Laser Beam Interactions with Solids

- In absorbing materials photons deposit energy

$$E = h\nu = \frac{hc}{\lambda}$$

where h = Plank's constant = 6.63 x 10^{-34} J s
c = speed of light

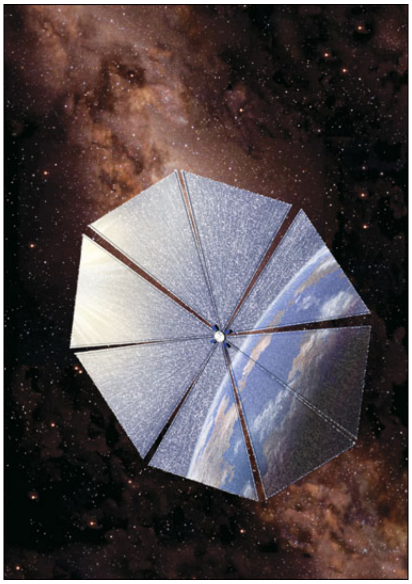
- Also photons also transfer momentum p

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

- Note: when light reflects from a mirror momentum transfer is doubled
- eg momentum transferred from Nd:YAG laser photon hitting a mirror (λ= 1.06 microns)

$$p = \frac{h}{\lambda} = \frac{2\left(6.6x10^{-34}\right)}{1.06x10^{-6}} = 1.25x10^{-27}\,kg\ m/s$$

- Not very much but Sunlight 1 KW/m^2 for 1 sec has $5x10^{21}$ photons: force of $6.25x10^{-6}$ N/m^2
- Proposed for Solar Light Sails in space (get that force/sq m of sail) small acceleration but very large velocity over time.
- Russian Cosmos 1 solar sail
  Failed to reach 500 km orbit June 2005



Absorbing in Solids

- Many materials are absorbing rather than transparent
- Beam absorbed exponentially as it enters the material
- For uniform material follows Beer Lambert law

$$I(z) = I_0 \, exp(-\alpha z)$$

where $\alpha = \beta = \mu_a$ = absorption coefficient (cm^{-1})

z = depth into material

- Absorption coefficient dependent on wavelength, material & intensity
- High powers can get multiphoton effects

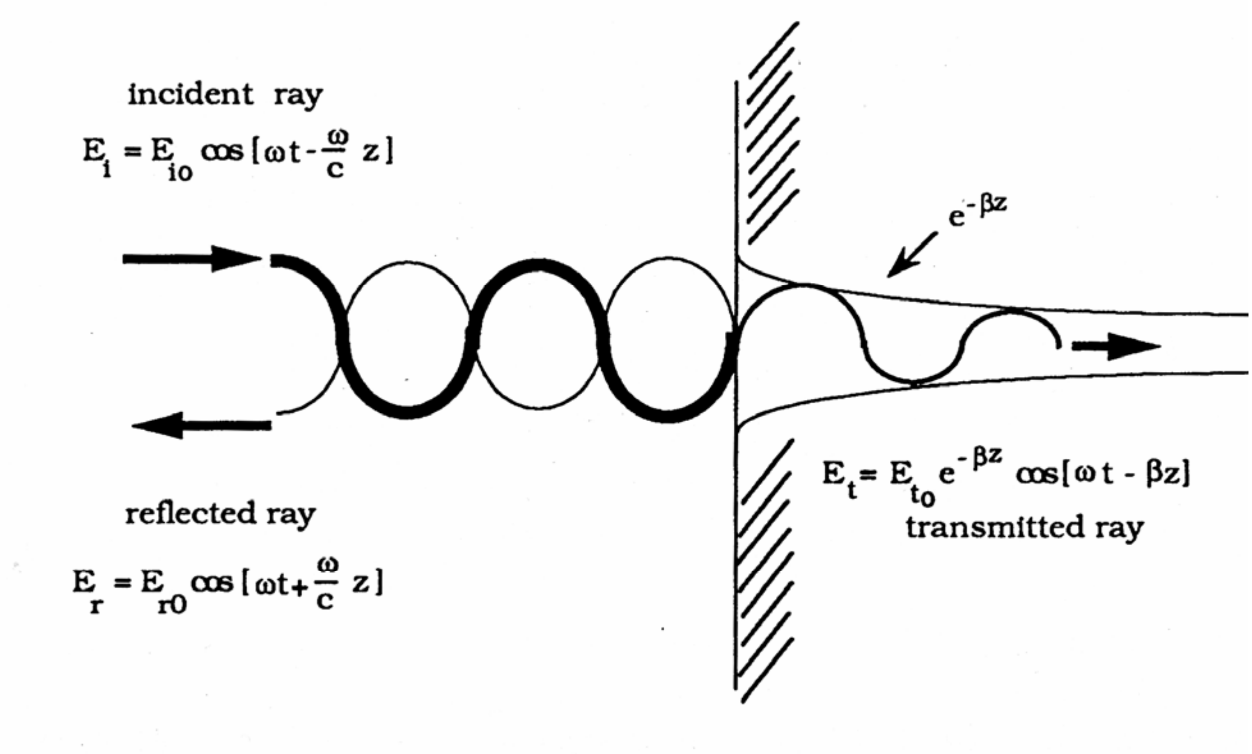


Fig. 2.1. The phase and amplitude of an electromagnetic ray striking an air/solid interface and undergoing reflection and transmission.

Single Crystal Silicon

- Absorption Coefficient very wavelength dependent
- Argon laser light 514 nm α = 11200/cm
- Nd:Yag laser light 1060 nm α = 280/cm
- Hence Green light absorbed within a micron
  1.06 micron penetrates many microns
- Very temperature dependent
- Note: polycrystalline silicon much higher absorption
  : at 1.06 microns α = 20,000/cm

