Optical Sensor Technology

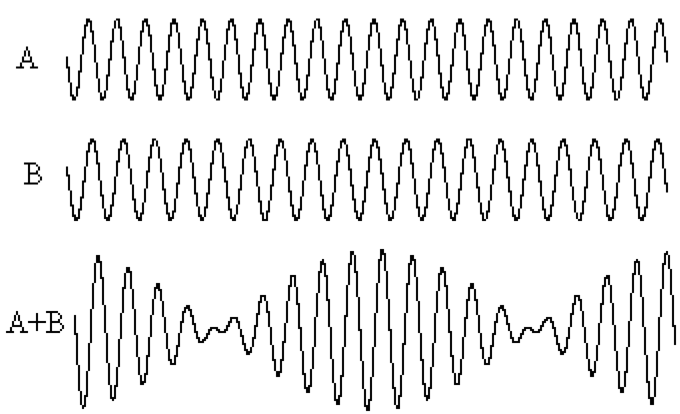
Wei-Chih Wang
University of Washington
Department of Mechanical Engineering

Objectives

The main goal of this course is to introduce the characteristics of light that can be used to accomplish a variety of engineering tasks especially in mechanical analysis.

Manipulate phase modulation for mechanical measurement:

monitoring changes in interference pattern due to a mechanical modulation



sinA+sinB = 1/2sin(A+B) *cos(A-B)

Let $A = \omega_1 t$

$B = \omega_2 t$

W.Wang

Course Outline

GOALS: To develop student understanding of

Lecture1 and 2 Ray-Optics Approach (Snell's law, Geometric optics, thin lens, matrix method) and Light sources and photodetectors

Lecture 3 and 4 Electromagnetic-Wave Approach (wave equation, polarization, diffraction, interference, diffraction grating, waveplate, Jones matrix)

Lecture 5 and 6 Fundamental of optical sensing: Intensity modulation

Lecture 7 and 8 Fundamental of optical sensing: Intensity modulation,Phase modulation

Lecture 9 and 10 Other optical techniques

Lecture 11 and 12 Bioimaging, biomedical sensing and biomechanical devices (Fourier, Raman, Fluorescent spectroscopy, Surface Plasmon Resonator, optical coherent tomography, confocal microscopy, endoscopy, near field imaging, distributed force pressure sensing, clinical glove sensor, etc.)

Week 3 Final project presentation

Who am I? Why am I here?

- Research Assistant Prof. from Department of Mechanical Engineering and Electrical Engineering, University of Washington

- Money!
- Recruiting YOU to UW!
- Making new friends
- Get students excited about optical sensor technology

What am I going to accomplish in one week?

- Hope to bring you a new “light” into your engineering curriculum.

God created the world in 6 days. He said, "**Let there be light**", and **there** was **light**.

illuminacion

What is Engineering?

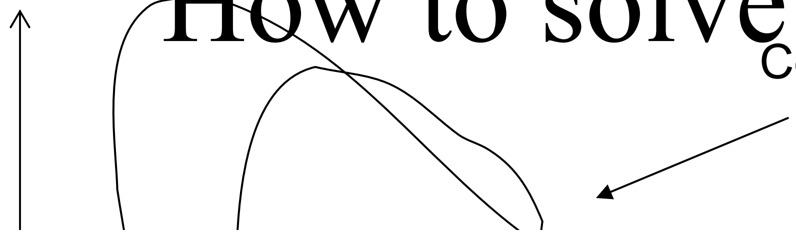
- To different people, it means different things
- To me, it’s an “Art” (constructive imagination) and sometimes it means making “Toy”

"the use of skill and imagination in the creation of aesthetic objects, environments, or experiences that can be shared with others"

What is difference between engineering and science?

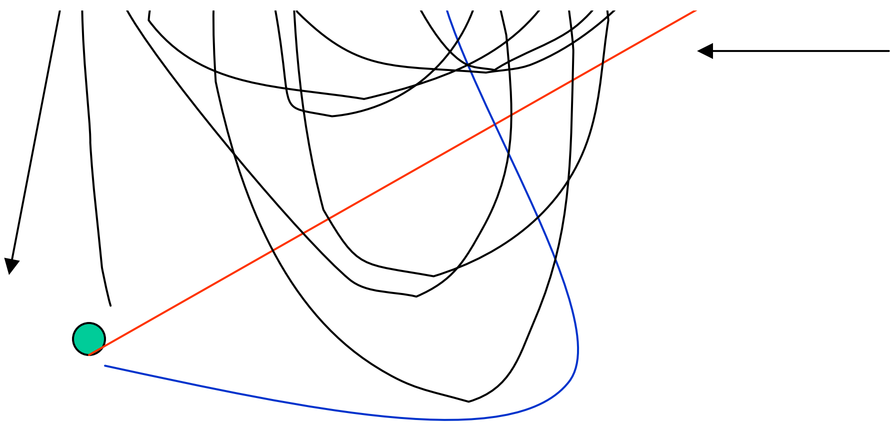
- Engineering is an application of science
- Methodical way of solving a particular large class of problems.
- Engineering solution is different from solving a Physics or Math problem where there are infinitely many different solution.

How to solve it?



There is no right way or wrong way of solving an engineering problem…..

It all depends on situation…….



