EGR491 Notes: Optics, Part II

Refs, some cited, some not:

1. https://cosmosmagazine.com/physics/what-is-light
2. http://www.canon.com/technology/s_labo/light/001/11.html
3. Optics, Eugen Hecht (Addison-Wesley publising)
4. Fundamentals of Physics, Halliday and Resnick
5. Telescopes and Eyepieces Astrographs, Smith et al.
6. How to Make a Telescope, Texereau

Wave Propagation

Frequency, wavelength, speed – The frequency (f) describes how quickly the wave cycles. The most common unit of frequency is the Hertz (Hz) which is cycles per second. The wavelength (λ) is the distance between two peaks of the wave. The speed (c) is the rate at which the wave propagates. These are related as: $\lambda = c/f$

Diffraction – Waves do not travel in straight lines, they "fan out" as they propagate. This is why you are able to hear someone speaking to you from around the corner. This has been observed in optics where two small slits are placed in a screen. The slits are small if they are comparable in size to the wavelength (Figure 1). As coherent monochromatic light strikes the slits, the slits act as point sources of light. Light propagates radially from the slits. An interference pattern may be observed some distance away where the waves have constructive and destructive interference.

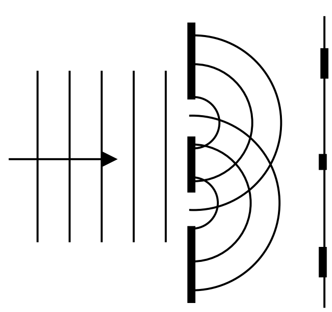


Figure 1 - Diffraction of a wave due to two slits.

The angle of diffraction is directly related to the wavelength. Since the wavelength of light is very much less than that of sound, light diffraction is much less noticeable.

Reflection – as a wave propagates from one medium to another, some portion of the wave's energy will be reflected. The angle of reflection will equal the angle of incidence (see Figure 10.2).

Refraction – As a wave moves from one medium to another the direction of the wave will change if the wave speed differs in the two media. This is known as refraction. If a straight stick is place in a pool of water, it will appear bent at the water's surface. It is not bent, rather the light coming from the immersed stick is bent. This is basic principle for lenses. Snell's law provides a quantitative measure of the change in direction (see Figure 10.2):

$$\sin(\alpha) / \sin(\beta) = c_1 / c_2$$

where α is the angle of incident wave, β is the angle of the transmitted wave, c_1 is the speed of the wave in Medium 1 and c_2 is the speed of the wave in Medium 2.

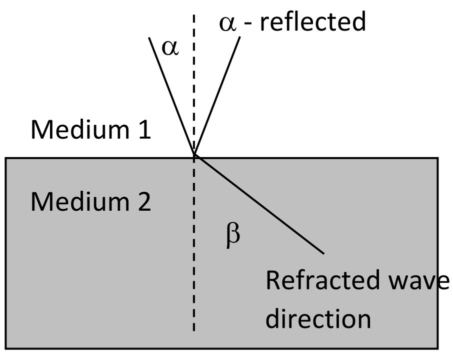


Figure 2 – Angle of reflected and refracted waves.

Interactions - For a wave to interact with a change in the medium it is traveling in, the object causing the change must be at least as large as the wavelength. For example, the slots shown in Figure 1 must be at least one wave length in width, or the wave will not be able to pass through. Conversely, if a wave is to reflect off of an object, the object must be at least one wavelength in size, or else there will be very little interaction between the wave and the object. This is one reason high frequency waves (short wave length) are more sensitive to anomalous conditions. It also is why higher frequency interrogation results in better resolution.

Attenuation – As a wave propagates, the energy may become dissipated through diffraction, scattering and absorption. The attenuation of waves is often a function of the frequency. In sound waves, higher frequencies are more readily absorbed and scattered. This is why you can easily hear low frequency (BOOM, BOOM, BOOM) but not high frequency sounds (screech, screech, screech) coming from your friend's car stereo when they shut their door.