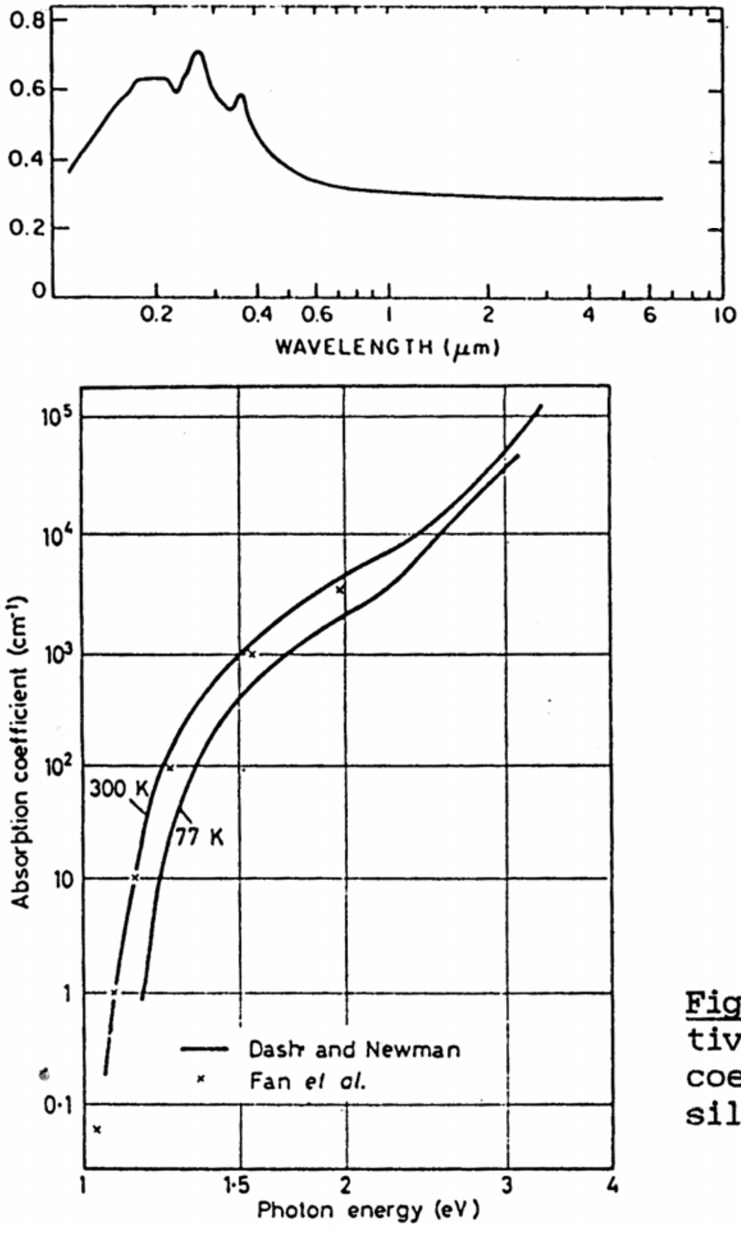


Fig.2.8. (a) Optical reflectivity, and (b) absorption coefficient of single crystal silicon [2.89,90],

Absorption Index

- Absorbing materials have a complex index of refraction

$$n_c = n - ik \qquad v = \frac{c}{n_c}$$

where n = real index of refraction

k = absorption index or extinction coefficient

- The Electric field then becomes

$$\vec{E}(t,z) = \hat{i}E_0 \exp\left[j\left(-\omega t + \frac{\omega n_c z}{c} \right) \right]$$

$$E(t,z) = E_0\, exp\left(i\left[\omega t - \frac{\omega nz}{c} \right] \right) exp\left(-\frac{\omega kz}{\lambda} \right)$$

- The k can be related to the absorption coefficient by

$$\alpha = \frac{4\pi k}{\lambda}$$

where wavelength is the vacuum value

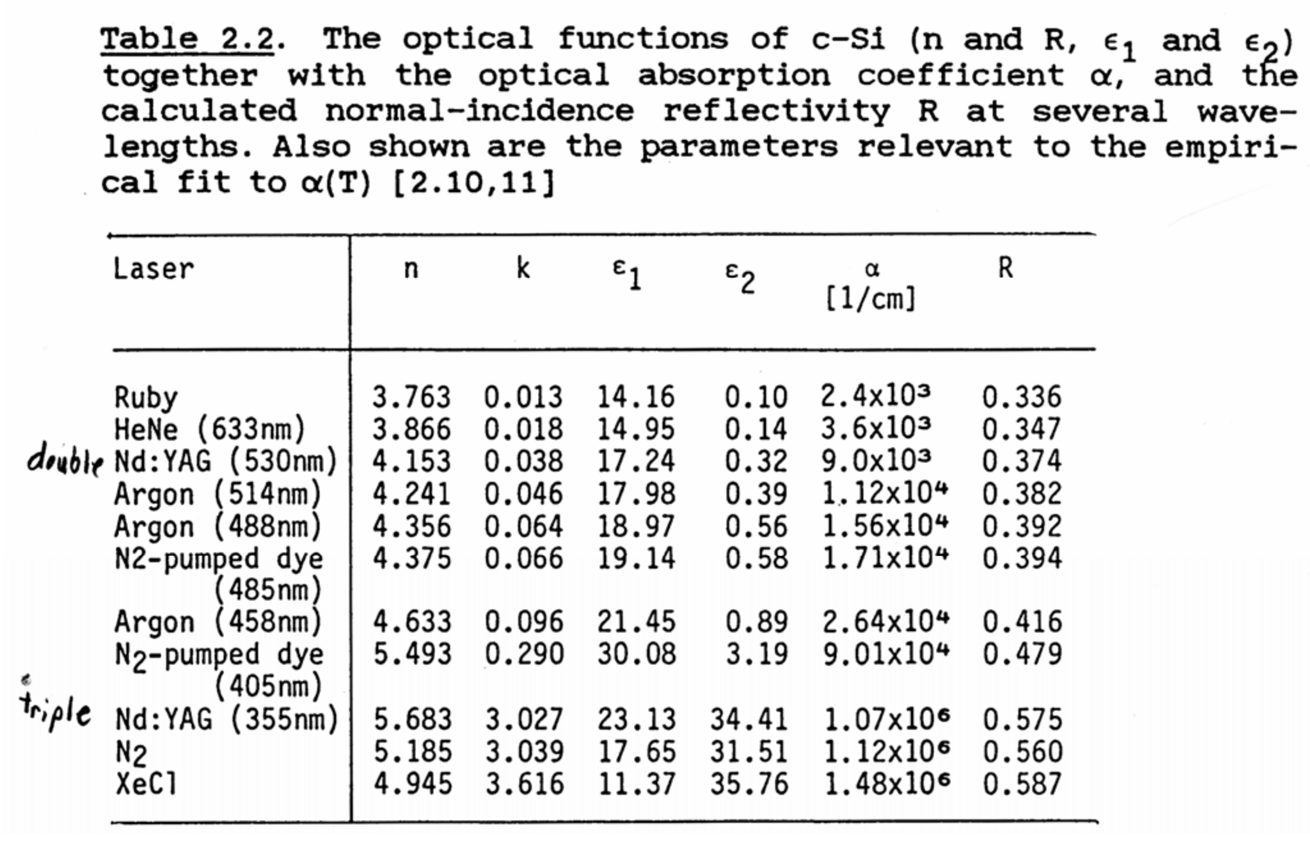


Table 2.2. The optical functions of c-Si (n and R, ϵ_1 and ϵ_2) together with the optical absorption coefficient α, and the calculated normal-incidence reflectivity R at several wavelengths. Also shown are the parameters relevant to the empirical fit to $\alpha(T)$ [2.10,11]

	Laser	n	k	ϵ_1	ϵ_2	α [1/cm]	R
	Ruby	3.763	0.013	14.16	0.10	2.4×10^3	0.336
	HeNe (633nm)	3.866	0.018	14.95	0.14	3.6×10^3	0.347
double	Nd:YAG (530nm)	4.153	0.038	17.24	0.32	9.0×10^3	0.374
	Argon (514nm)	4.241	0.046	17.98	0.39	1.12×10^4	0.382
	Argon (488nm)	4.356	0.064	18.97	0.56	1.56×10^4	0.392
	N2-pumped dye (485nm)	4.375	0.066	19.14	0.58	1.71×10^4	0.394
	Argon (458nm)	4.633	0.096	21.45	0.89	2.64×10^4	0.416
	N_2-pumped dye (405nm)	5.493	0.290	30.08	3.19	9.01×10^4	0.479
triple	Nd:YAG (355nm)	5.683	3.027	23.13	34.41	1.07×10^6	0.575
	N_2	5.185	3.039	17.65	31.51	1.12×10^6	0.560
	XeCl	4.945	3.616	11.37	35.76	1.48×10^6	0.587

Absorption Index & Electrical Parameters

- k and n are related to the dielectric constant ε and the conductivity σ of the material

$$n^2 - k^2 = \varepsilon$$

$$nk = \frac{\sigma}{\nu}$$

where ν= the frequency

- High conductivity Metals have high k relative to n: hence high R
- Note n can be <1 for absorbing materials but $|n_c|>1$
- Insulators: k=0 when transparent

