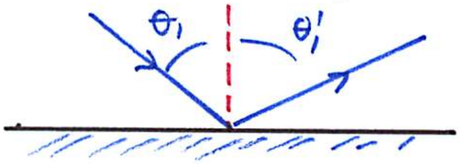
**Reflection:** When light reflects from a surface that is smooth on the scale of $\lambda$, then we have *specular reflection*, such that $\theta_1 = \theta_1'$.



**Refraction:** When light propagates through a transparent gas, liquid or solid, light is being continually absorbed by atoms or molecules, and then re-emitted, typically within $10^{-8}$ sec. The result is that, while the light is travelling always at $c$ when it is travelling, it takes longer to get through the material. Its effective speed $v$ is less than $c$. This is parametrized by the index of refraction: $n = c/v$. Note therefore that the product $n_i v_i$ is always $c$, for any material $i$.

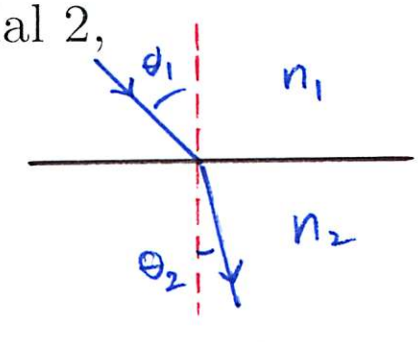
It is also vital to note that the frequency of the light is unaffected. Because the effective speed is different, however, the effective wavelength is different. $\lambda = c/f$ becomes $\lambda' = v/f$ which is LESS than $\lambda$ in a vacuum.

By drawing the waves lying along the rays, it is easy to show that

$$n_i \sin\theta_i$$

is the same constant for all materials. Thus for an interface between material 1 and material 2,

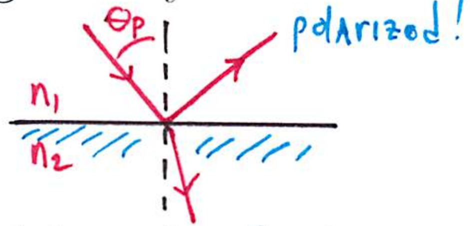
$$n_1 \sin\theta_1 = n_2 \sin\theta_2, \text{ etc.}$$



**For gases** the index of refraction depends on temperature, and $n(T)$ decreases as the temperature increases, since the density of the material decreases as the temperature increases. This leads, on earth, to phenomena such as mirages.

**Brewster's Angle** There is a certain $\theta_p$ which results in a reflected ray being completely polarized parallel to the surface. This angle is given by

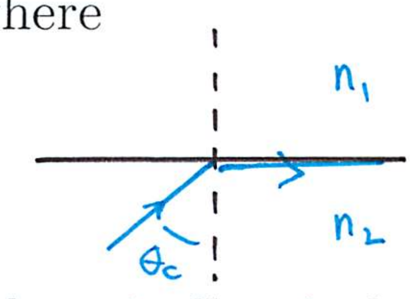
$$\tan\theta_p = n_2/n_1,$$



where the ray is incident from material 1 and reflects from a surface of material 2.

**Total Internal Reflection** occurs when a ray in medium 2 encounters an interface with region 1, and $n_2 > n_1$. The ray will be totally reflected for any angle of incidence greater than $\theta_c$, where

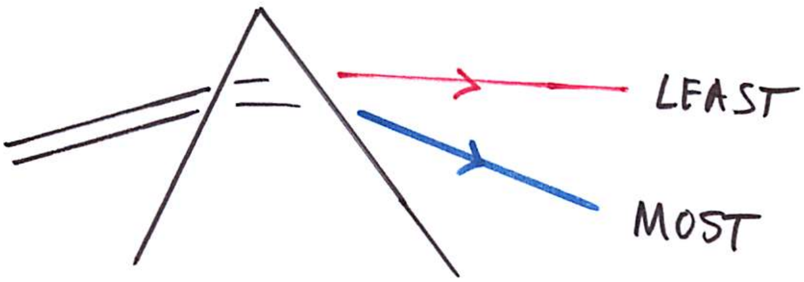
$$\sin\theta_c = \frac{n_1}{n_2}.$$



Fiber optics are a beautiful and technogically vital example of media which "pipe light" for huge distances. This is also a sharp-boundary version of a mirage.

**DISPERSION:** In fact, in transparent materials, $n$ is a strong function of wavelength or frequency. The value of $n$ increases as the wavelength decreases, or the frequency increases. [For most transparent materials there is a resonance in the ultraviolet region!]

As Newton demonstrated, a wedge-shaped piece of glass will disperse white light into its component frequencies, with the longest wavelengths deflected the least, and the shortest wavelengths deflected the most.



# Metamaterials and n $<$ 0!

Since 1967 physicists have been exploring systems with a *negative index of refraction.* These materials usually consist of an array of identical elements that act as antennas or resonators when electromagnetic radiation passes through them. Such materials are currently the focus of extremely intense research. Various remarkable technological possibilities exist for these systems, including "superfocussing lenses" that produce sharp images of details *much smaller than the wavelength of the electromagnetic radiation used to form them,* something that sounds like a physical impossibility but is in fact easily achieveable.