

Introduction to Biophotonics

Photonics uses photons to probe and manipulate matter. Since the invention of lasers in the 1960s, which provide an intense source of coherent radiation, photonics techniques have revolutionized several areas such as high-bandwidth communication channels. The development of ultrafast lasers, which are capable of producing laser pulses with pulse widths as low as a few femto-seconds (fs, 1×10^{-15} s), enabled the use of non-linear optical processes for high-resolution imaging, providing novel information about biological systems. The high instantaneous power delivered by such ultrafast lasers while keeping very low radiation energy levels, enables the use of such lasers for micro-surgery or even laser-ablation of tissues. With the development of nanotechnology and plasmonics, we today have optically responsive nanoparticles that can be used as novel image contrast agents or selective removal of cancer tissues by the heat generated due to photoabsorption of the nanoparticles, which are selectively taken up by the tumor cells.

Biophotonics refers to the topics that lie at the intersection of Biology and Photonics. In recent times there has been significant development in the use of optical techniques to probe and manipulate biological systems. Optical microscopy using fluorescence emission has reached a point where structures even as small as 50 nm can be imaged using super resolution imaging techniques, breaking the diffraction barrier of optical resolution. Similarly, techniques such as optical tweezers, highly sensitive molecular sensors and so on allow one to probe bio-physical phenomena at the single molecular level. Biophotonics is a rapidly growing field with immense opportunities to researchers with pretty much any educational background. Biologists and Chemists can contribute in the development of molecules with engineered optical response for various applications such as image contrast agents, photosensitizers for photodynamic therapy and so on. Physicists can contribute in the development of novel imaging and sensing modalities that push the capabilities of tools to probe complex biological systems. Engineers can contribute in areas such as the fabrication and miniaturization of devices with automated process flow for high throughput bio-analytical studies. There is also requirement for applied mathematicians, computer scientists and

statisticians for developing computationally efficient techniques for analyzing massive volumes of data that modern bio-analytical and imaging systems produce.

This course is intended to provide a basic introduction to the field of Biophotonics to students from a wide range of academic background from pure science to Engineering. The attempt has been to communicate the essential ideas behind some of the current techniques being used in the field with appropriate background materials while avoiding most of the mathematical details for the sake of simplicity. The material presented here has been divided into 4 modules. The first module introduces basic notions in geometric, wave and electromagnetic description of light. The second module introduces the quantum picture of matter and the photon. The third module describes microscopy techniques and optical manipulation and the last module describes some optical biosensing techniques. The hope is that this material will provide a starting point for students desirous of advanced study in this field. A list of textbooks and online material suitable for advanced study is listed at the end of the last module.

Geometric Optics

Geometric Optics

- Geometric optics treats light as a ray (consisting of corpuscles) which obeys certain laws at interfaces between two different materials.
- In this lecture, we will discuss geometric optics analysis of light
- Keywords: Geometric optics, ray theory, basic optical components

Overview

- In this lecture you will learn,
- A historical perspective of optics
- Reflection and refraction
- Total internal reflection
- Planar and spherical optical elements
- Matrix method to analyze optical systems
- Some lens systems

Early Days of Optics

- Mirrors dating back to 2000 BC
 - Pyramid of Sesostris Egypt
 - Polished metal
 - Metal on glass, alloys
- Burning glass (lens for focusing)
 - Mentioned in Aristophanes 424 BC
- Refraction studies
 - Plato's Republic (380 BC)
 - Ptolemy (100 AD)
- Straight line propagation of light, which is empirically observed, would imply "rays" of light (particle model) travelling obeying some laws. Hero of Alexandria (~ 40 AD) postulated shortest distance path for light rays

Early Days of Optics

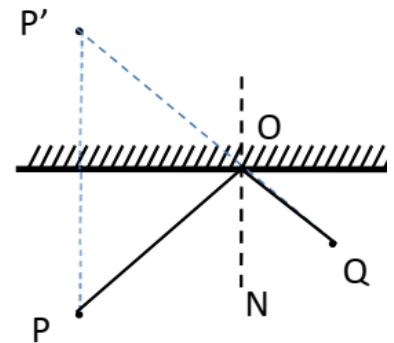
- Roger Bacon (1215 – 1294) suggested using lenses for correcting eyesight
 - Concepts of refraction appreciated
 - Focusing (or bending of light) in curved surfaces
- Tinkering with these lenses results in
 - Lippershey invents refracting telescope (1608)
 - Janssen invents compound microscope
 - Kepler discovers small angle law of refraction (1611)
 - Refracted angle is proportional to incident angle
 - Snell discovers law of refraction (1621)
 - Descartes puts it in terms of sine function (1637)
 - Fermat proposed law of least time (shortest optical path) (1637)
 - In essence a restatement of Hero's postulate but with the concept of refractive index
 - Refractive index of a material identified as its capacity to bend light

Early Days of Optics

- Application of law of refraction leads to the design (and improvement) of several optical components like lenses, microscopes, telescopes etc.
- In addition calculus developed around 1700's to enable studies of curvilinear surfaces like spherical lenses, parabolic mirrors etc

