Radiation transfer in environmental sciences

Lecture 3. Interaction of radiation with surfaces

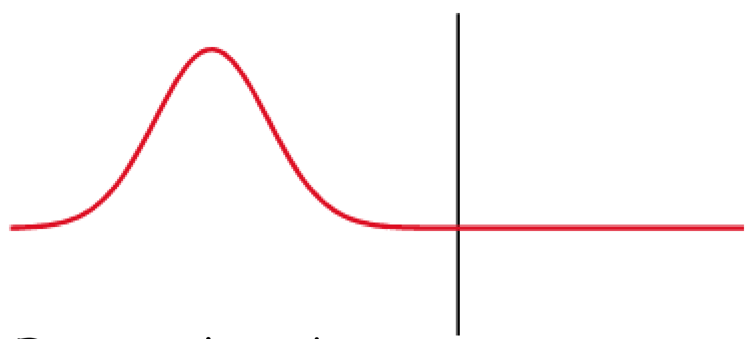
Upcoming classes

When a ray of light interacts with a 'surface', several interactions are possible:

1. It is absorbed.
2. It is reflected (scattered, specular/diffuse).
3. It is transmitted into the material.

These interaction are important as both the radiance field directionality and magnitude may change following this interaction.

Thermal emission by the surface (e.g. a source) are sometime also considered as part of these process.



From: wikipedia

The index of refraction:

$$N = n_r + i n_i$$

n_r-controls the phase speed of light relative to a given medium (often vacuum).
n_i -describes the absorption by the wave.

Note: the two are related (Kramer-Kronig relations)

Related to the dielectric constant (relative permittivity-$\varepsilon/\varepsilon_o$).
For non-magnetic materials:

$$N^2 = \varepsilon/\varepsilon_o$$

ε is more convenient when we want to compute the index of refraction of a mixture.

In most problem we are interested in the relative index of refraction, e.g. particles in water (μ-permeability).

$$N^2 = \varepsilon_r \mu_r$$

The index of refraction varies with wavelength – (dispersion)→ separation of spectra using prism. For most materials the longer λ the smaller n (normal disp.).

Some important concepts/principles:

During the interaction with surfaces, radiant energy must be conserved.

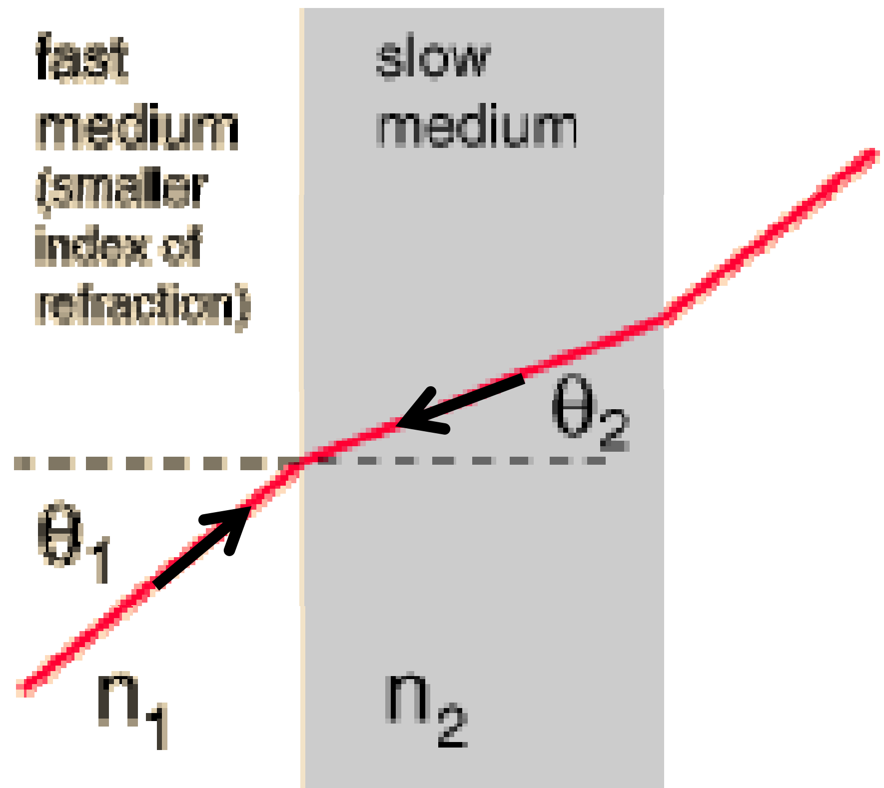
Reciprocity: if a light ray follows a certain path the same path will be taken in the opposite direction if we replace the source and receiver geometry (very important for Monte Carlo simulations).

Effect due to an interface:

Refraction (Snell's Law):