My questions to you

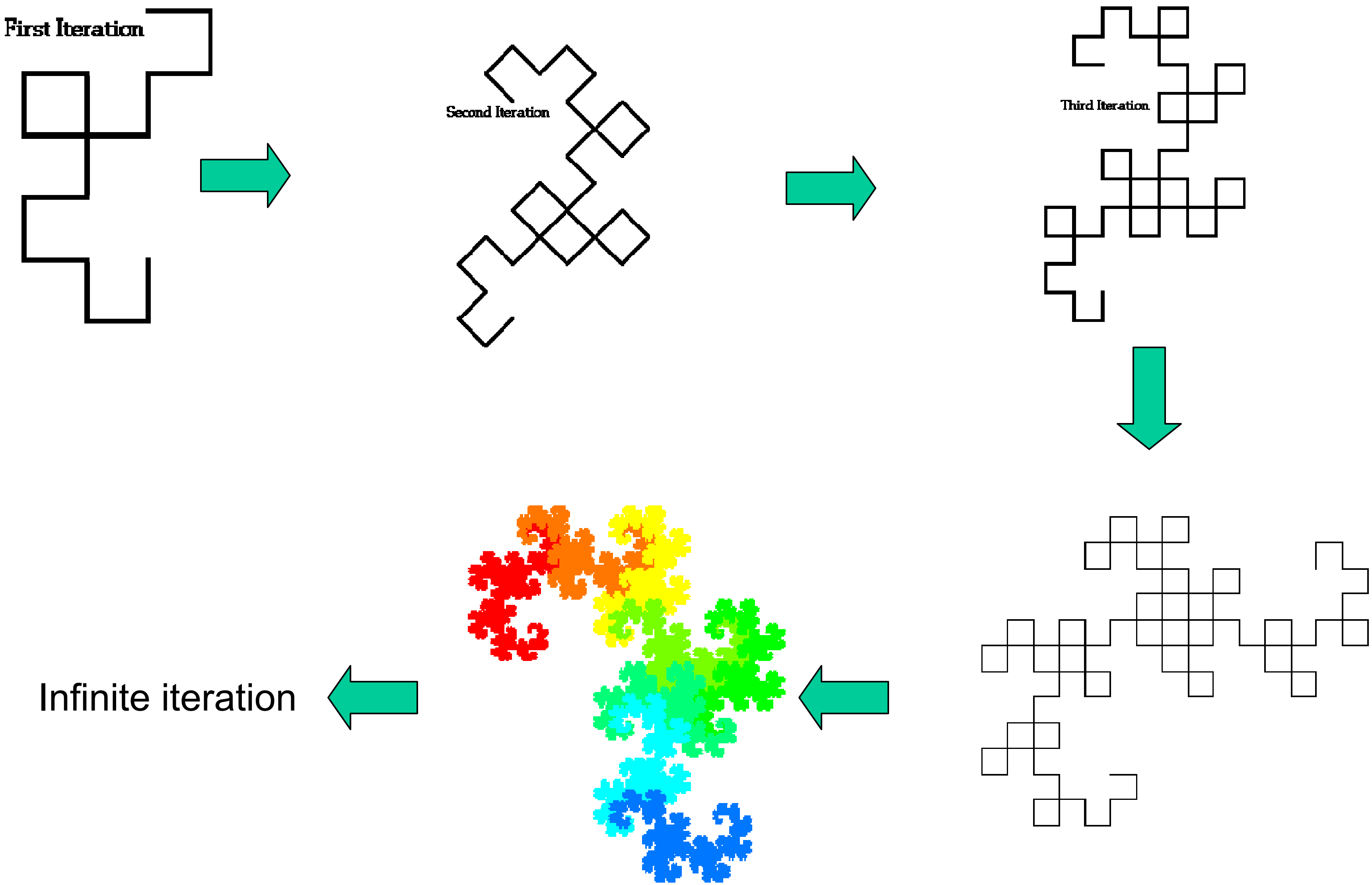
- Why majoring in engineering?
- What is your career goal?
- What have you design that works?
- Can you come up with a design and application using a simple electrical switch? (group of 3, 1 hour, present your idea in the afternoon)

Final Presentation

- Pick a design based on some of the topics we talk about in class. It does not have to be very complicated.
- Utilizing conventional literature search and online resources
- Observe your surrounding
- Use what you know
- Use What you have
- Pick an optical technique to measure something that people haven't thought of

Final Presentation

- Choose an interesting application on what you learn from this week
- 8 pages Powerpoint slides (send to me electronically me557@u.washington.edu)
- Show only the key points, font size minimum 24
- Lot of visual aids
- Voice needs to be loud and clear and engaging
- Be animated
- Surprise the audience
- Say only what you know.. don't pretend
- Goal: sell your idea to the audience!!!


First Iteration
Second Iteration
Third Iteration
Infinite iteration

W.Wang

Sensor Definition

A device that responds to a physical stimulus, such as thermal energy, electromagnetic energy, acoustic energy, pressure, magnetism, or motion, by producing a signal, usually electrical.

My sensor definition

- Sensors imitating after the five human senses: gustatory (taste), olfactory (smell), tactile, auditory, and visual.
- Extension of our senses