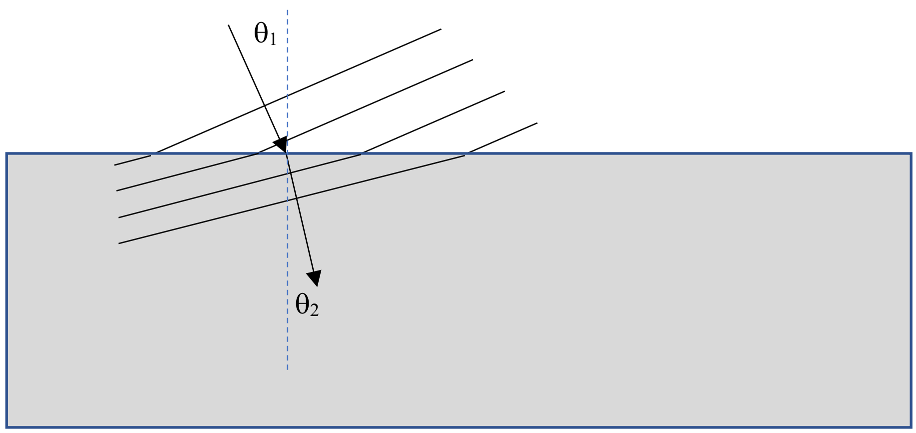
Geometric Optics

Geometric optics allows optical designers to trace the path of light through lenses and from mirrors. Light “rays” are assumed to travel is straight path, and lenses and mirrors redirect the path.

For waves, $\lambda = v/f$, where λ is the wave length (distance from peak-to-peak), v is the velocity, and f is the frequency (cycles per second, Hz).

Refraction

The velocity at which a wave is moving typically is a function of the material, but the frequency is not. Since the velocity changes as the wave moves from one medium to another, and frequency remains constant, the wave length, λ, is also affected. If velocity decreases, so does the wave length. Let’s look at a light wave traveling from air into glass. The velocity is slower in glass than air, therefore, the wave length must decrease. As a result, the light path curves.

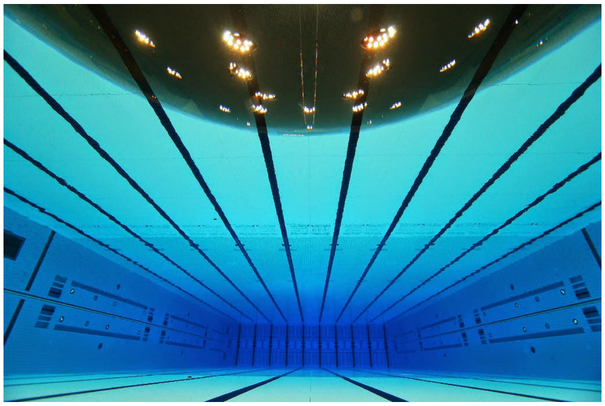


θ_1 is the angle of incidence and θ_2 is the angle of propagation. They are related through Snell’s law of refraction:

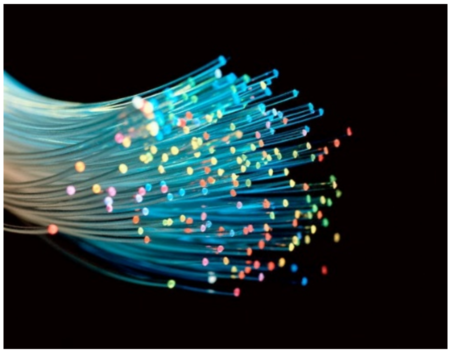
$\sin\theta_1/\sin\theta_2 = v_1/v_2 = \lambda_1/\lambda_2$ and obviously: $\sin\theta_2/\sin\theta_1 = v_2/v_1 = \lambda_2/\lambda_1$

v_1 and v_2 are the wave velocity in medium 1 and medium 2, respectively.
λ_1 and λ_2 are the wave length in medium 1 and medium 2, respectively.

Implication: if a wave is traveling in a medium with lower velocity than the adjacent medium, and if the angle of incidence is great enough, none of the wave will be refracted – all of it will be internally reflected. This is how fiber optics are able to carry light such great distances – all of the light is contained within glass fibers – none of the energy escapes. You may have noticed this effect while swimming underwater. You can see outside the water above your head, but when you look towards the edge of the pool, you cannot.

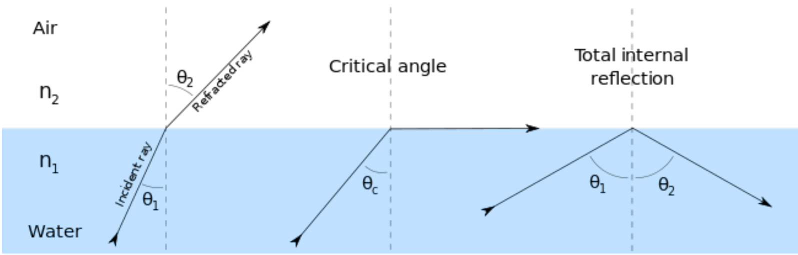


Photograph underwater – the arena lights are visible overhead, but total internal reflection occurs for higher angles. http://snc2p1.blogspot.com/2014/05/may-16-total-internal-reflection.html



Fiber optic bundle – no light escapes except through the ends.
http://snc2p1.blogspot.com/2014/05/may-16-total-internal-reflection.html

The “critical angle” is the minimum angle that causes total reflection.