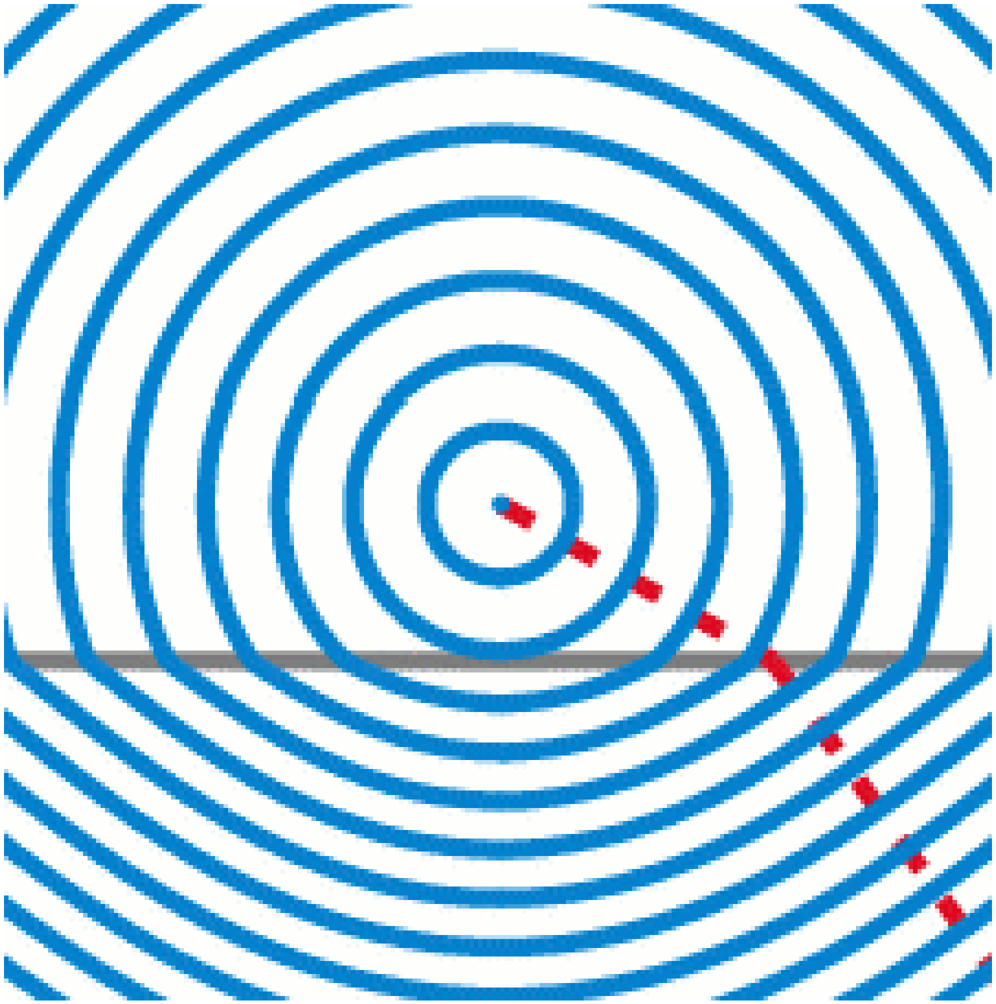
Snell's Law

$$\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1}$$



http://hyperphysics.phy-astr.gsu.edu/hbase/geoopt/refr.html#c3

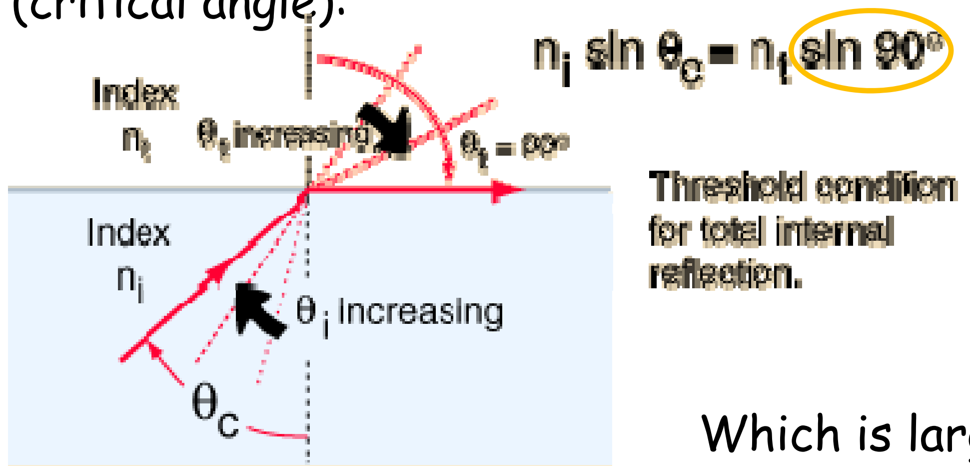
Another view (Feynman's lifeguard):