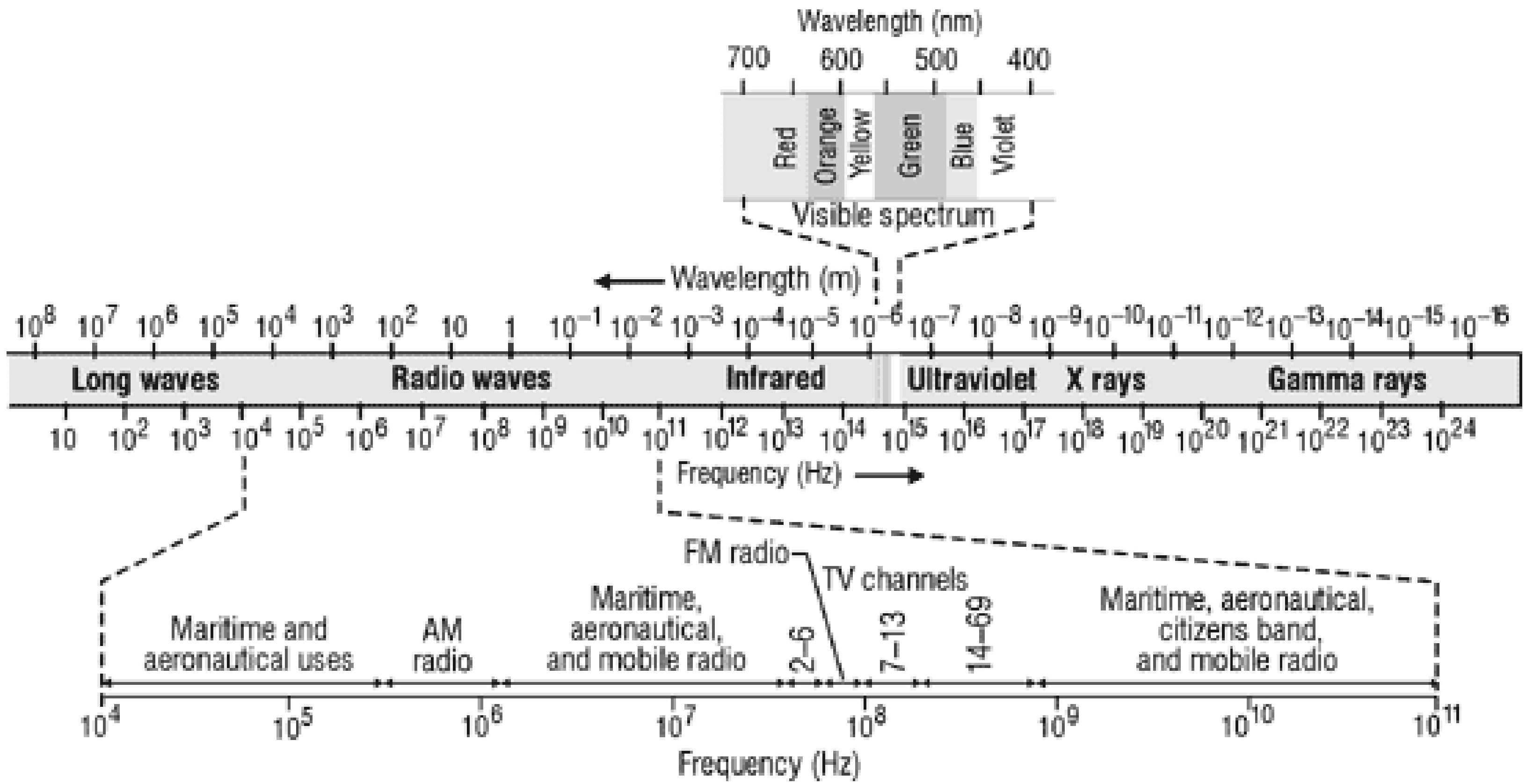
Method for sensing

- Optical
- Piezoelectric
- Thermal
- Chemical
- Electric
- Magnetic

Que es Optical Sensor?

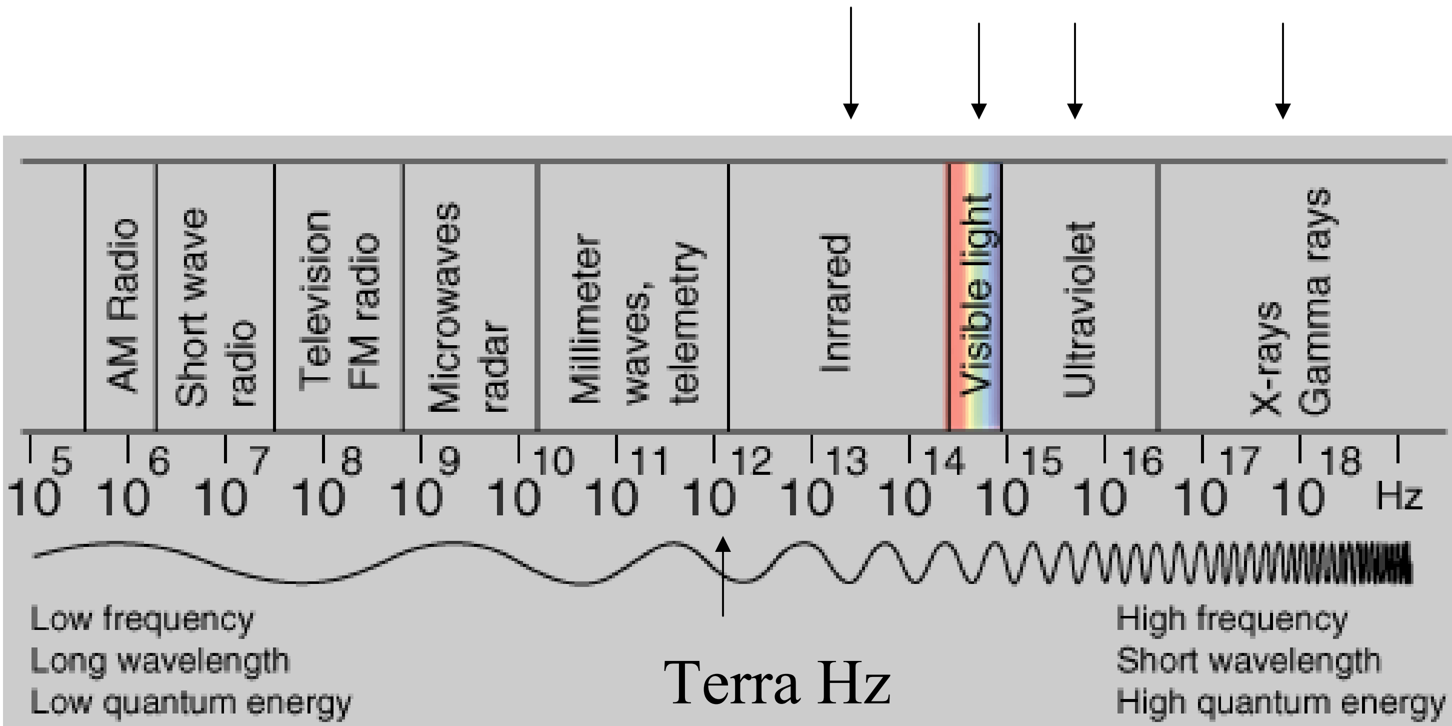
- Light is a form of energy which allow a physical entity to see and feel
- Optical sensor provides quantitative mesurant using optical energy.
- What can it sense?
  - pretty much everything...sight sound, taste, touch and smell in macro and micro and nano scale.
- Why optical technique?
  - sensitivity
  - free of EMI and RFI
  - compact
  - broadband
  - wide range spectrum provides unique applications

Electromagnetic spectrum



W.Wang

Electromagnetic spectrum



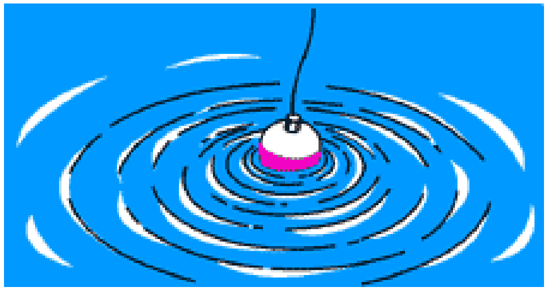
Visible light is a narrow part of the electromagnetic spectrum and in a vacuum all electromagnetic radiation travels at the speed of light:

$$c_o = 299{,}792{,}458 \pm 1.2 \text{ m/s}$$

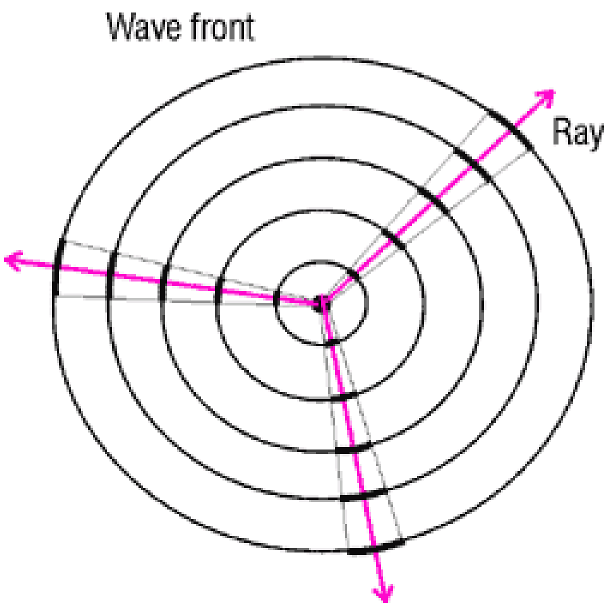
Speed of light $\approx 3 \times 10^8$ m/s.

Light rays and light waves

We can classify optical phenomena into one of three categories: **ray optics**, **wave optics**, and **quantum optics**.

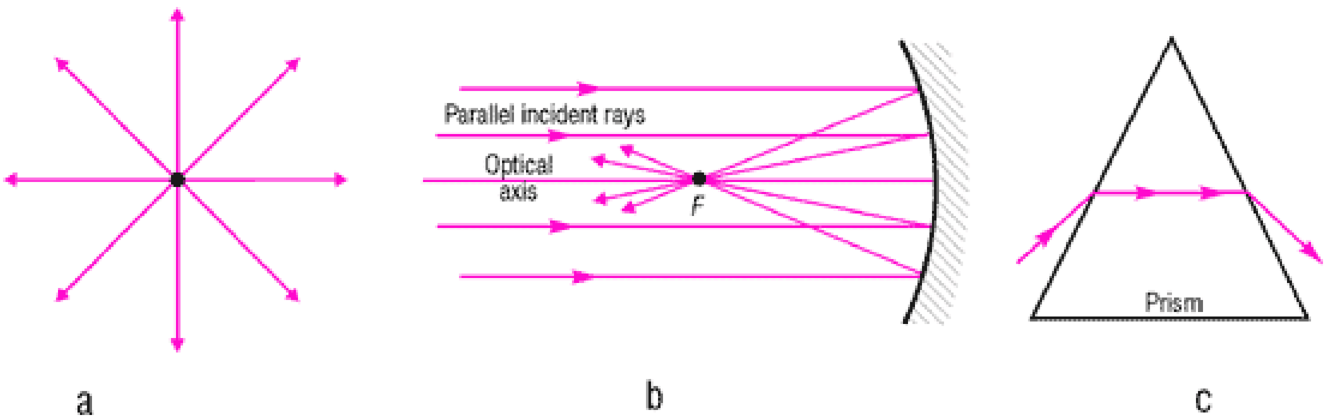


Wave from the bubble



Light rays and wavefronts

Geometric construct of a light ray we can illustrate propagation, reflection, and refraction of light



Light as a particle

Typical light rays in (a) *propagation,* (b) *reflection, and* (c) *refraction*

Geometric optics is also called ray optics. Light travels in the form of rays. Ray optics only concern with the location and direction of light rays.

We define a **ray** as the path along which light energy is transmitted from one point to another in an optical system. The basic laws of geometrical optics are the law of reflection and the law of refraction.

Law of reflection: $|\theta_r| = |\theta_i|$
Snell's law, or **the law of refraction**: $n_i \sin\theta_i = n_t \sin\theta_t$.

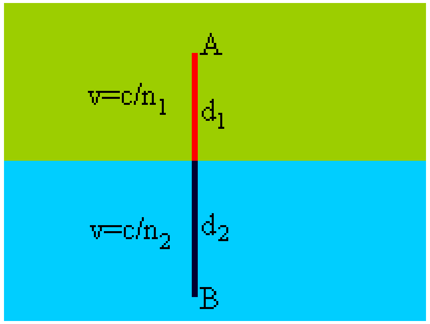
If not being reflected or refracted, a light ray travels in a straight line.

The **optical path length** of a ray traveling from point A to point B is defined as c times the time it takes the ray to travel from A to B.

Assume a ray travels a distance d_1 in a medium with index of refraction n_1 and a distance d_2 in a medium with index of refraction n_2.

The speed of light in a medium with index of refraction n is c/n. The travel time from A to B therefore is

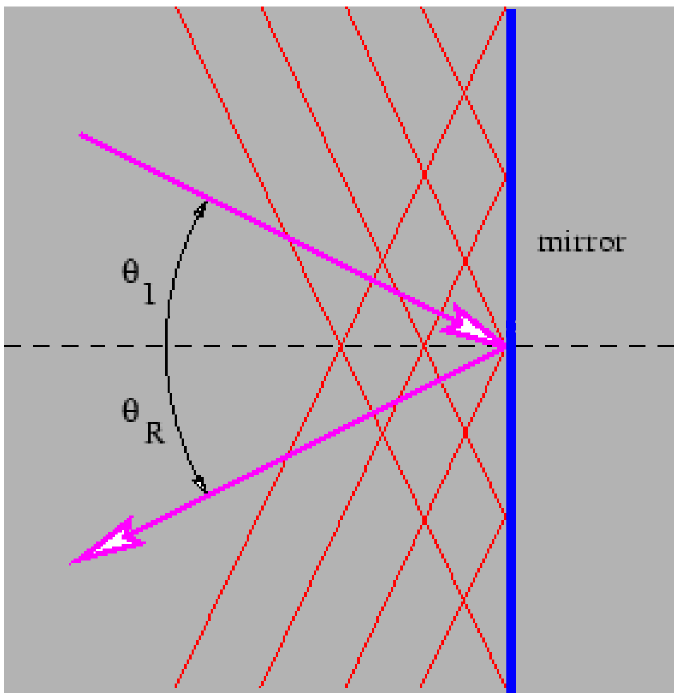
$$t = n_1 d_1/c + n_2 d_2/c.$$



The **optical path length** is $OPL = n_1 d_1 + n_2 d_2$.