Refraction for $v_2 > v_1$, critical angle (θ_2=90°), total internal reflection (no refraction). Wikipedia

For light waves, the following describes the index of refraction. For light, unless otherwise specified, the index of refraction (aka, refractive index) is with respect to a vacuum: n = c/v, and is always greater than or equal to 1 – until Einstein is proven wrong. n is the index of refraction, c is the speed of light in a vacuum, and v is the speed of light in the medium. If light is traveling from one non-vacuum medium to another, the refractive index is: $n_{21} = v_1/v_2$:

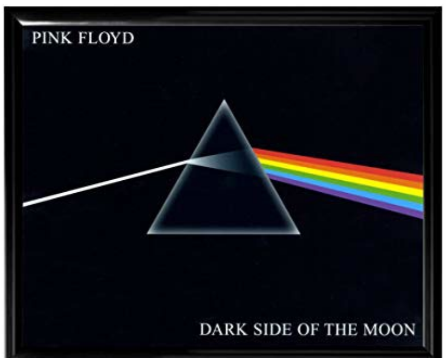
$$v_1/v_2 = n_2/n_1 = n_{21}$$

Where n_1 and n_2 are the refractive indices (with respect to a vacuum) for medium 1 and 2, respectively.

Some refraction-related data:

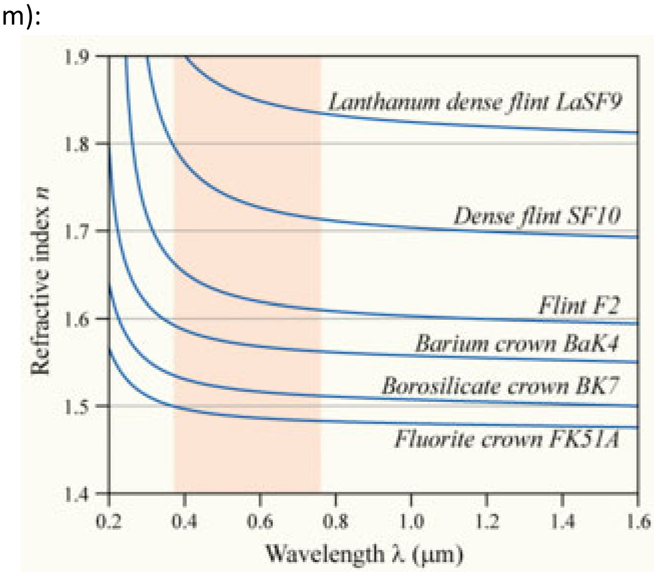
Light	Sound
Speed of light in a vacuum is about $300X^6$m/sec Speed of light in air is also about $300X^6$m/sec Refractive index of water: 1.3 Refractive index of glass: 1.5	Speed of sound in air (STP), v_{air} = 343 m/s Speed of sound in water, v_{water} = 1498 m/s Speed of sound in glass, v_{glass} = 4540 m/s

As with most things in engineering, we start out with generalization and approximate data. Often, that is "good enough" for design. For example, we often assume that the structure we are analyzing stresses in has "negligible weight". The above table provides that sort of data. In reality, the refractive index of most materials is a function of wave length. Most optical glasses bend short wave lengths (blue) more than longer wave lengths (red). This is how prisms and rainbows "split" white light:



https://www.howitworksdaily.com/what-causes-a-double-rainbow/

Also, "glass" is ambiguous, it's sort of like saying "metal." There are many different types of glass. The following shows the index of refraction for several different optical glasses (visible wave lengths range from about 390 to 700nm):