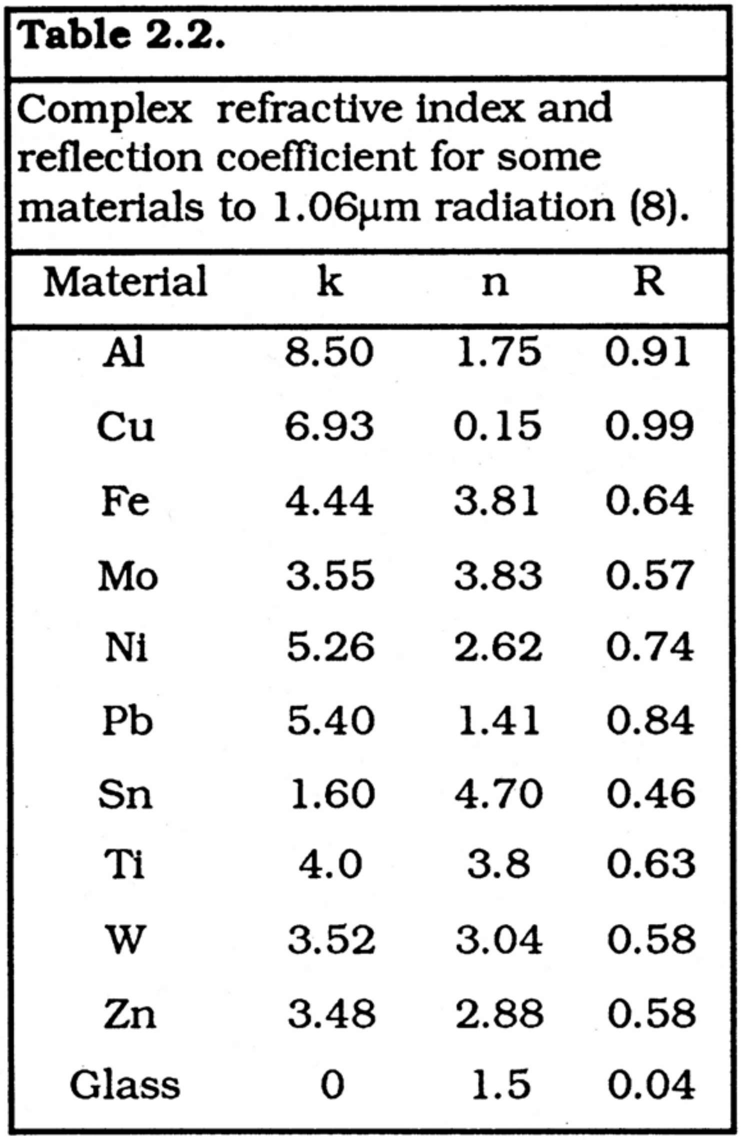


Table 2.2.

Complex refractive index and reflection coefficient for some materials to 1.06μm radiation (8).

Material	k	n	R
Al	8.50	1.75	0.91
Cu	6.93	0.15	0.99
Fe	4.44	3.81	0.64
Mo	3.55	3.83	0.57
Ni	5.26	2.62	0.74
Pb	5.40	1.41	0.84
Sn	1.60	4.70	0.46
Ti	4.0	3.8	0.63
W	3.52	3.04	0.58
Zn	3.48	2.88	0.58
Glass	0	1.5	0.04

Opaque Materials

- Materials like metals have large numbers of free electrons
- High conductivity, reflectivity and absorption
- Reflectivity given by (for normal incidence of light)

$$R = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2}$$

- For opaque materials light absorbed A is

$$A = 1 - R$$

- R and k are very wavelength dependent
- Also these are very dependent on
  the absence of other materials from the surface.

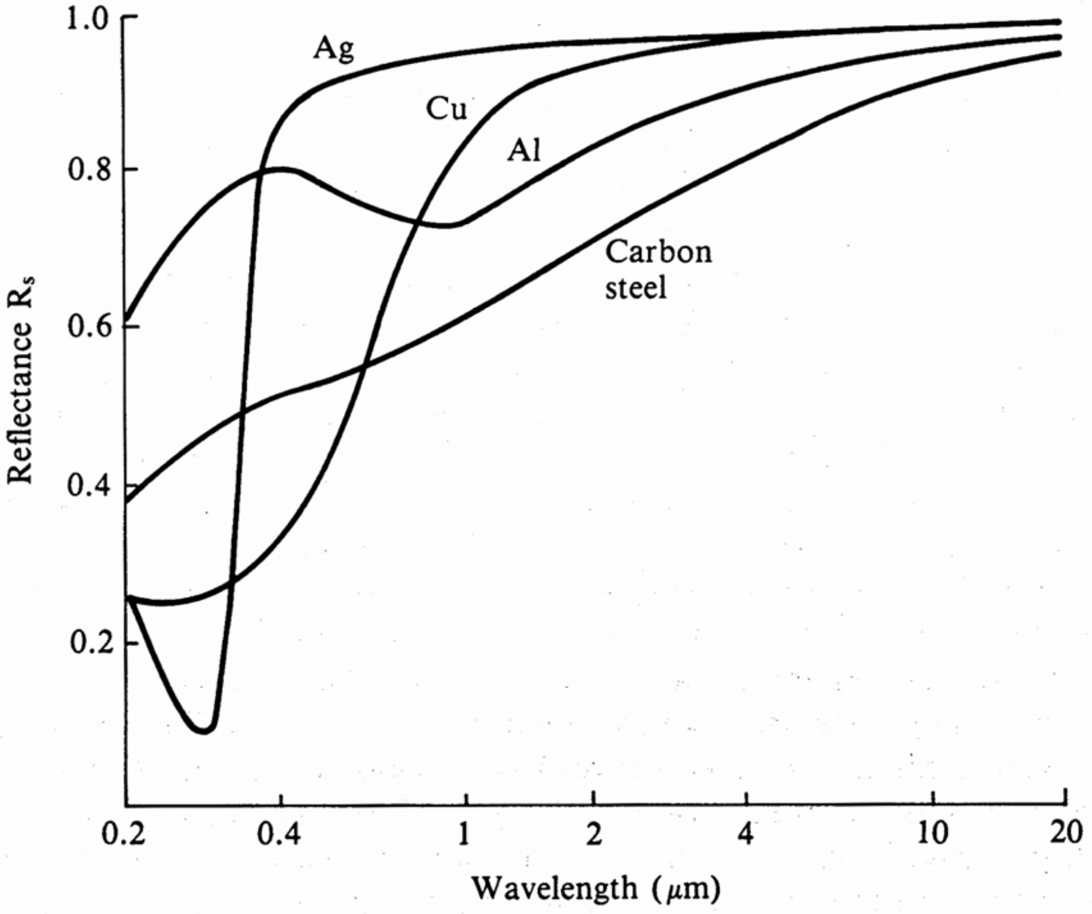


Fig. 5.1 Reflectance versus wavelength for various polished metal surfaces.

Temperature Dependence

- Absorption and reflectivity are very temperature dependent
- Often undergo significant changes when material melts
- eg Silicon, steel becomes highly reflective on melting

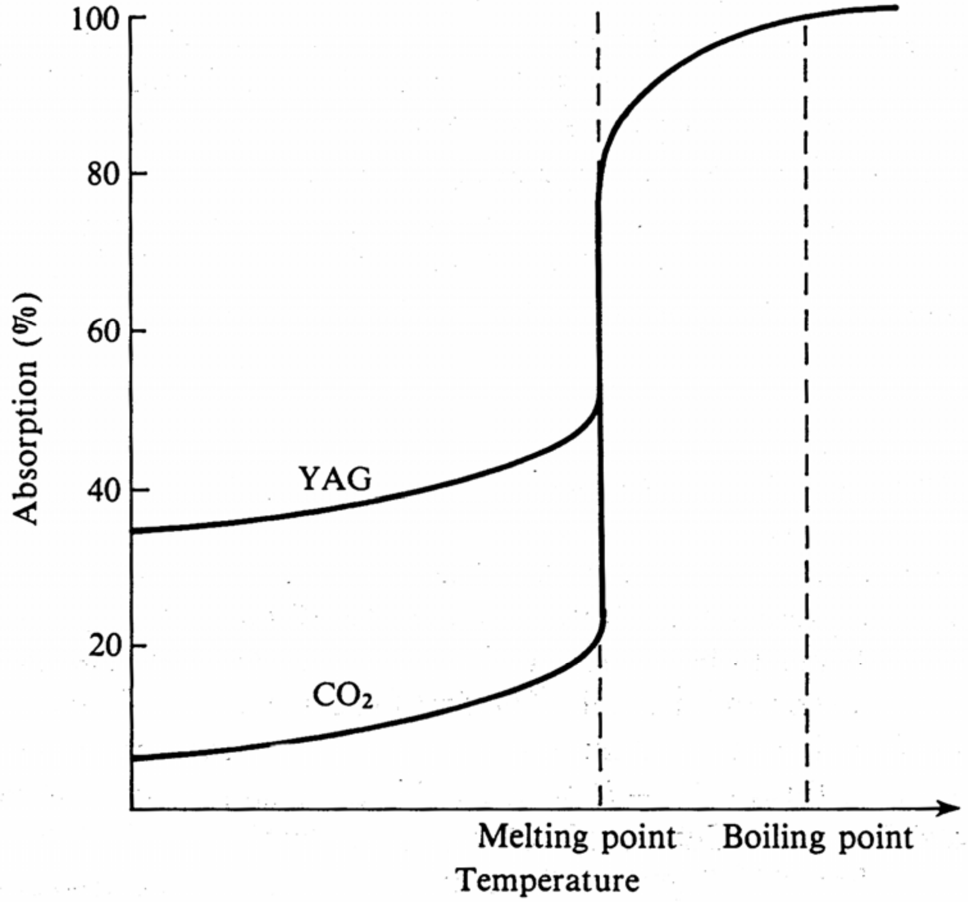


Fig. 5.2 Schematic variation of absorption with temperature for a typical metal surface for both the YAG and CO_2 laser wavelengths.

Scattering

- Within a medium light can be absorbed or scattered
- Ideally scattering does not absorb light but only changes direction
- But may remove energy from light (change wavelength)
- Generally occurs with non-homogeneous mediums
- Highly material specific
- Dominant effect in air. fog and turbid media e.g. tissue
- As object moves into fog it becomes blurred
- Reason – scatted light contains little information about object
- Scattered light hides the object with distance
- E.g. objects in fog disappear when scattering gets high enough

Effects

- Non-deterministic wave propagation
- Focusing of light not really possible
- Bolus or large ball of light created

References

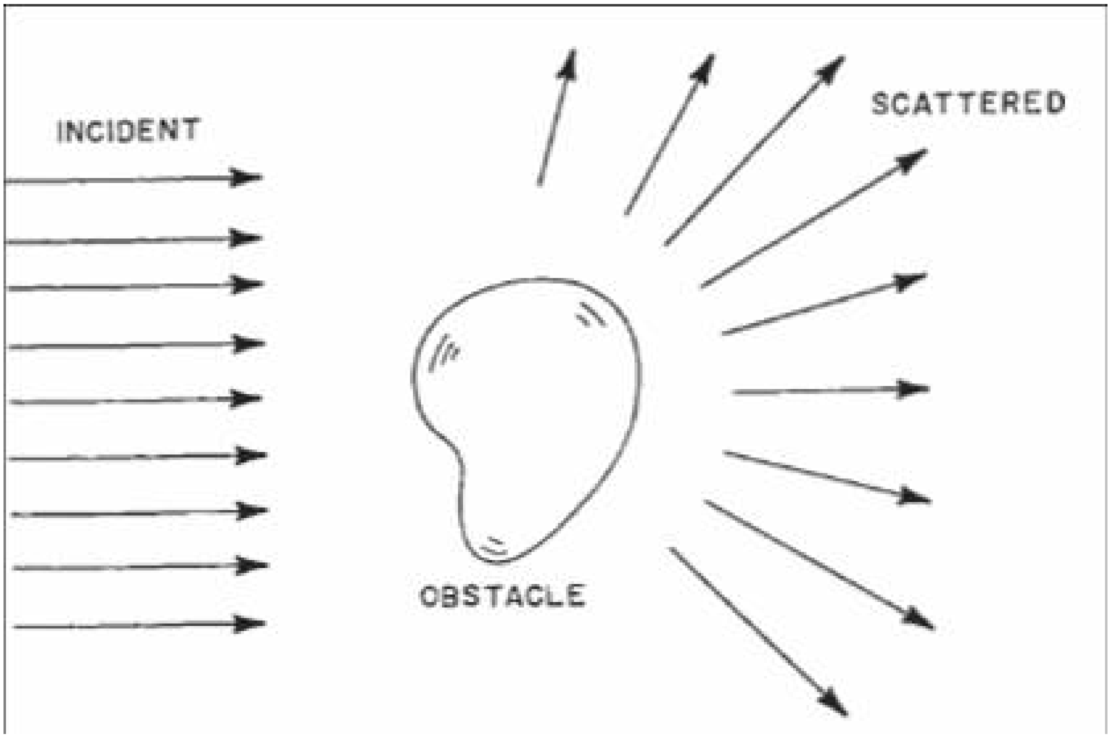
- Oregon Medical Laser Center: http://omlc.ogi.edu/
- Prof. Jacques online notes
- used images from it in much of this presentation

What is Scattering?

- Scattering occurs when light interacts with a particle
- Particle has different index of refraction than medium
- Dominant effect in fog and turbid media e.g. tissue
- In solids like tissue constituent cell and sub-cellular creates
- Depends on particles in the medium
- e.g. Clouds, fog in air (particles are water)
- Depends on particle size, and index of refraction change
- Wavelength dependent