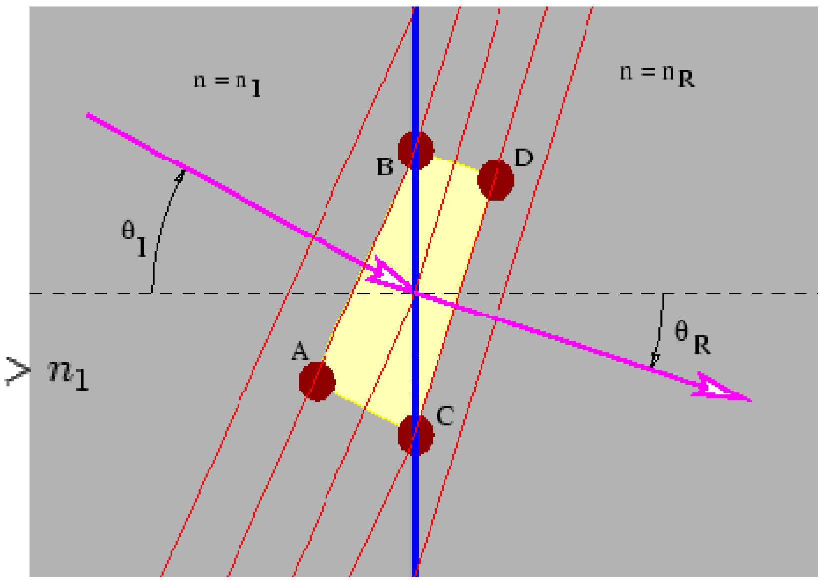
Most of what we need to know about geometrical optics can be summarized in two rules:

1) the laws of reflection
2) The law of refraction.



wave vector and wave front of a wave being reflected from a plane mirror

$n_2 > n_1$



refraction of a wave from an interface between two dielectric media

W.Wang

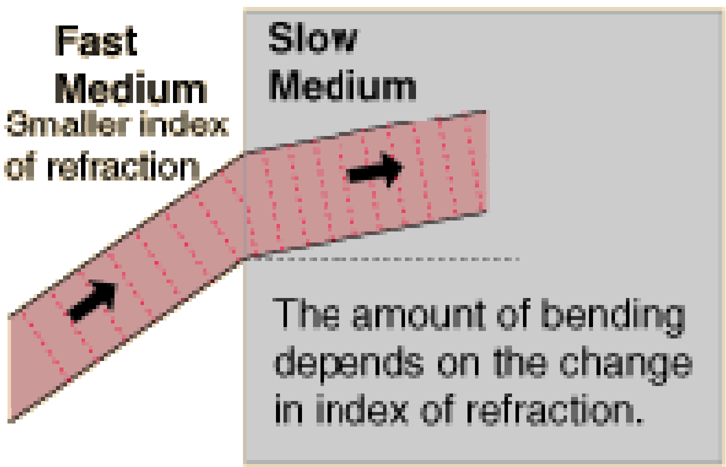
Fermat’s Principle:

An alternate approach to geometric optics is fermat’s principle. The path of a ray of light between two points is the path that minimizes the travel time.

In Fermat's Principle the optical path length between points A and B can be calculated in either direction, A to B or B to A, the result is the same. This leads to the principle of geometrical reversibility.

Index of Refraction

In a material medium the effective speed of light is slower and is usually stated in terms of the index of refraction of the medium. The index of refraction is defined as the speed of light in vacuum divided by the speed of light in the medium.



HyperPhysics

$$n = \frac{C_o}{C}$$

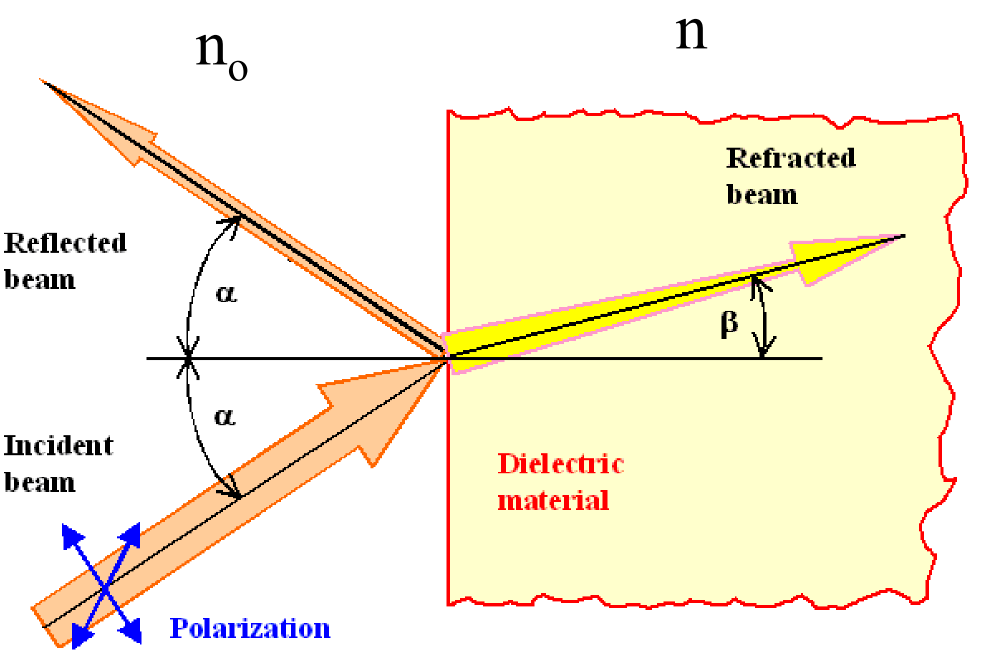
W.Wang

The indices of refraction of some common substances

Vacuum	1.000	Ethyl alcohol	1.362
Air	1.000277	Glycerine	1.473
Water	4/3	Ice	1.31
Carbon disulfide	1.63	Polystyrene	1.59
Methylene iodide	1.74	Crown glass	1.50-1.62
Diamond	2.417	Flint glass	1.57-1.75