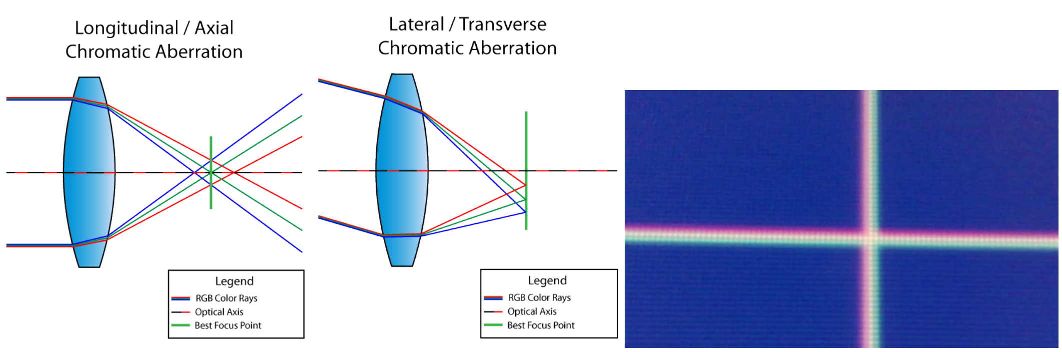


http://microscopy.berkeley.edu/courses/tlm/optics/chromatic.html

Dispersion: if the index of refraction is nearly constant regardless of wavelength, the material is said to have low dispersion. The index of refraction for highly dispersive materials changes more significantly with wavelength. If the graph above, fluorite crown glass and borosilicate crown glass have lower dispersion than dense flint. All materials have some degree of dispersion.

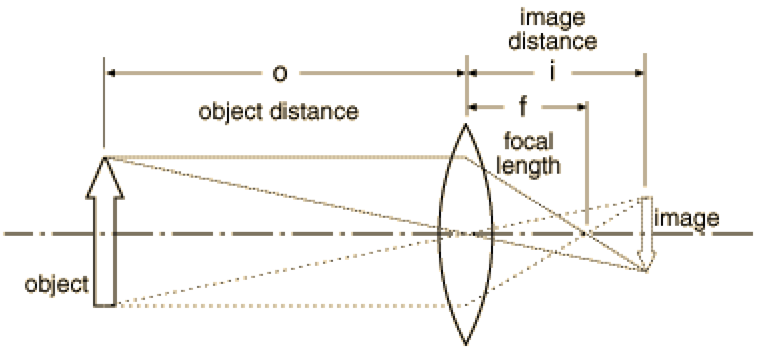
Implication: lenses bend light based on refraction. Since the amount of "bending" is a function of wavelength, different wave lengths will have different focal points. A certain amount of "rainbowing" will occur either symmetrically (rings of various colors around a star, aka "axial chromatic aberration") or asymmetrically (lateral chromatic aberation) where the star becomes stretched in one direction with varying colors. This is referred to as a chromatic aberration. Telescopes can be designed using multiple lenses to reduce or eliminate this effect. Achromatic telescopes are designed to bring red and blue light to the same focal point, but green is still out of focus. Apochromatic telescopes (aka *apo's*) have more complicated optics (multiple lenses) and hence are more expensive than achromatic, but effectively bring all wave length light to the same focal point. Achromatic telescopes are less expensive than apochromatic telescopes, but suffer from some amount chromatic aberration.

> *Greek: the prefix "a" (as in* achromatic*) means "opposed to". The prefix "apo" (as in* apochromatic*) means "very far away from." Achromatic telescopes are designed to reduce chromatic aberrations, apochromatic telescopes are designed to greatly reduce chromatic aberrations.*

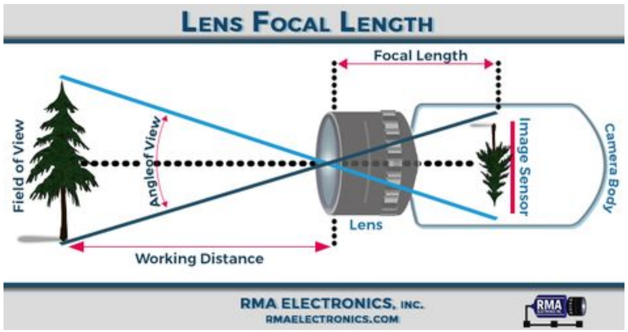


https://photographylife.com/what-is-chromatic-aberration, https://www.hometheatershack.com/forums/home-theater-projectors/10361-misconvergence-chromatic-aberration-post-screenshots-here.html

Lenses come in two basic designs: converging and diverging. A converging lens has a convex curvature which brings objects into focus at the focal plane.



http://hyperphysics.phy-astr.gsu.edu/hbase/Class/PhSciLab/imagei.html



https://www.pinterest.com/pin/452189618820504994

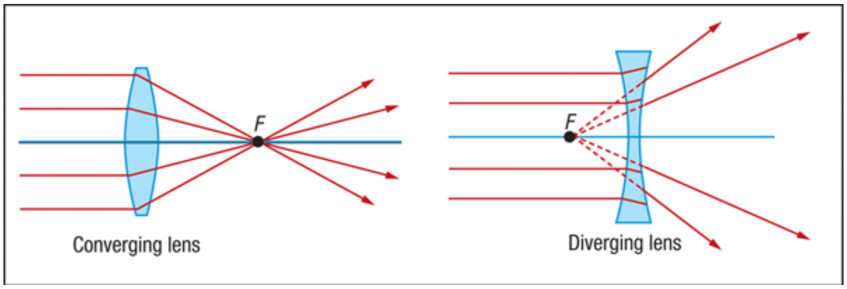
The lens equation: 1/(focal length) = 1/(object distance) + 1/(image distance)

Since the focal length is a fixed length for a given lens, as the object moves further away from the lens, the image distance approaches the focal length. The closer the object is to the lens, the further back the focal plane will be. All celestial objects are effectively "infinitely" far away.