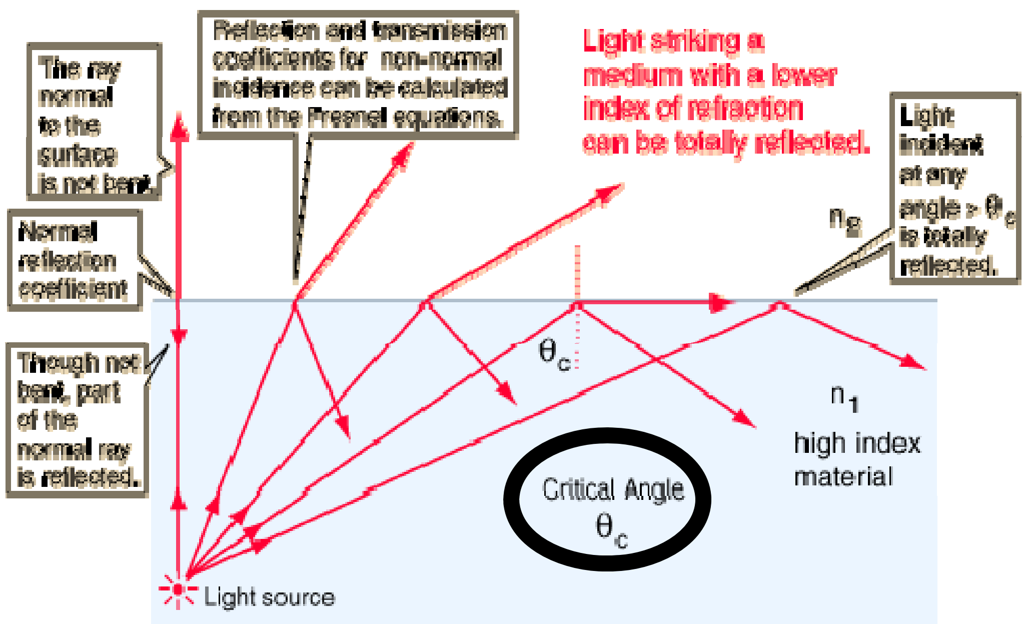
From: Wikipedia

Effect due to an interface

Refraction & Reflection (critical angle):



Which is larger, n_i or n_t?



Air and water:

$n_i/n_t \cong 1.33$,
$\theta_c \cong 49°$

http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/totint.html#c1

Effect due to an interface

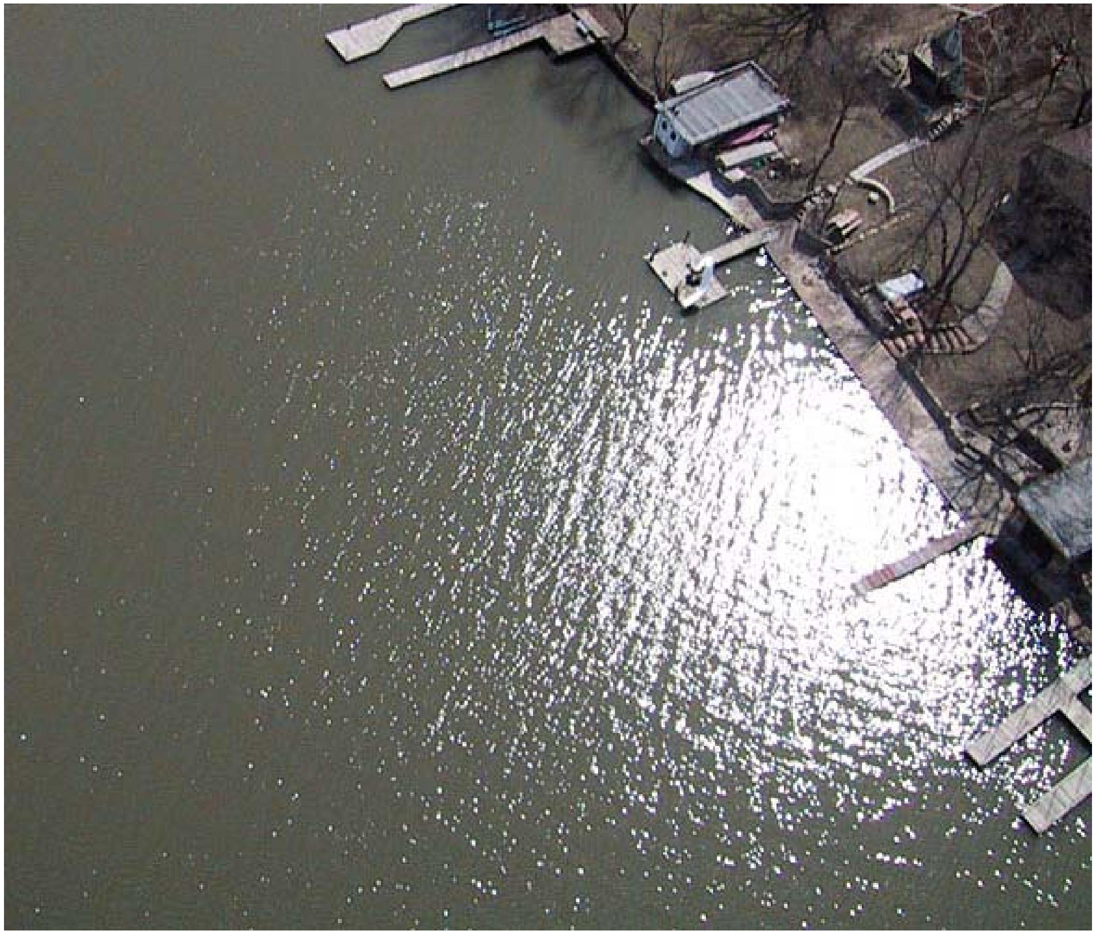
Refraction (Snell's cone/window):

www.maths.uwa.edu.au/~adrian/scuba/log743.html

www.seafriends.org.nz/phgraph/f042305t.jpg

Effect due to an interface

Specular reflection (Sun glint):
Directionality of specularly reflected beam: $\theta_r = \theta_i$, $\phi_r = \phi_i + 180°$



Effect due to the interface

Fresnel (specular) reflection

Reflectivities (derived from Maxwell's equations, translated to plane waves + BCs, for nonmagnetic substances, Bohren and Huffman, 1987):