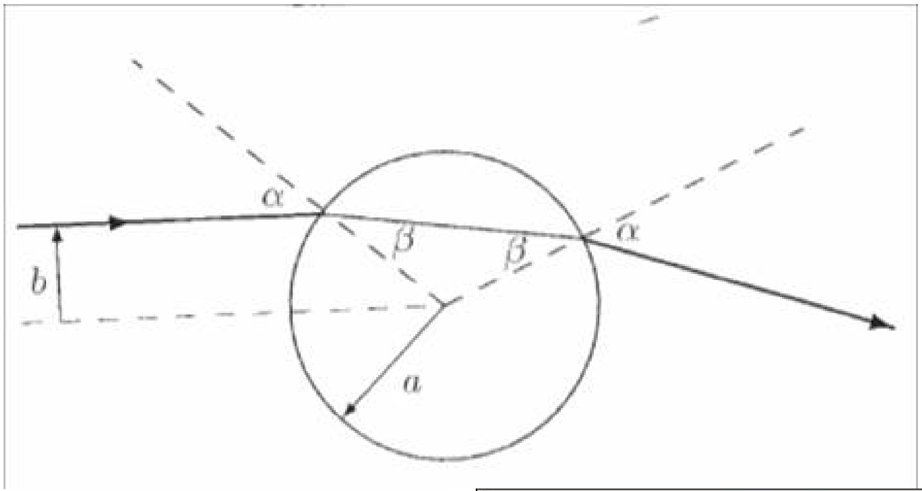
Classical description

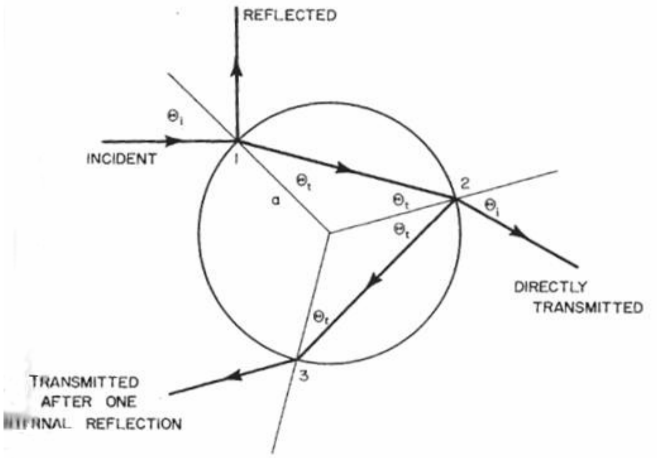
- EM wave interacts with the electron cloud
- Electric charges are set into oscillatory motion
- Energy re-radiated in all directions
- Absorption & scattering are thus related
- Similar mathematical expressions

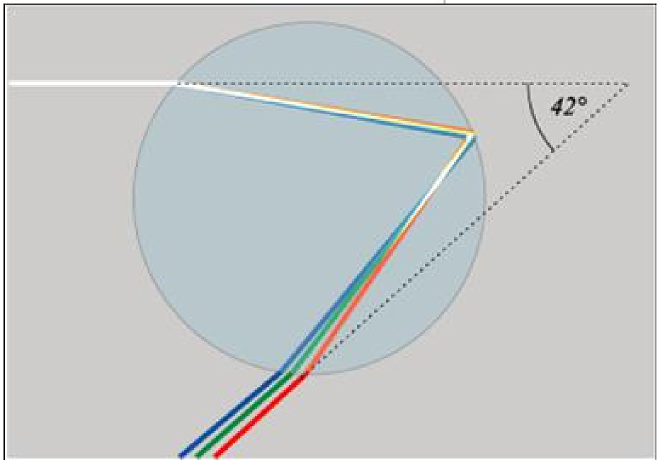


Classical Scattering

- Scattered particles assumed to be dielectric spheres with index n
- e.g. water droplet in fog
- Light entering sphere is bent
- Follows Snell's law: distance b from center set angle α & n sets β
- Bent again on exit
- Due to dispersion (change in n with λ) different directions with λ
- example the rainbow: light from behind droplets
- Rainbow – red on top (least deviated) violet bottom (most)
- If light bright enough in front then two rainbows
- Changes in angle is within Total Internal Reflection
- Beam bounces 2nd time and exits near original direction
- Creates a second rainbow, but revered (red bottom, violet top)
- Full scattering: higher density particles so many scatterings
- The objects begin to disappear into scattered light







Types of Scattering

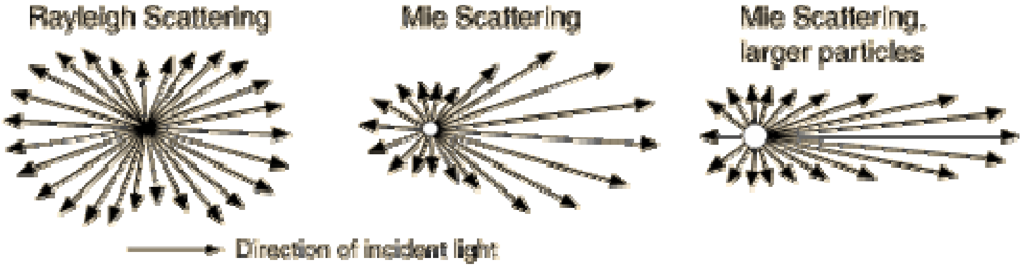
- Two types of scattering

Elastic scattering

- No change in energy
- $\lambda_{in} = \lambda_{out}$
- Classical example: collision of two billiard balls
- Two types of elastic scattering depending on particle size
- Rayleigh scattering: particles with size << λ
- Mie Scattering particle is spherical with size~> λ

Inelastic scattering

- Energy from the light is absorbed by the scatterer
- $\lambda_{in} > \lambda_{out}$
- Classical example: silly-putty thrown against the wall energy absorbed in shape deformation
- Brillouin scattering, Raman scattering: light interacts with phonons or excitons (energy packets in material)
- E.g. also occurs when electron ejection by incident photon
- Associated with short wavelengths (UV and X-ray)
- These are ionizing radiation (breaks atomic bonds)
- Will not consider this here (only elastic)



Scattering With Depth

- When light in absorbing medium follows Beer Lambert Law
- With μ_a = absorption coefficient (cm^{-1})

$$I(z) = I_0 \, exp(-\mu_a z)$$

- Scattering also follows Beer's Law but with scattering portion
- Now add scattering coefficient μ_s (cm^{-1})
- Combined effect of absorption+ scattering is

$$I(z) = I_0 \, exp(-[\mu_a + \mu_s]z)$$

- Here we measure not how much light leaves material,
- But rather how much light continuous along original path
- Called Ballistic Photons
- In tissue, μ_a and μ_s are very different
- Both are wavelength dependent
- Both exhibit molecular specificity
- Typical values in breast tissue
  @λ~635nm: μ_a =0.2cm^{-1}, μ_s =400cm^{-1}
  @λ~1000nm: μ_a =0.2cm^{-1}, μ_s =50cm^{-1}
- Also use Mean Free Path (MFP) = 1/μ

Scattering Coefficient

- Assume particle with index n is causing scattering
- Then scattering coefficient is related to size of particle
- Define **Scattering Cross Section** = σ_s (cm^2)