Notice that the image is inverted (left becomes right, up becomes down). In telestial optics (such as binoculars) additional lenses and/or mirrors are used to produce a 'true' (not inverted image). However, since there is no "up or down" in space, inverted images through telescopes are not problematic. Since there is some amount of light lost through every lens and mirror, unnecessary optics are avoided.

Keep in mind that the optical direction can be reversed. A converging lens can be used to take a point source of light (such as a light bulb) and produce a focused beam.

Converging lenses take parallel rays of light and converge them to a point. Diverging lenses have convex curvature, and cause parallel rays of light to spread out (shown below).

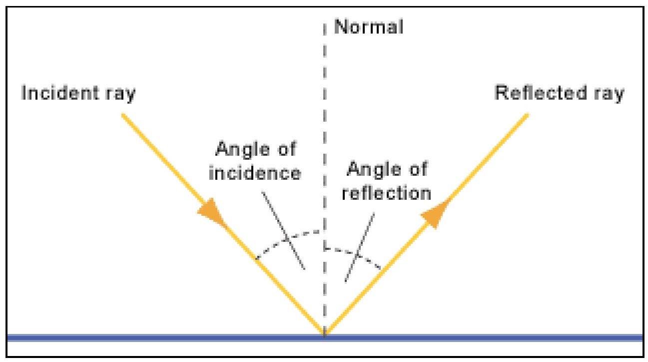


https://sciencefacts.net/wp-content/uploads/2015/12/Converging-Vs-Diverging-Lens.jpg

Reflection

Mirrors are used to change the path of light using reflection, just like lenses are used to change the path using refraction.

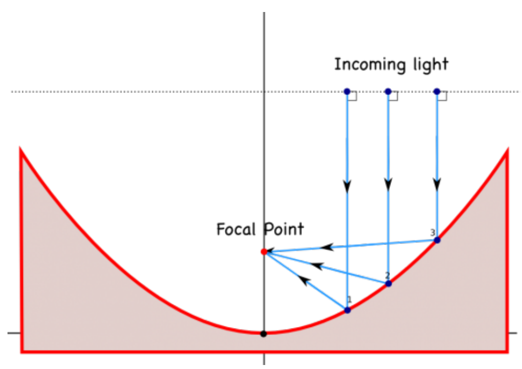
The law of reflection states that the incident ray, the reflected ray, and the normal to the surface of the mirror all lie in the *same plane*. Furthermore, the angle of reflection is *equal* to the angle of incidence. Both angles are measured with respect to the normal to the mirror.



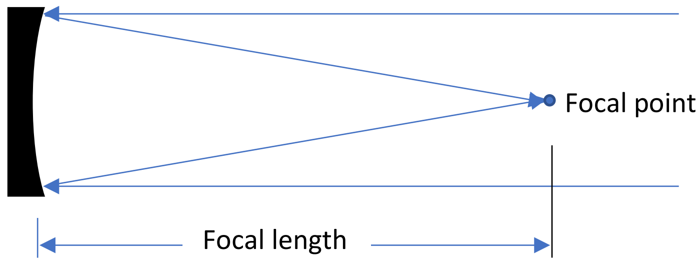
https://www1.curriculum.edu.au/sciencepd/readings/ligh_reflection.htm

Ideally, the surface of the mirror should be “optically smooth” – with no “ridges” or “valleys” bigger than the wave length being reflected. The same is true with lenses.

The primary mirror in telescopes have a paraboloid surface which will bring objects far away into focus at a point:



In telescopes, the amount of curvature is far flatter than the above image indicates. The focal point typically is 4 to 10 times the diameter away from the mirror. **<u>Never</u>** does the focal point lay within the mirror as is shown in the above sketch! The sketch below shows a typical focal length for telescope mirrors:



Since your eye (or camera) needs to be located near the focal point, the above arrangement will not work very well. If you put your head at the focal point, you will be blocking on the incoming star light. A flat secondary mirror is place in the optical path to redirect the light towards the side – a good place to put your eye! Typical reflector telescope optical arrangement: a parabolic primary mirror with a flat secondary mirror is shown here: