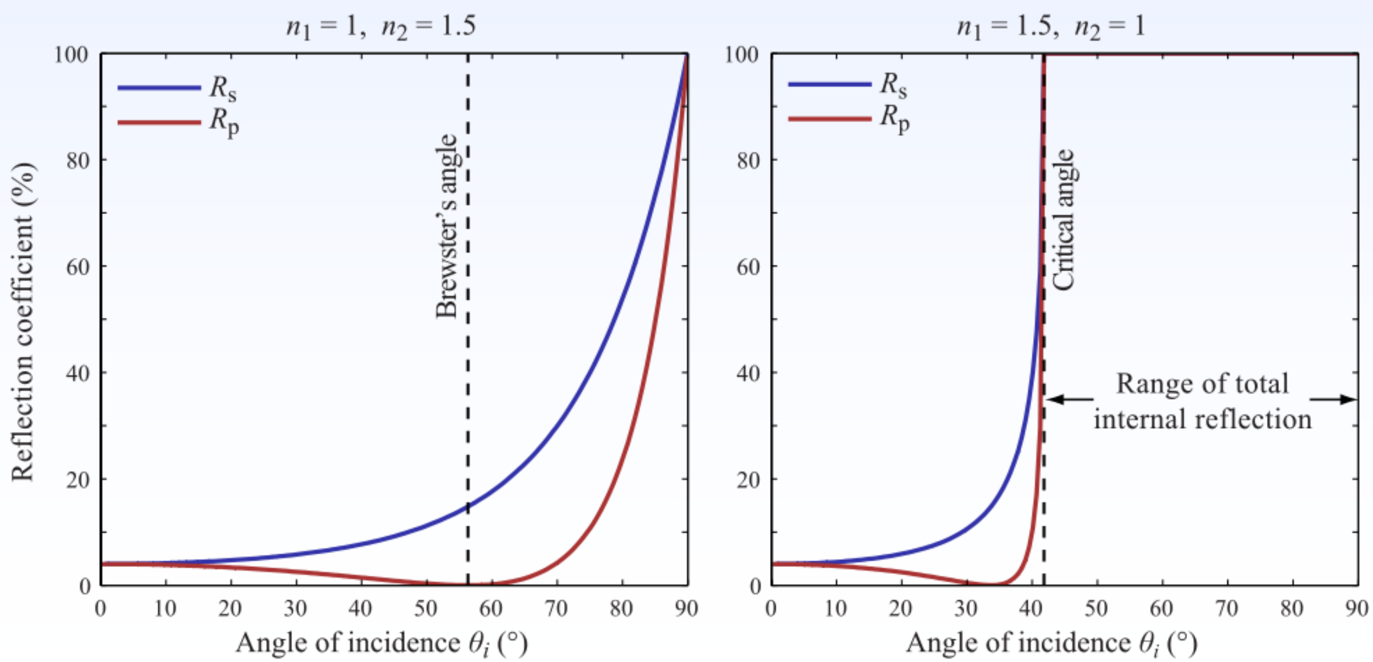
- S-polarized: "senkrecht" means vertical, refers here to perpendicular to the **plane of incidence**. (Plane of incidence defined by the incident and reflected waves.)
- P-polarized: parallel to the plane of incidence.