$$\sigma_s = QA_s$$

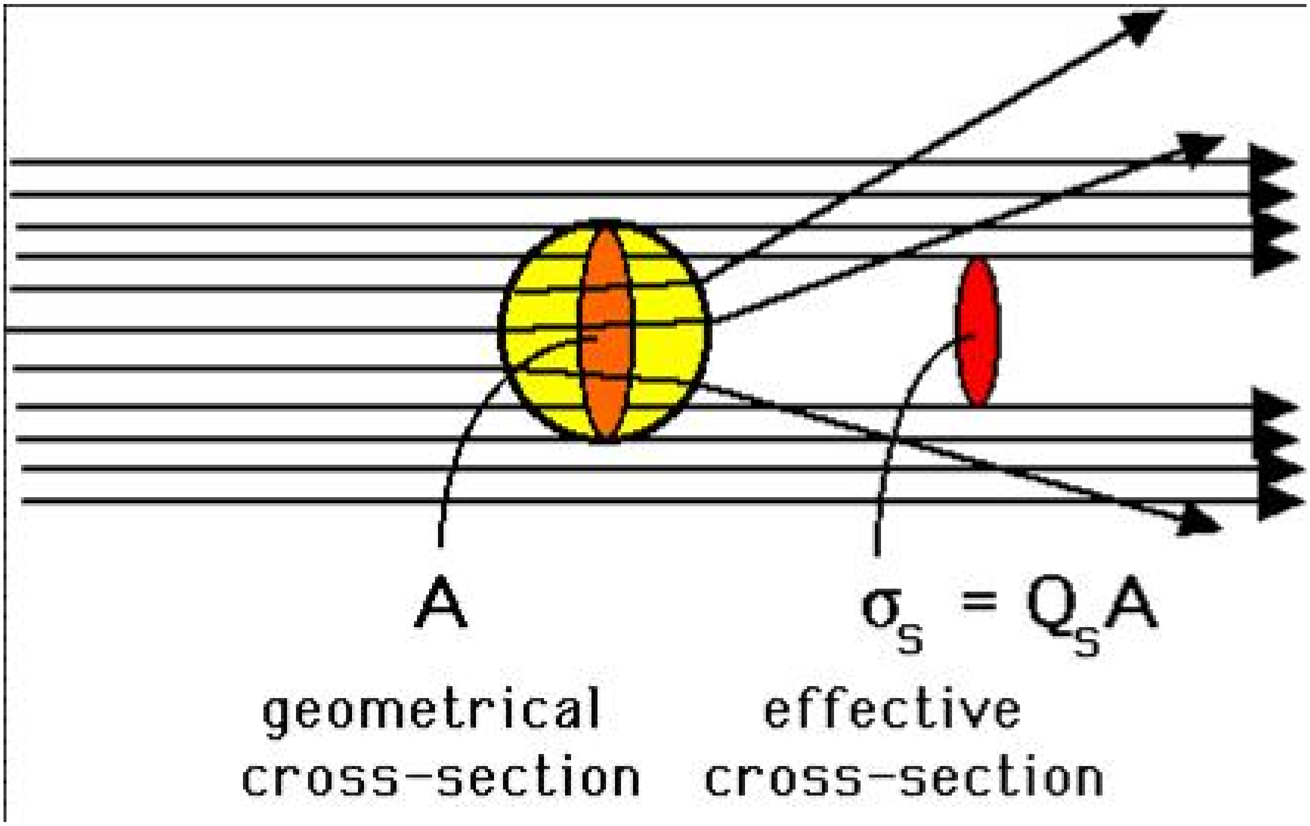
Where A_s = actual cross section of particle

Q = fractional scattering efficiency

- Scattering coefficient is related to particle density and cross section

$$\mu_s = \rho_s \sigma_s$$

- Where ρ_s is the density of scattering particles per volume (cm^{-3})
- Thus more particles, more scattering

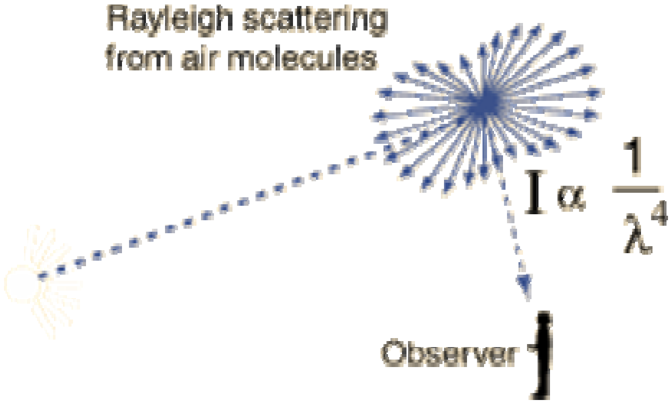


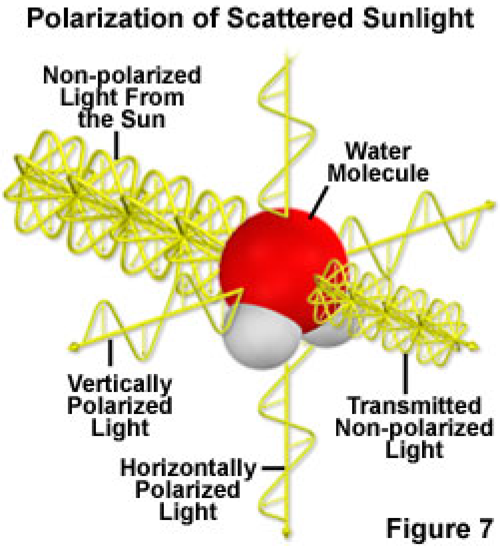
Rayleigh Scattering

- Rayleigh scattering occurs when particle is << λ
- E.g. scattering from molecules or atoms
- Scattering cross section is now strongly related to wavelength

$$\sigma_s \propto \frac{1}{\lambda^4} \quad \text{thus} \quad I \propto \frac{1}{\lambda^4}$$

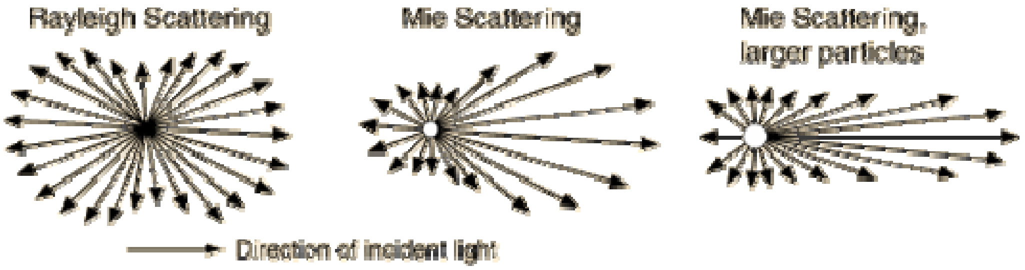
- Has to do with EM wave interaction with electron cloud of atom
- Thus blue light is highly scattered
- Red light is almost unscattered
- Thus sky appears blue
- Setting sun red because all blue scattered away
- Blue is removed from sunlight traveling in air & scattered to us
- Rayleigh results in different polarization in different direction
- Thus use polarizering filters to darken blue of sky in photography

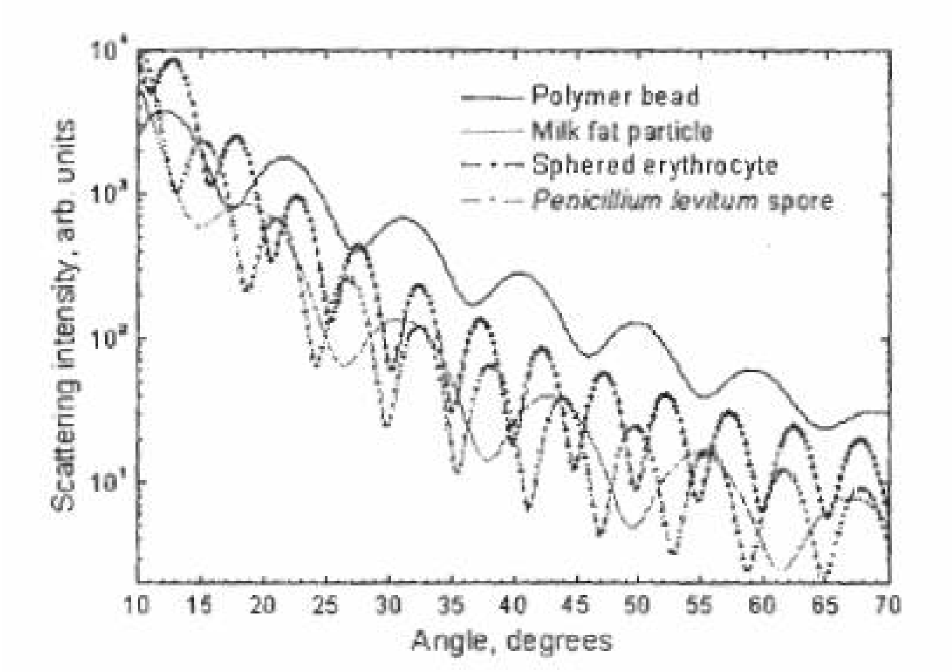




Mie Scattering

- Mie Scattering particle is spherical with size~> λ
- Comes from general solution for scattering from a dielectric sphere
- Series solution to wave equation
- Weakly wavelength dependent
- Hence white appearance of clouds and fog
- Mie scattering is not same in all directions: anisotropic
- Get more forward scattering
- Anisotropy increases with particle size
- Angular intensity scattering dependence related to
  Dielectric constant of sphere
  Dielectric constant of medium
  Size of sphere