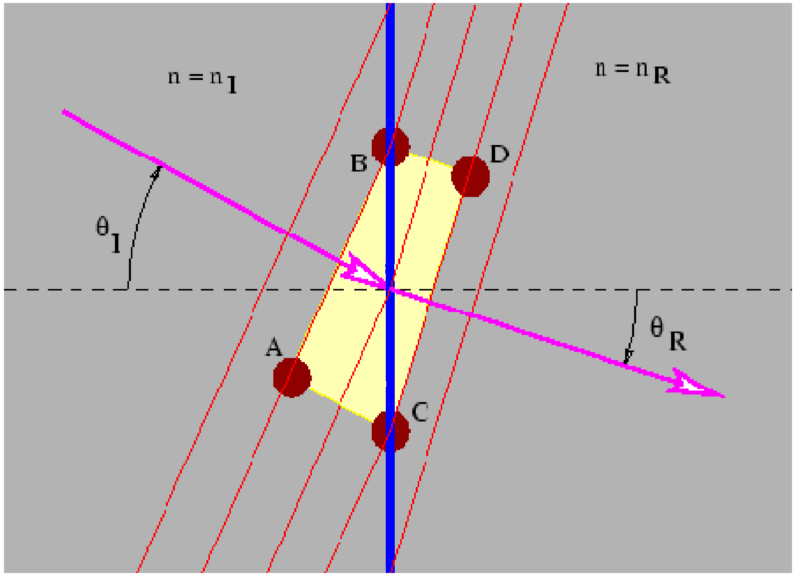
The values given are approximate and do not account for the small variation of index with light wavelength which is called dispersion (n = function of wavelength).

Law of Refraction



Snell's Law: $n_o \sin\alpha = n \sin\beta$

How is it derived?



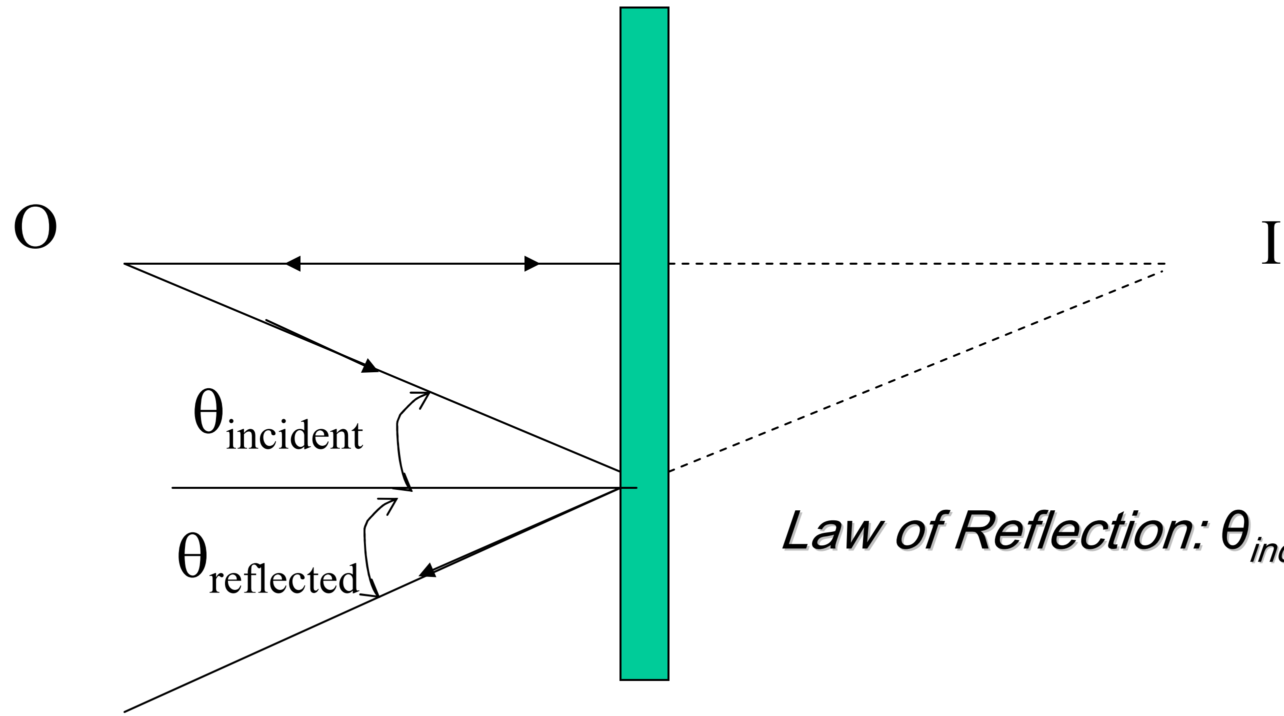
Since $n_R > n_I$, the speed of light in the right-hand medium is less than in the left-hand medium. The frequency of the wave packet doesn't change as it passes through the interface, so the wavelength of the light on the right side is less than the wavelength on the left side.

The side AC is equal to the side BC times $\sin\theta_I$. However, AC is also equal to $2\lambda_I$, or twice the wavelength of the wave to the left of the interface. Similar reasoning shows that $2\lambda_R$, twice the wavelength to the right of the interface, equals BC times $\sin\theta_P$. Since the interval BC is common to both triangles, we easily see that

$$\frac{\lambda_I}{\lambda_R} = \frac{\sin\theta_I}{\sin\theta_R}$$

Since $\lambda_R = Cf$ and $\lambda_I = Cf$ => $\boxed{n_I \sin\theta_I = n_R \sin\theta_R}$

Reflection



Law of Reflection: $\theta_{incident} = \theta_{refllected}$

The angles of incidence, $\theta_{incident}$, and reflection, $\theta_{reflected}$, are defined to be the angles between the incoming and outgoing wave vectors respectively and the line normal to the mirror. The law of reflection states that $\theta_{incident} = \theta_{refllected}$. This is a consequence of the need for the incoming and outgoing wave fronts to be in phase with each other all along the mirror surface. This plus the equality of the incoming and outgoing wavelengths is sufficient to insure the above result.