More general Fresnel Equations

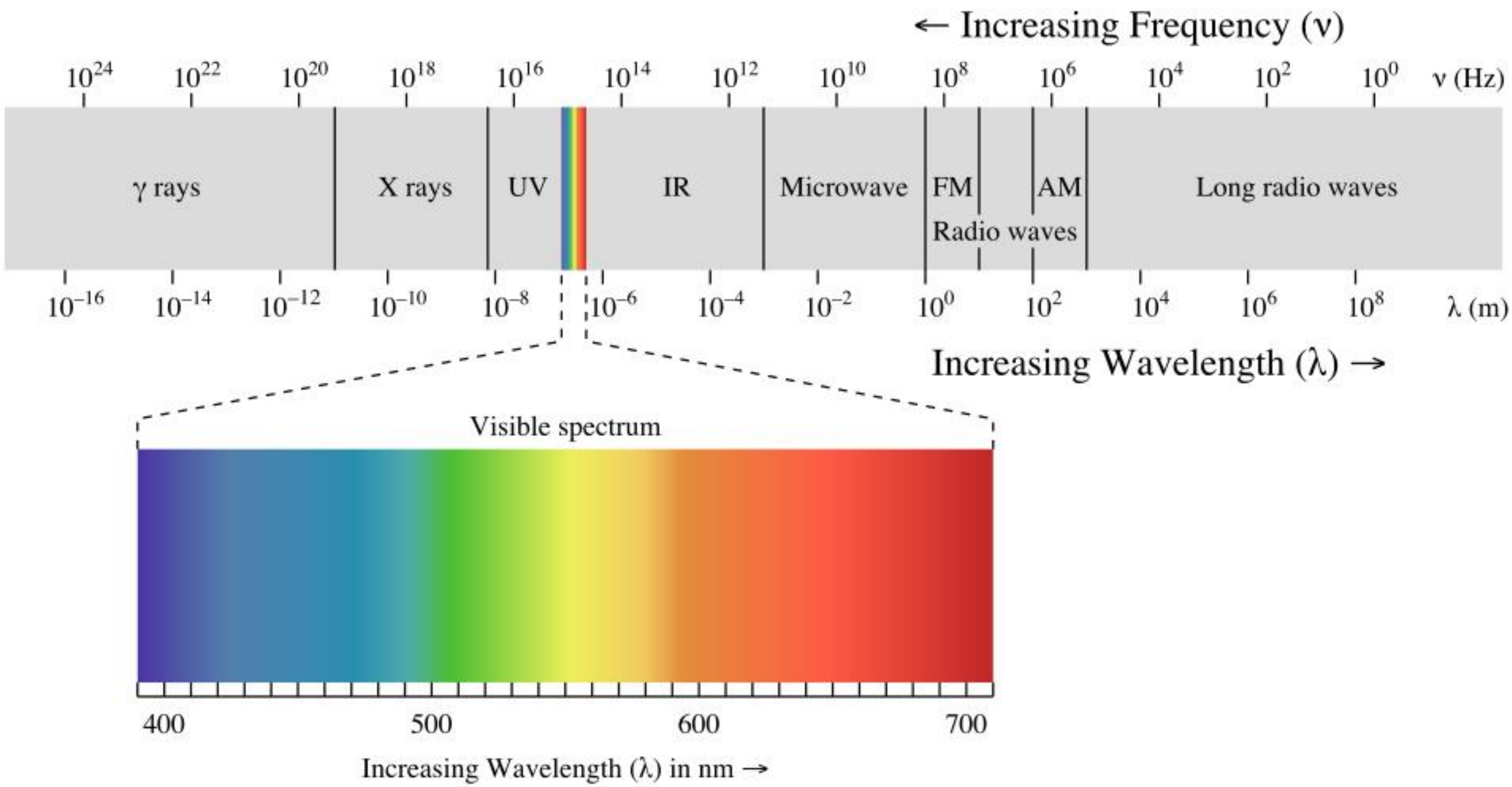
$$R_s = \left|\frac{n_1 \cos\theta_i - n_2 \cos\theta_t}{n_1 \cos\theta_i + n_2 \cos\theta_t}\right|^2 = \left|\frac{n_1 \cos\theta_i - n_2\sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_i\right)^2}}{n_1 \cos\theta_i + n_2\sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_i\right)^2}}\right|^2$$

$$R_p = \left|\frac{n_1 \cos\theta_t - n_2 \cos\theta_i}{n_1 \cos\theta_t + n_2 \cos\theta_i}\right|^2 = \left|\frac{n_1\sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_i\right)^2} - n_2 \cos\theta_i}{n_1\sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_i\right)^2} + n_2 \cos\theta_i}\right|^2$$



http://en.wikipedia.org/wiki/Fresnel_equations

The Electromagnetic Spectrum



Units and Measures for light

Radiant Energy: light energy (J)

Radiant Flux: same as *Power* (W)