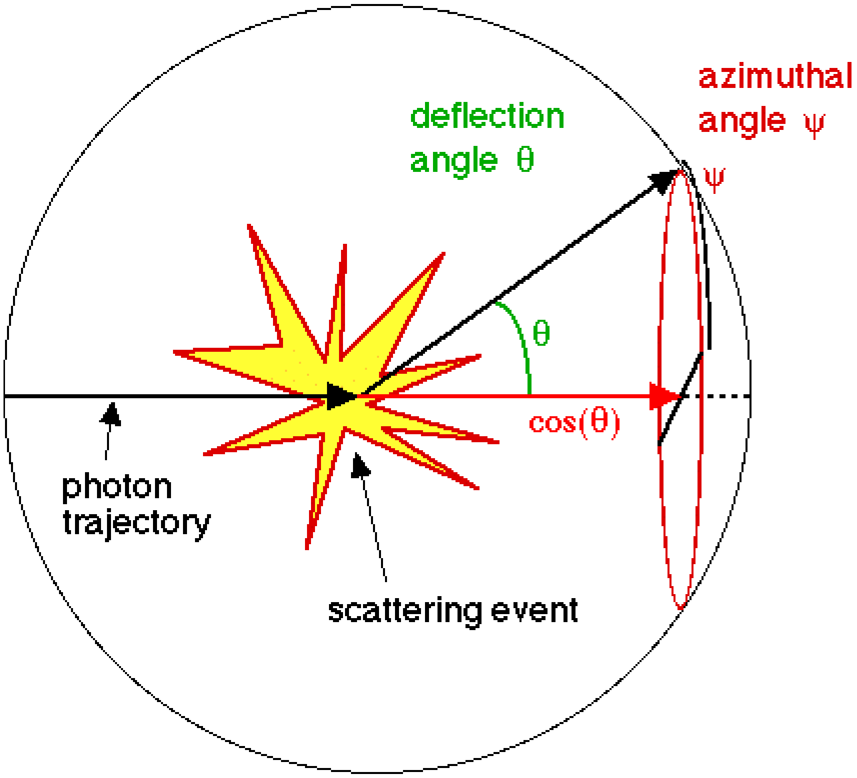
Anisotropy in Scattering

- Many materials are Mie like scattering
- Have distribution in direction of scattered light
- Consider a single photon scattering event
- After scattering get deflection angle θ relative to initial path
- Scattering function (Phase function) p(θ) (in sr^{-1}) is probability of scattering into angle θ where

$$\int_0^{\pi} p(\theta)\, 2\pi\, sin(\theta) d\theta = 1$$

- Shape of phase function varies with different material
- Isotropic scattering would have p(θ) a constant of

$$p(\theta) = \frac{1}{4\pi}$$



Anisotropy Factor

- Many phase functions define an Anisotropy Factor g

$$g = \langle cos(\theta) \rangle = \int_0^{\pi} p(\theta)\, cos(\theta) 2\pi\, sin(\theta) d\theta$$

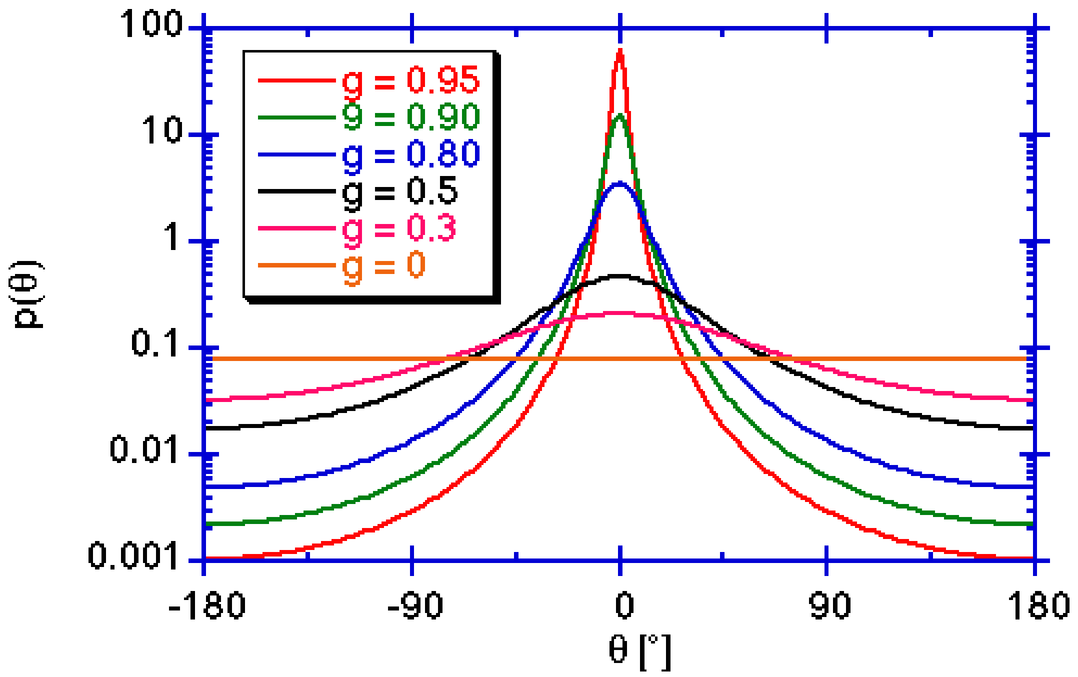
- g is average scattered photons into cos(θ) over all directions

g = 0 means isotropic scattering
g = 1 is total forward scattering
g = -1 total reverse scattering (ie reflection)

- In most materials 0 < g <1
- Many materials, eg tissue, follow the Henyey-Greenstein function

$$p(\theta) = \frac{1}{4\pi} \frac{1 - g^2}{\left[1 + g^2 - 2g\, cos(\theta)\right]^{3/2}}$$

- HG function comes from scattering in interstellar clouds
- Tissue approximately follows HG function with g ~0.8-0.98



Anisotropy and Reduced Scatter Factor

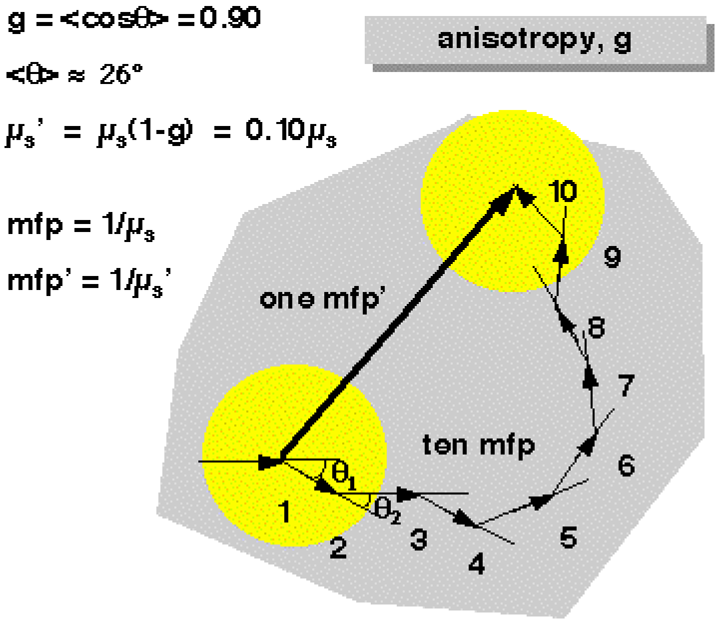
- Effect of anisotropy is to alter scattering
- With g near 1 effectively reduces effect of scattering significantly
- Get an effective scattering coefficient μ_{eff} (or μ') where

$$\mu_{eff} = \mu_s(1 - g)$$

- μ_{eff} adds up the effect of a random walk of scatters
- Mean Free Path becomes

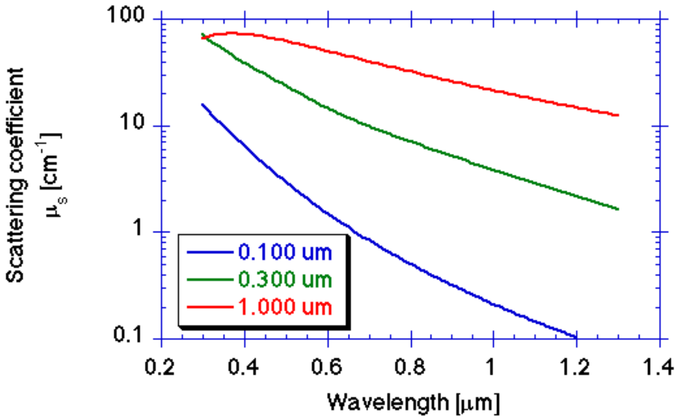
$$MFP = \frac{1}{\mu_{eff}}$$

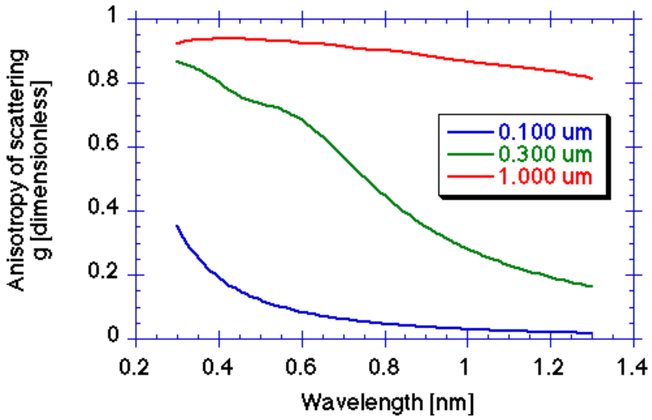
- With g=0.9, then $\mu_{eff} = \mu_s/10$
- Note if g = 1 (full forward scattering) $\mu_{eff} = 0$
- Reason: fully forward scattering photon continues in original path
- Scattering has nill effect

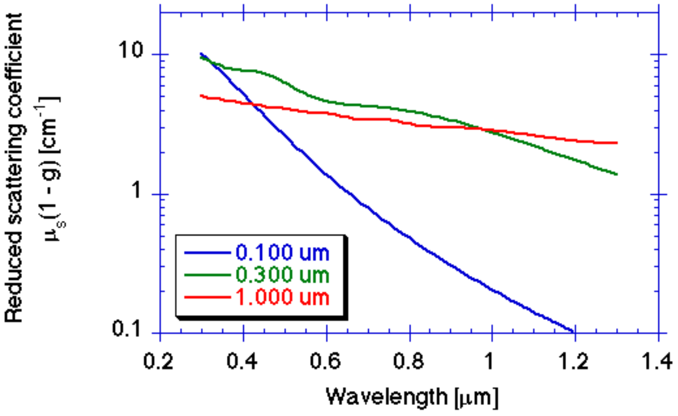


Mie Scattering and g factor

- Can calculate μ_s and g factors directly for Mie scattering
- e.g. Consider sphere n=1.572 in medium n= 1.332 (~water)
- Look at spheres of 0.1, 0.3 and 1.0 microns with 0.1% of solution
- 0.1 micron has strong decline of scattering and g with λ
- 1.0 micron only modest scattering and g change with λ
- Tissue covers these ranges







Diffusion of Photons in Scattering Media

- Light entering scattering medium breaks into different types

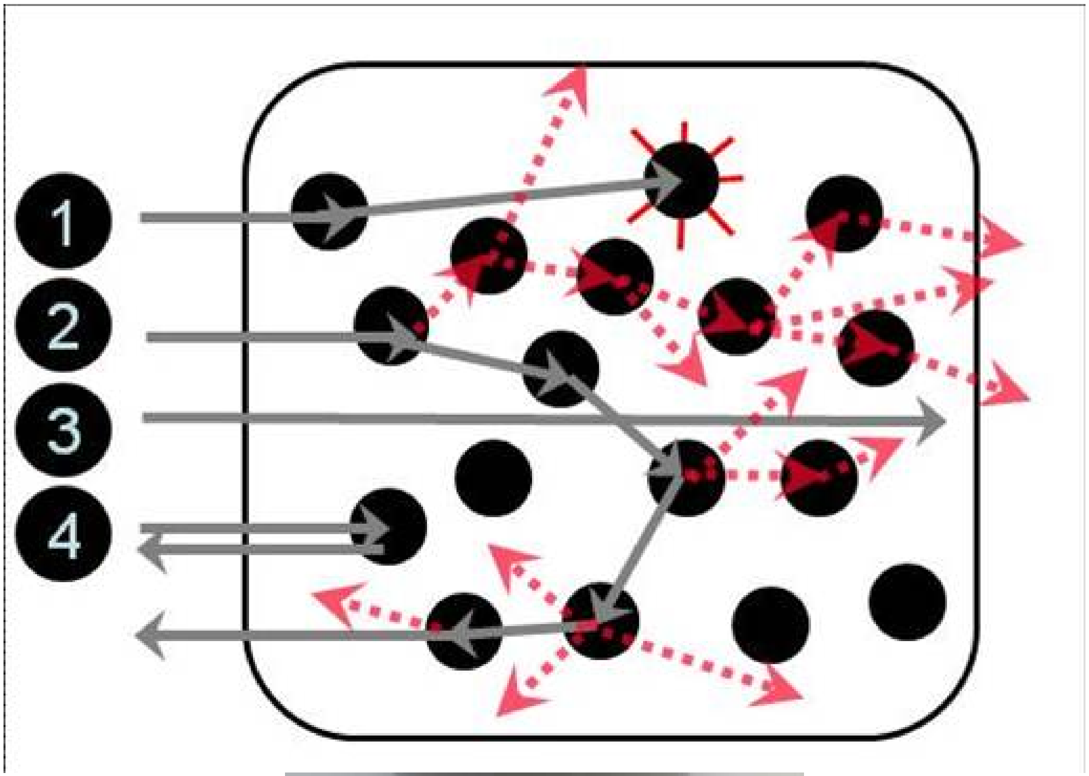
1 Photons may be absorbed

2 Photons may be highly scattered (many paths) until nearly uniform
Scattered photons lose almost all information of internal structure

3 Photons may travel without scattering: called Ballistic photon
If photon scattered: but nearly ballistic path called quasi-ballistic

4 Photons may be reflected back from the medium

- What is seen depends on ratio of each
- Thin fog – some scattered but ballistic dominates: contrast reduced
- Thicker fog – scattered total overwhelms ballistic
  Objects disappear



Light Injected into Scattering Medium

- What happens when light injected into scattering medium
- Penetrates until mostly scattered
- Forms a “Glow Ball” nearly spherical scattering sphere
- More light, larger ball, deeper depth of penetration
- Only small amount of ballistic light continues