Reflection

$AA' = AB/\tan(\theta_I)$
$AB = \lambda_I$

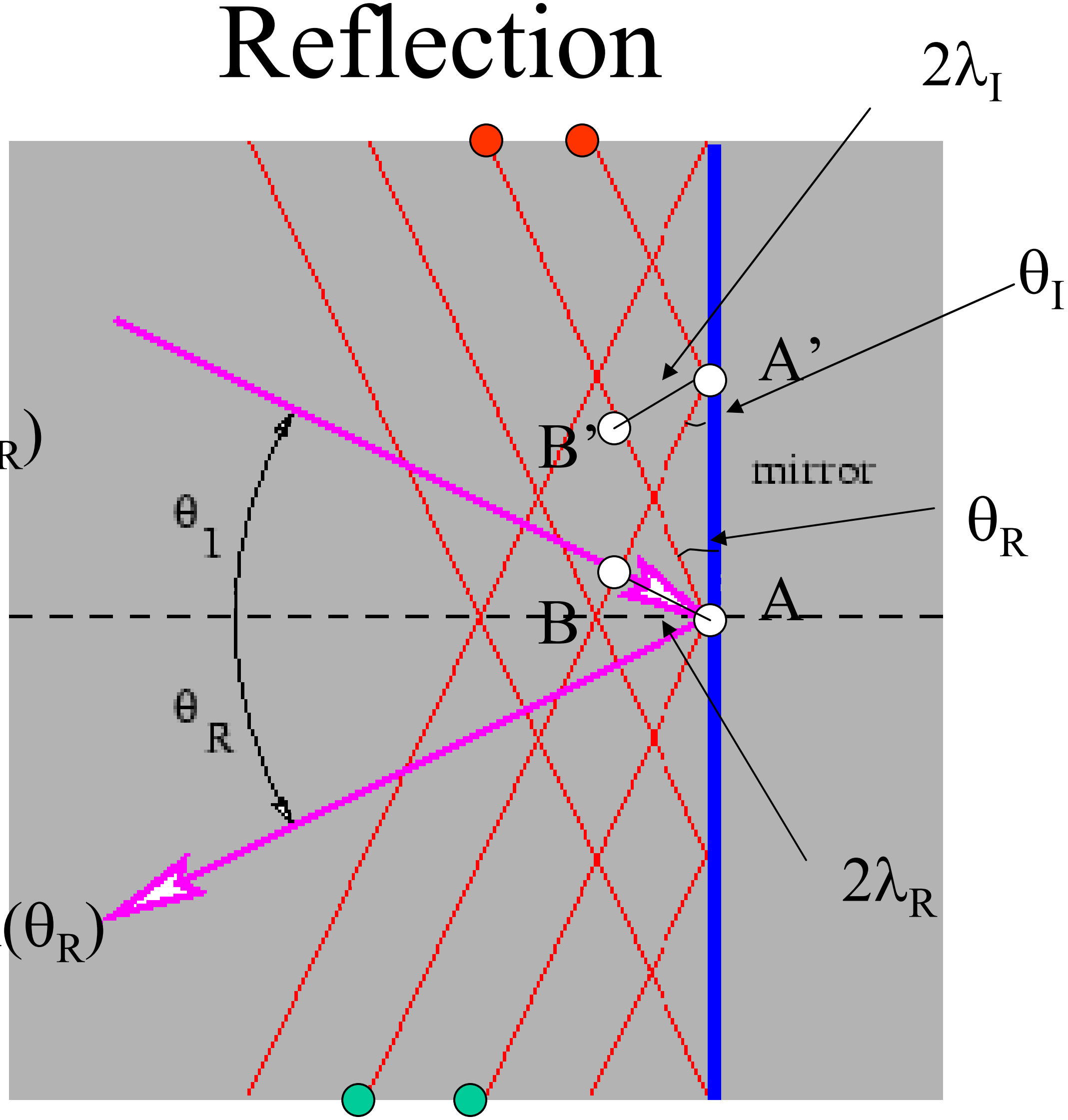
$AA' = A'B'/\tan(\theta_R)$
$A'B' = \lambda_R$

Since $\lambda_I = \lambda_R$
Then

$\lambda_I \tan(\theta_I) = \lambda_R \tan(\theta_R)$

So

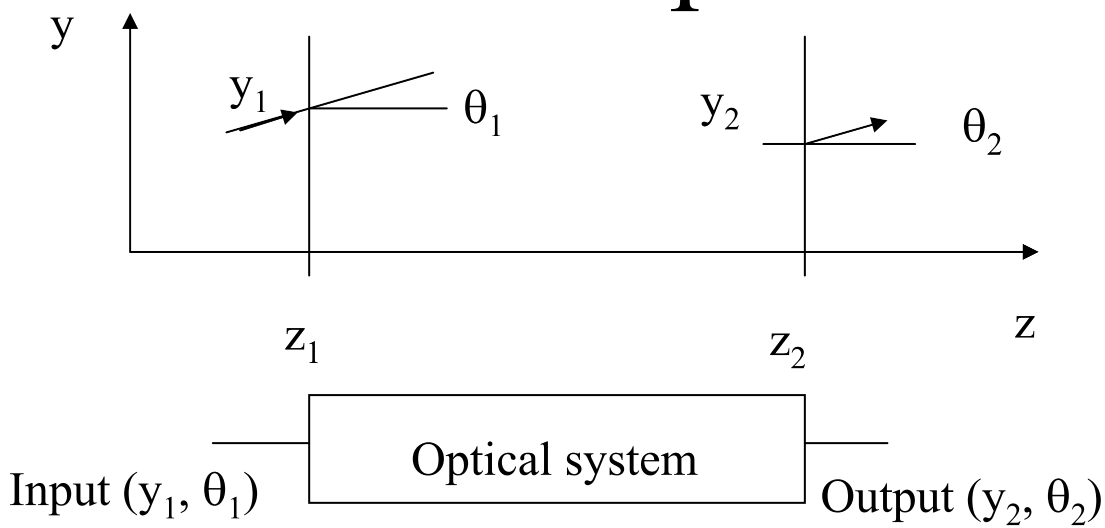
$\boxed{\theta_I = \theta_R}$



A and B are incident, A' and B' are reflectant

W.Wang

Matrix Optics



Matrix optics is a technique for tracing paraxial rays. The rays are assumed to travel only within a single plane (as shown in yz plane)