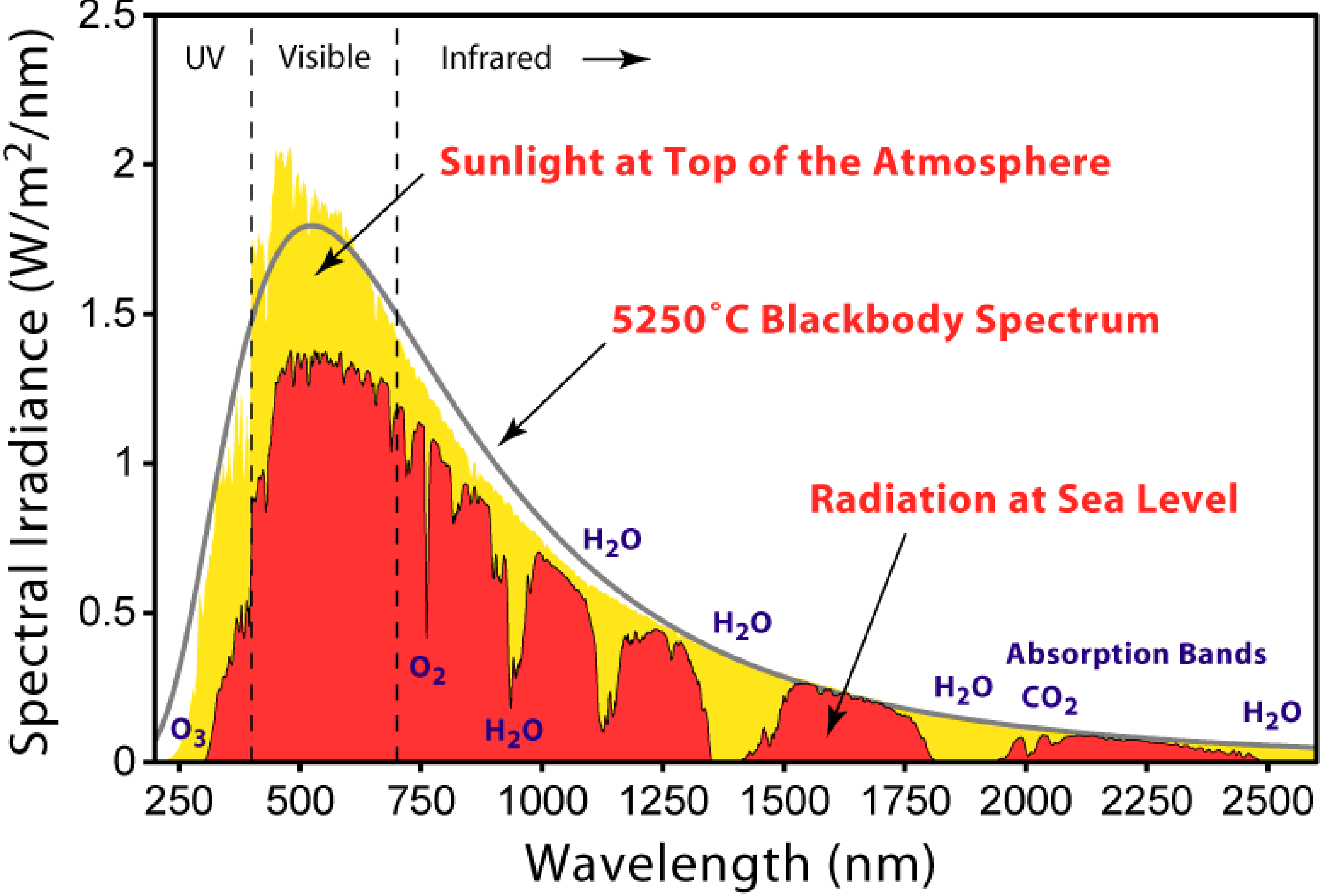
Irradiance: same as *Intensity* (W/m^2)

Spectral Irradiance: essentially, intensity per unit of spectral bandwidth (W/m^2 per nm of bandwidth, or just $W\ m^{-2}\ nm^{-1}$)

(Note that if these units were reduced to $W\ m^{-3}$, the significance of the units would be concealed and likely more confusing!)

Look ahead: learn to convert Spectral Irradiance from $W\ m^{-2}\ nm^{-1}$ to photons $sec^{-1}\ m^{-2}\ nm^{-1}$

Solar Radiation Spectrum



Photons as particles of light

The *photon* is the fundamental quantum of light, with an energy dependent on *frequency*:

$$E = h\nu$$

The particle nature of photons has many implications, especially with regard to interactions with matter.