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

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

Polarization plane

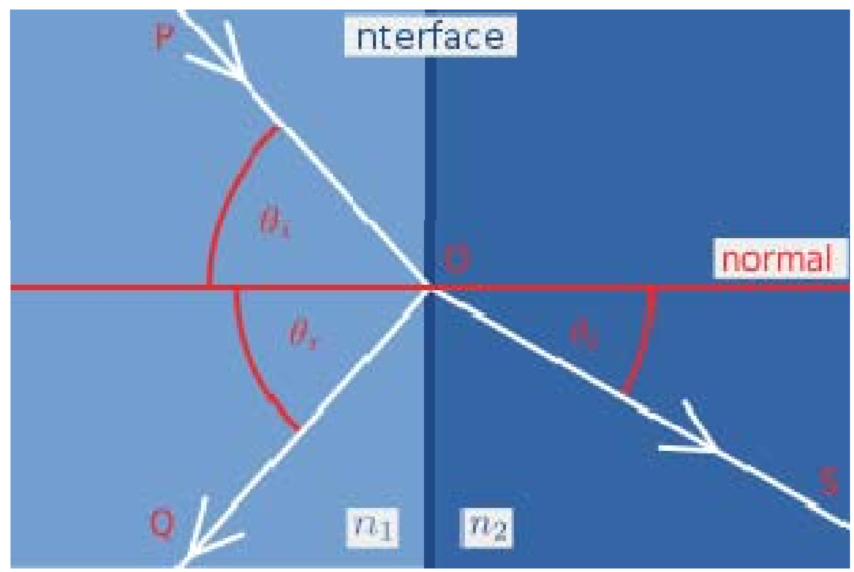
$R=0.5(R_s+R_p)$

Transmittance (T)=1-R

Normal incidence:

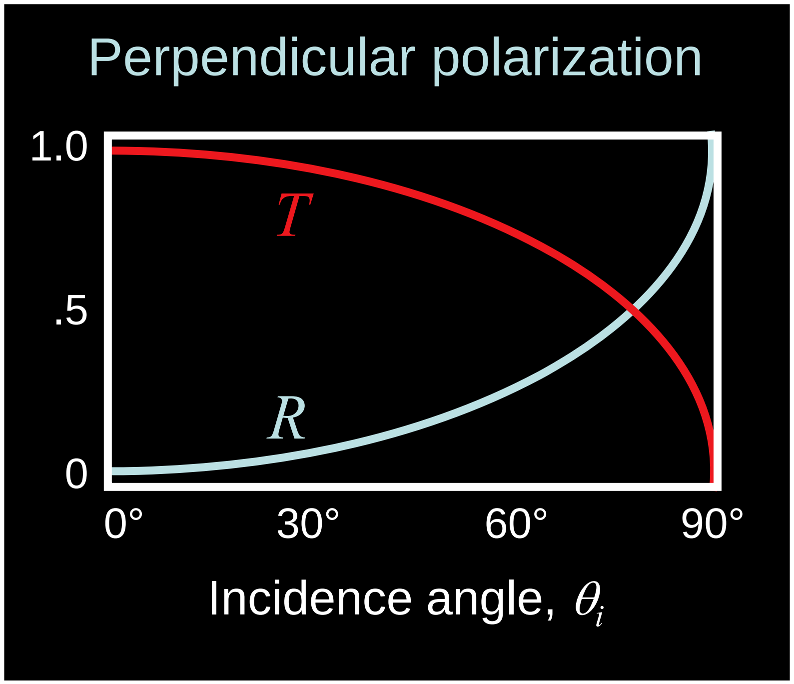
$$R = R_s = R_p = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2$$

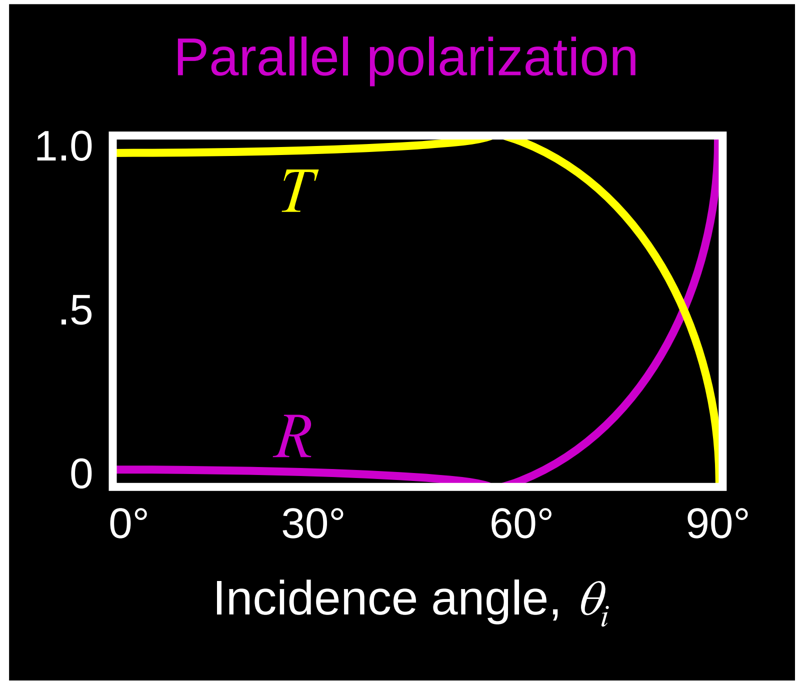
$$T = T_s = T_p = 1 - R = \frac{4n_1n_2}{(n_1+n_2)^2}$$