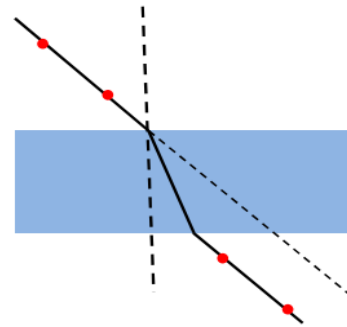
Reflection and Shortest Optical Path

- Law of reflection
 - Any point P has a conjugate point P'
 - Q is the point of observation
 - We can view the light ray as emerging from the conjugate point P'
 - Shortest path is $P'Q$
 - From the geometry $\angle PON = \angle NOQ$
 - i.e., incident and reflected angles are same
- Reflection will be symmetric with respect to normal
- Note that we derive this result using the shortest path hypothesis



Refraction

- Empirical observation that light bends when moving between different media, e.g. glass
- This means that speed of light in the two media have to be different (why?)



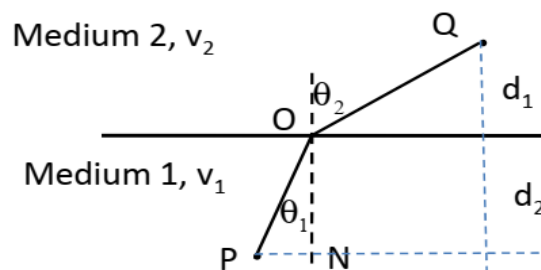
- Law of refraction

– Minimize $\frac{d_1 \sec \theta_1}{v_1} + \frac{d_2 \sec \theta_2}{v_2}$

– Subject to constraint $d_1 \begin{pmatrix} v_{1x} \\ v_{1y} \end{pmatrix} + d_2 \begin{pmatrix} v_{2x} \\ v_{2y} \end{pmatrix} = \text{const.}$

Refraction

- Minimizing the expression under the constraint given in the previous slide provides the famous law of refraction. It is left as an exercise for the more mathematically inclined readers to show this.



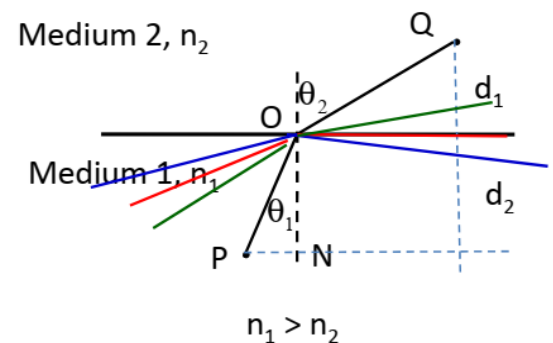
$$\frac{\sin \theta_1}{v_1} = \frac{\sin \theta_2}{v_2}$$

Refractive Index and Speed of Light

- From the observation of light refracting through a glass slab, one can conclude that light speed in glass must be lower than the light speed in air to explain the shortest path hypothesis in the context of the observed light path
- We define $v = \frac{c}{n}$ $n_1 v_1 = n_2 v_2 = c$
 - We will see later that this c is a universal speed of light
- Using snell's law and the definition above we can show that rays bend towards normal when going from a *rarer* medium to a *denser* medium and away from the normal when going from *denser* to *rarer*. *Denser* and *rarer* refer to refractive index being higher and lower respectively

Total Internal Reflection

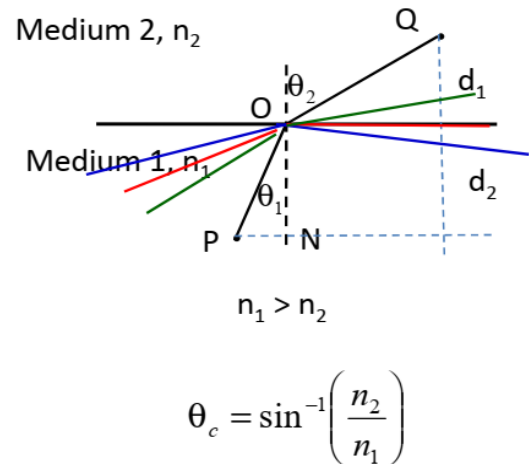
- Rays bend towards normal when going from a *rarer* medium to a *denser* medium and away from the normal when going from *denser* to *rarer*
- This implies that when light travels from denser to a rarer medium it will get reflected beyond a critical angle



$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

Total Internal Reflection

- This phenomenon is called total internal reflection
- TIR results in natural phenomena such as mirage. TIR is also the basic concept behind optical fibers and is also exploited in certain imaging and molecular sensing techniques to be discussed later



Recap

- Law of reflection and refraction follow from the postulate that light rays travel in the path that minimizes time of flight
- Alternately, minimize the 'Optical path length' where OPL = $\int_{path} n ds$

OPL = ref. index multiplied by geometric path length

- Refractive index is related to speed of light in the medium as

$$v = \frac{c}{n}$$

- All of geometric optics can be analyzed by applying the laws of reflection and refraction at the boundaries (interfaces) of the objects which may be comprised of various geometrical shapes such as a *parabolic* mirror or a *spherical* lens