Light energy

Examples of light energy: E_{photon} = (1240 eV nm)/ (λ in nm)
350 nm (UV) ≈ 3.5 eV
750 nm (NIR) ≈ 1.65 eV

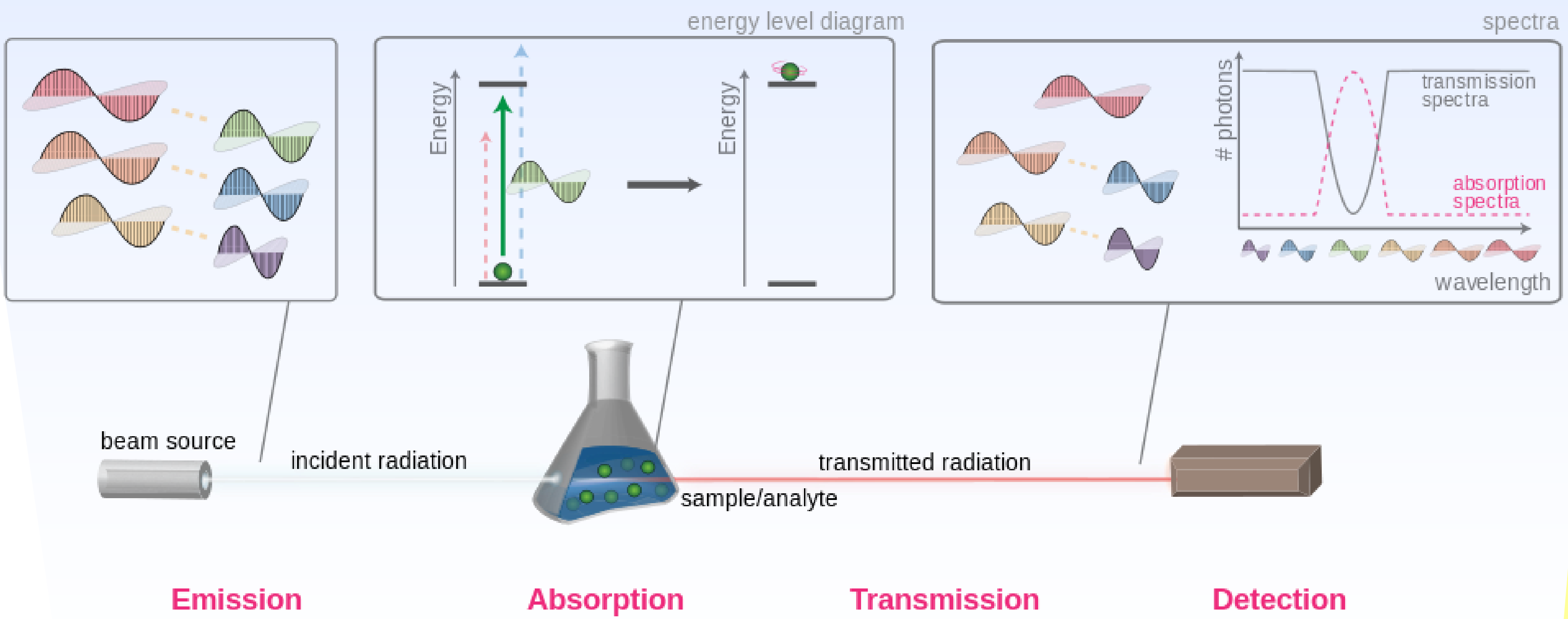
To convert eV to J, multiply by the magnitude of the charge on an electron, 1.6×10^{-19}. Or just calculate $E_{ph} = hc/\lambda$ directly in SI units.

Consider a 0.5 mW laser pointer, λ = 670 nm (red). When the laser beam is on continuously, how many photons are emitted per second?

$hc/\lambda = (6.63 \times 10^{-34}$ J s$)(3 \times 10^{8}$ m s$^{-1})/(670 \times 10^{-9}$ m$) = 2.97 \times 10^{-19}$ J. 0.5 mW → 0.5×10^{-3} J/s → 1.68×10^{15} photons/sec.

Light processes

When matter absorbs light, the photon's energy is imparted to the material. Transmitted and reflected photons do not impart energy to the material.



Light absorption

When matter absorbs light, the photon's energy is imparted to the material. Transmitted and reflected photons do not impart energy to the material, and the photon's energy is typically retained.

We define an absorption coefficient, α, for a material, depending upon how strongly it absorbs light. The absorption coefficient is generally wavelength (λ) dependent:

$$\alpha = \alpha(\lambda)$$

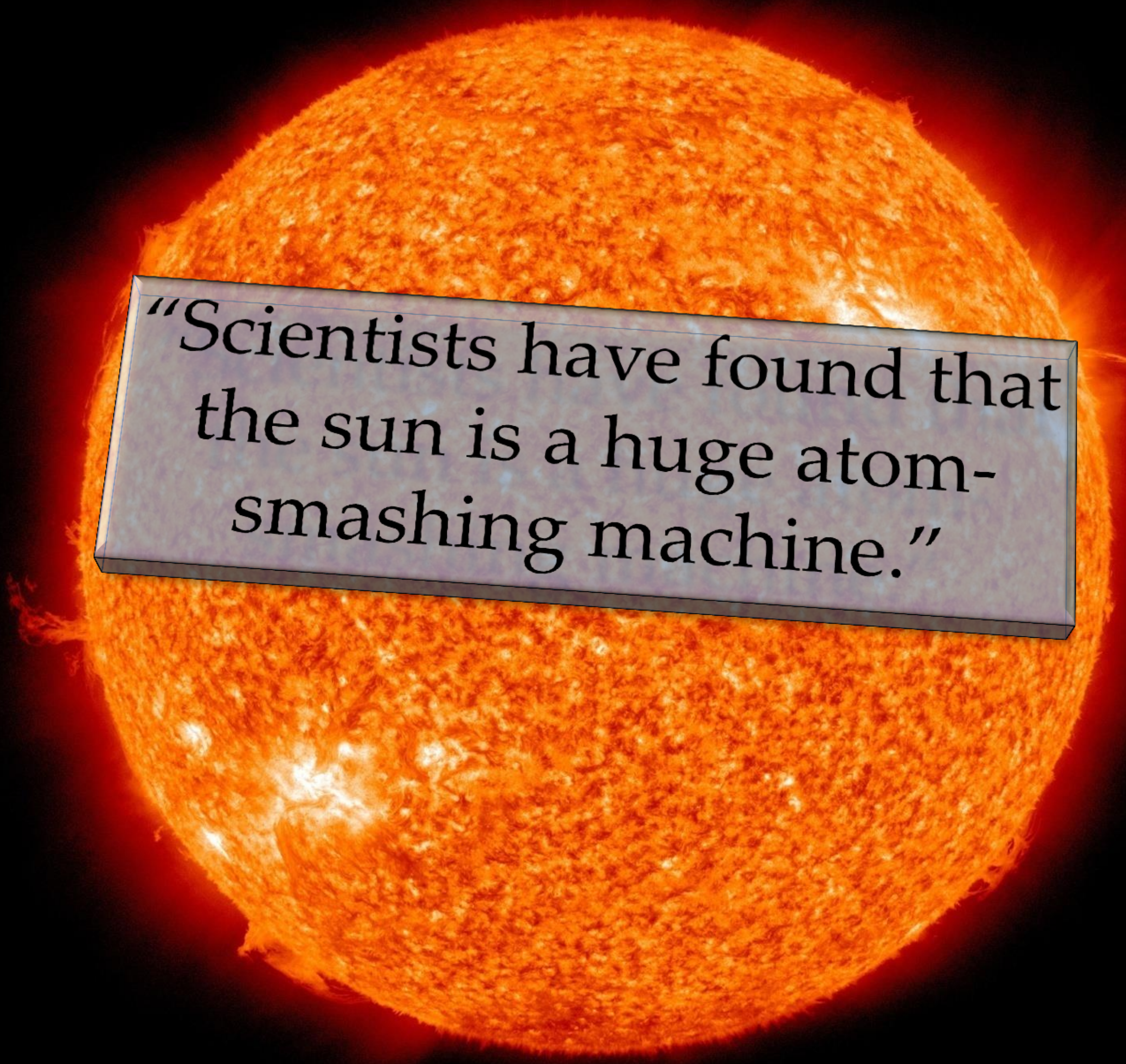
The units for $\alpha(\lambda)$ are typically cm^{-1}, or in units of 1/length. The transmission of light through an absorbing medium (material) is then given by:

$$T(\lambda) = e^{-\alpha(\lambda) l}$$

Where l is the length of the path through the absorbing material, given in the same (inverse) units as $\alpha(\lambda)$ – so that the exponent in unitless as all exponents in mathematical expressions should always be. As light travels through a material, the intensity of the light drops as it is absorbed:

$$I(\lambda, x) = I_0 e^{-\alpha(\lambda) x}$$

The Sun (worth revering)



"Why Does the Sun Shine?"
by *They Might Be Giants*

The sun is a mass of incandescent gas
A gigantic nuclear furnace
Where hydrogen is built into helium
At a temperature of millions of degrees

Yo ho, it's hot, the sun is not
A place where we could live
But here on Earth there'd be no life
Without the light it gives

We need its light
We need its heat
We need its energy
Without the sun, without a doubt
There'd be no you and me