From: wikipedia

Reflectance and Transmittance for an Air-to-Glass Interface





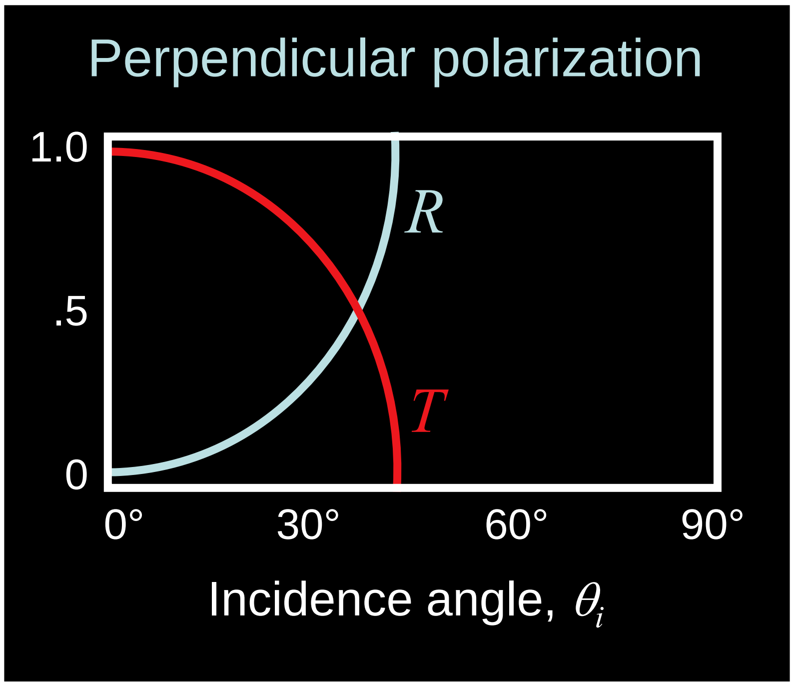
Brewster angle: $\theta_B = \tan^{-1}\left(\frac{n_2}{n_1}\right).$

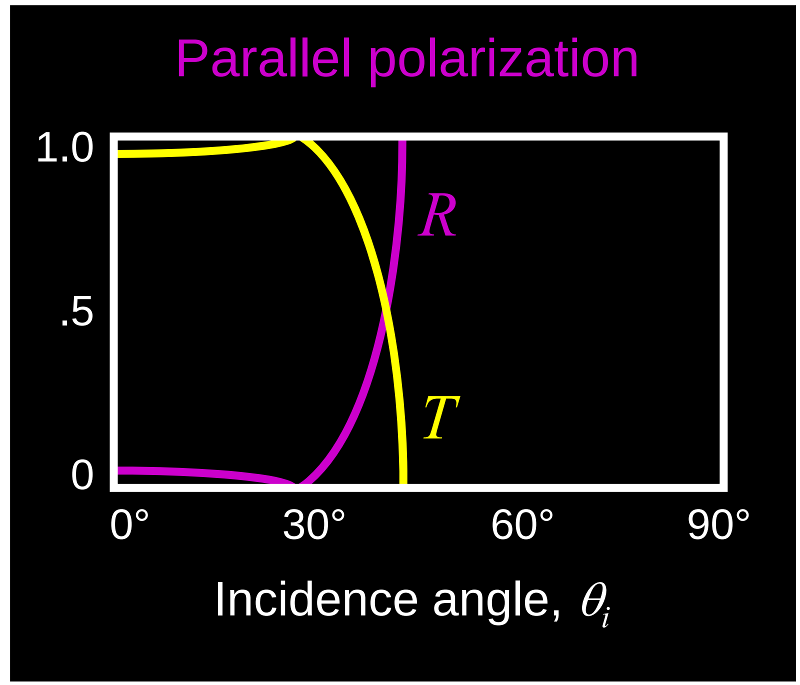
θ_b=53° air→water

Note that $R + T = 1$

http://www.physics.gatech.edu/gcuo/UltrafastOptics/3803/OpticsI09FresnelsEqns.ppt

Reflectance and Transmittance for a Glass-to-Air Interface





Note that $R + T = 1$ θ_b=37° water→air

http://www.physics.gatech.edu/gcuo/UltrafastOptics/3803/OpticsI09FresnelsEqns.ppt

Specular reflectance at the air-sea interface

Table 2.1. *Reflectance of unpolarized light from a flat water surface. The values of reflectance have been calculated using eqns 2.12 and 2.15, assuming that the water has a refractive index of 1.33*

Zenith angle of incidence, θ_a (degrees)	Reflectance (%)	Zenith angle of incidence, θ_a (degrees)	Reflectance (%)
0.0	2.0	50.0	3.3
5.0	2.0	55.0	4.3
10.0	2.0	60.0	5.9
15.0	2.0	65.0	8.6
20.0	2.0	70.0	13.3
25.0	2.1	75.0	21.1
30.0	2.1	80.0	34.7
35.0	2.2	85.0	58.3
40.0	2.4	87.5	76.1
45.0	2.8	89.0	89.6

As a function of sun angle

As a function of sun angle

And wind speed

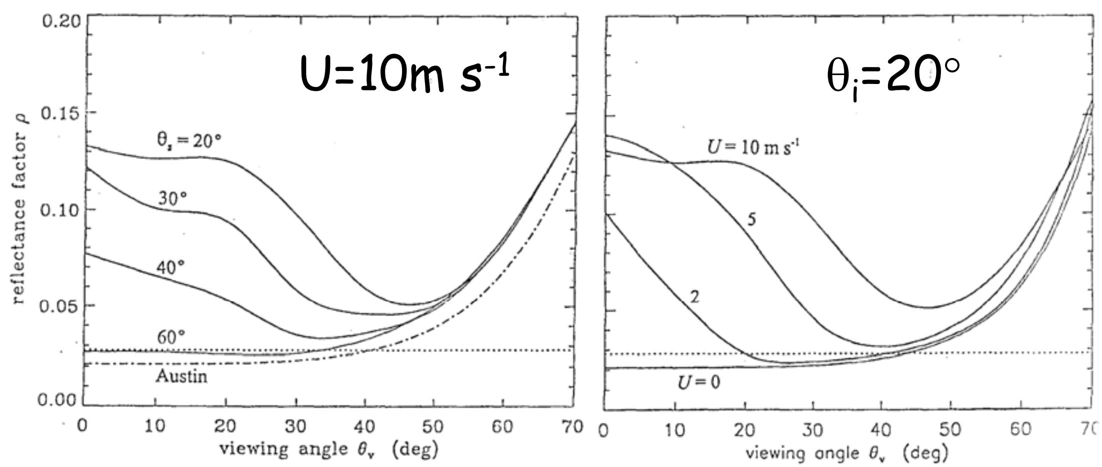


Fig. 7. Effects of sun glitter on ρ. The wind speed is $U = 10$ m s^{-1} and the sky has a non-uniform radiance distribution characteristic of a clear sky; θ_s is the solar zenith angle. The dash-dot line is Austin's c rve from Fig. 5.

Effect of wind speed U on ρ for a sun angle of $\theta_s = 20°$ and a clear-sky radiance distribution.

Effect due to the interface:

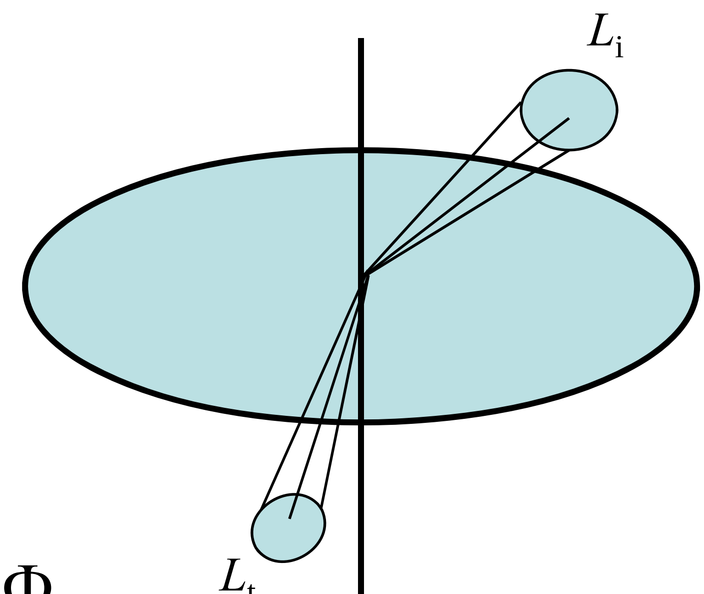
Immersion effects, n^2-law of radiance (energy conservation)

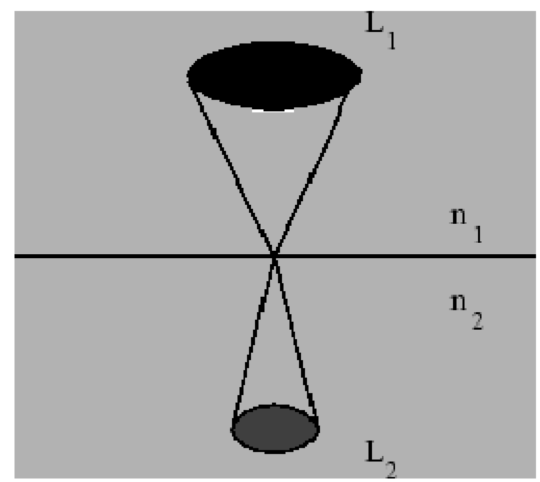
$$\Delta\Omega = \sin\theta d\theta d\phi$$

$$n_t \sin\theta_t = n_i \sin\theta_i$$

$$\rightarrow n_t^2 \sin\theta_t \cos\theta_t d\theta = n_i^2 \sin\theta_i \cos\theta_i d\theta$$

$$\rightarrow n_t^2 \cos\theta_t d\Omega_t = n_i^2 \cos\theta_i d\Omega_i$$





$$L \equiv \frac{\Phi}{\Delta A \Delta\Omega}$$

$$T = \frac{\Phi_t / \Delta A_1}{\Phi_i / \Delta A_2}$$

$$\rightarrow \frac{L_t}{L_i} = T(\theta_i)\frac{n_t^2}{n_i^2}$$

Note: L_t can be larger than L_i

http://omlc.ogi.edu/pubs/prahl-pubs/prahl88/node95.html

Reflection from natural surfaces.

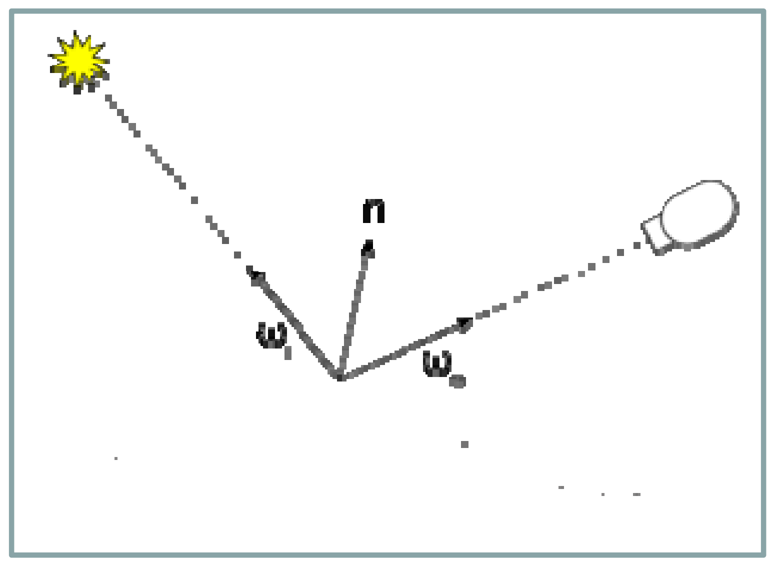
R and T defined above apply to irradiances.

Irradiance reflectance is in fact: $R \equiv \frac{E_u}{E_d}$

The Bi-directional reflection distribution function (BRDF):

$$BRDF \equiv \frac{L_r(\Omega_r)}{E_i(\Omega_i)}$$

Units? How does one measure it?



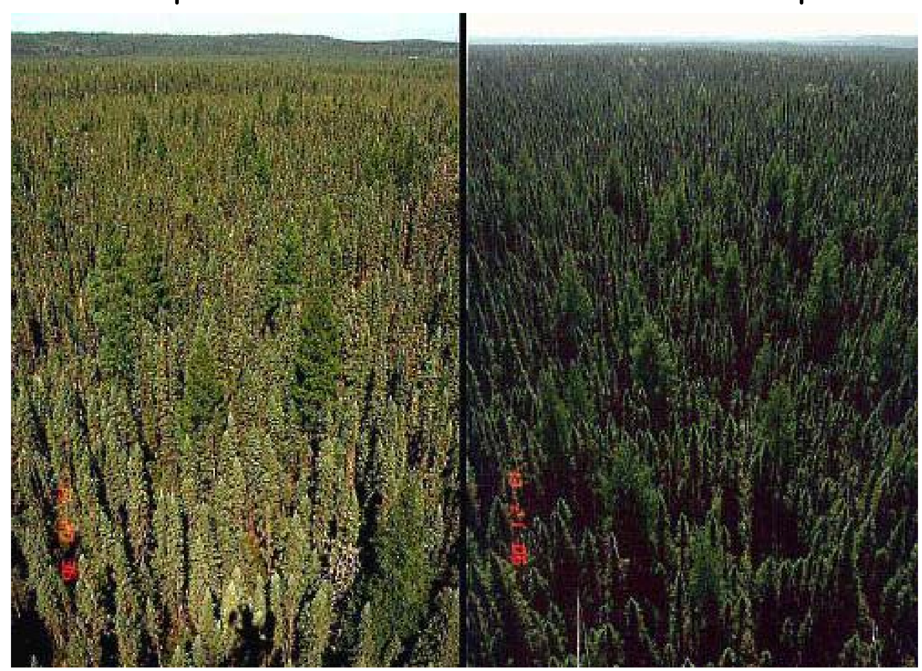
From: wikipedia

Example of light field reflected from natural surfaces.

Concepts:

Shadows
specular reflection
Hot spot (backscattering)

Pictures from: http://www-modis.bu.edu/brdf/brdfexpl.html

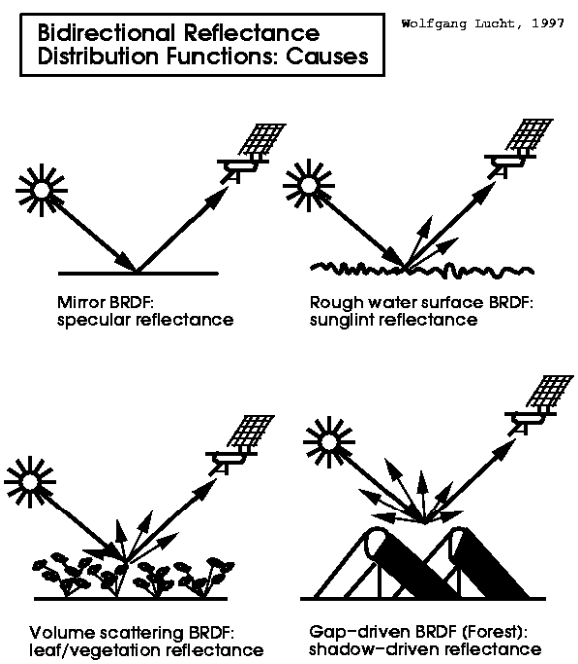


Basic models of BRDFs:

1. Lambertian surface: BRDF is independent of direction of observation and direction of incidence: $L = \dfrac{\rho}{\pi} E$

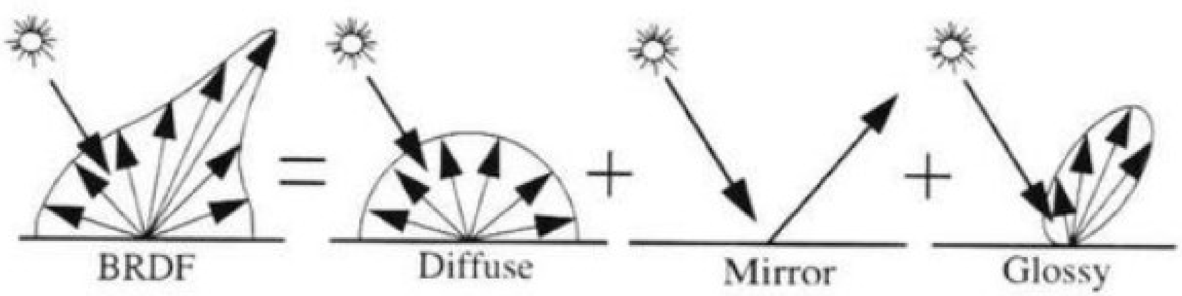
2. Specular: $$BRDF \propto \delta(\theta_i)\delta(\phi_i + 180°)$$

For more models see, e.g., Thomas and Stamnes.



Calculation the radiance when the BRDF is known:

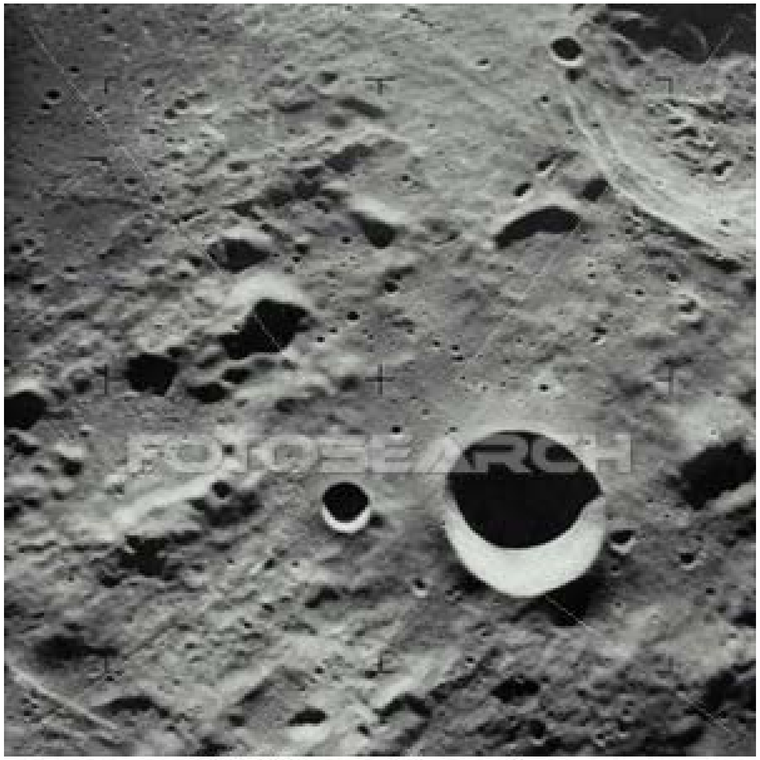
$$L(\Omega_r) = \int_{2\pi} BRDF(\Omega_i;\Omega_r) E(\Omega_i) d\Omega$$



http://www.vetscite.org/publish/articles/000063/index.html

What about macro surface features?

What ρ should we use?



aa053565 www.fotosearch.com

For a Lambertian surface and a collimated source:

$$\rho_{\mathrm{eff}} = \rho\langle\cos|\theta_z - \theta_b|\rangle$$

http://www.stmarysmedia.co.uk/jb19/project/Wind.htm

More @ Zaneveld and Boss, 2003

Albedo, emissivity and reflectivity

Until now all we described are spectral concepts (narrow band).

We ignored absorption and the possibility that the surface emits light.

In general:

$$E_{\lambda,r}(\theta_r,\phi_r) = R(\lambda,\theta_i,\phi_i,\theta_r,\phi_r)E_{\lambda,i}(\theta_i,\phi_i)$$

And:

$$R(\lambda,\theta_i,\phi_i,\theta_r,\phi_r) + A(\lambda,\theta_i,\phi_i,\theta_r,\phi_r) = 1$$

Ignoring angular dependence and lambertian reflection

$$E_{\lambda,u} = R(\lambda)E_{\lambda,d} \quad \Rightarrow \quad \Delta E = E_{\lambda,d} - E_{\lambda,u} = A(\lambda)E_{\lambda,d}$$

Albedo, emissivity and reflectivity

Integrating the irradiance over a wide band (~ assuming a constant absorptivity, grey-body approximation), we define the 'Albedo':

$$\overline{R}_{\Delta\lambda} \equiv \frac{E_u}{E_d}$$

Not a bad assumption if E_d ~ flat spectrally (why?).

Albedo, emissivity and reflectivity

In the 1st lecture we talked about black-body radiation. Natural bodies emit less than a black-body, and we define the ratio as the emissivity:

$$\varepsilon_\lambda \equiv \frac{E_{\lambda,u}}{\pi B_\lambda(T)}, \text{ where}: B_\lambda(T) = \frac{2hc^2}{\lambda^5\left(e^{hc/k_B\lambda T}-1\right)}$$

Broadband 'grey-body' emissivity:

$$\varepsilon_{\Delta\lambda} \equiv \frac{E_{\Delta\lambda,u}}{\pi\int_{\lambda_1}^{\lambda_2} B_\lambda(T)\,d\lambda}$$

Wide enough spectral gap:

$$\varepsilon \equiv \frac{E_u}{\sigma T^4}$$

Albedo, emissivity and reflectivity

Kirchhoff's law: in local thermodynamic equilibrium:

$$\int_0^\infty \varepsilon_\lambda E(\lambda)d\lambda = \int_0^\infty A_\lambda E(\lambda)d\lambda$$

From the 'principle of detailed balance' (time reversal symmetry of Maxwell's equ.) it follows that:

$$\varepsilon_\lambda = A_\lambda$$

It is most common to apply this law to broad-band radiation.

Next week: interaction of light with matter

Rainbow tutorial on U-tube:
http://www.youtube.com/watch?v=rQukmSPctks