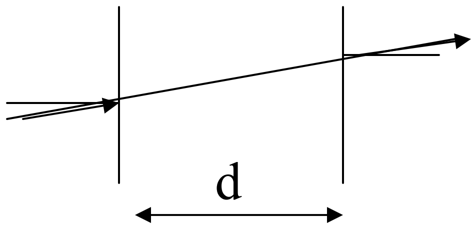
-A ray is described by its position y and its angle θ with respect to the optical axis. These variables are altered as the ray travels through the optical system, where The system can be represent by a transfer function like matrix to represent the relation between (y_2, θ_2) and (y_1, θ_1) as,

$$\begin{bmatrix} y_2 \\ \theta_2 \end{bmatrix} = \underbrace{\begin{bmatrix} A & B \\ C & D \end{bmatrix}}_{M} \begin{bmatrix} y_1 \\ \theta_1 \end{bmatrix}$$

Where A,B,C,D are elements characterizes the optical system

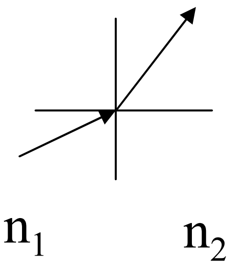
Matrices of Simple Optical Components

Free-space propagation



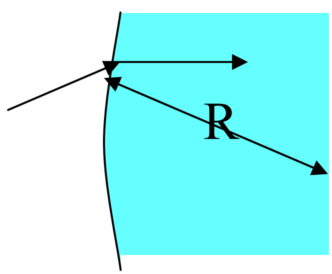
$$M = \begin{bmatrix} 1 & d \\ 0 & 1 \end{bmatrix}$$

Refraction at a planar boundary



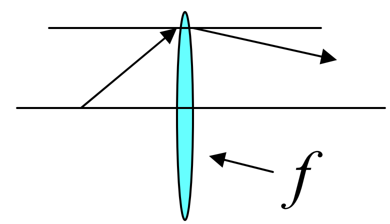
$$M = \begin{bmatrix} 1 & 0 \\ 0 & \dfrac{n_1}{n_2} \end{bmatrix}$$

Refraction at a spherical boundary



$$M = \begin{bmatrix} 1 & 0 \\ \dfrac{-(n_2 - n_1)}{n_2 R} & \dfrac{n_1}{n_2} \end{bmatrix}$$

Transmission through a thin lens



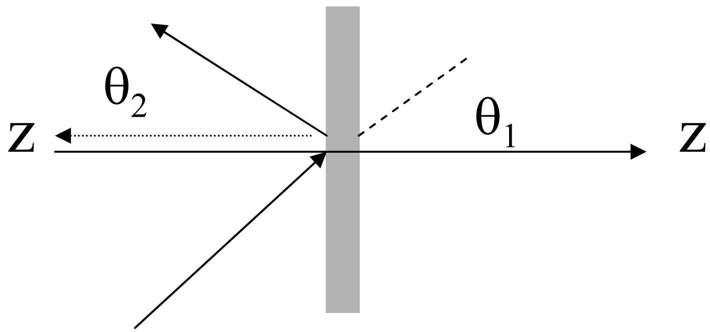
Convex f > 0
Concave f < 0

$$M = \begin{bmatrix} 1 & 0 \\ -\dfrac{1}{f} & 1 \end{bmatrix}$$

W.Wang

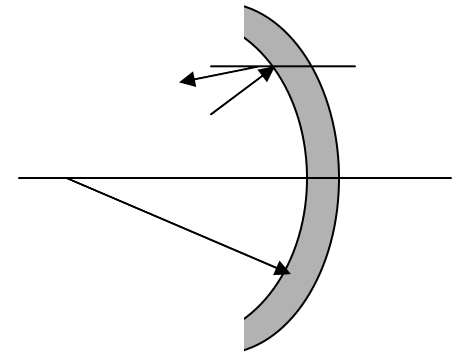
Matrices of Simple Optical Components

Reflection from a planar mirror



$$M = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

Reflection from a spherical mirror



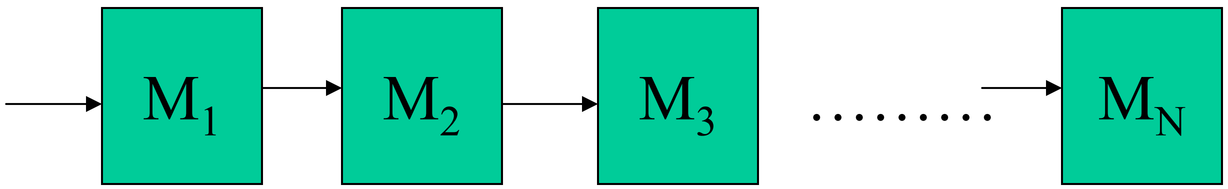
Concave R<0

Convex R>0

$$M = \begin{bmatrix} 1 & 0 \\ \dfrac{2}{R} & 1 \end{bmatrix}$$

Work only for simple refraction and reflection

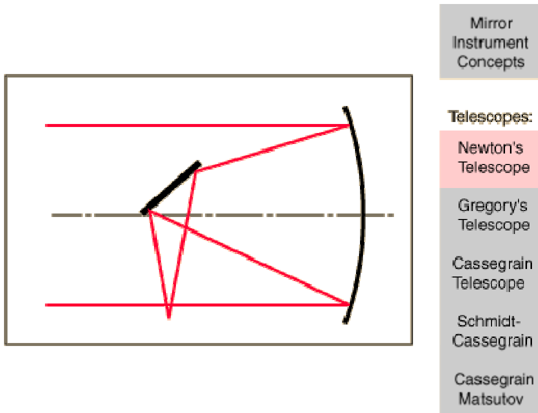
Cascaded Matrices

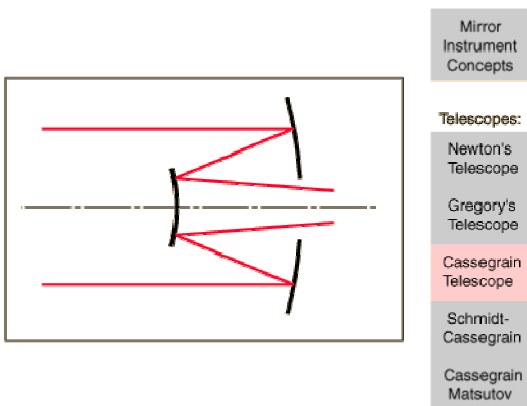


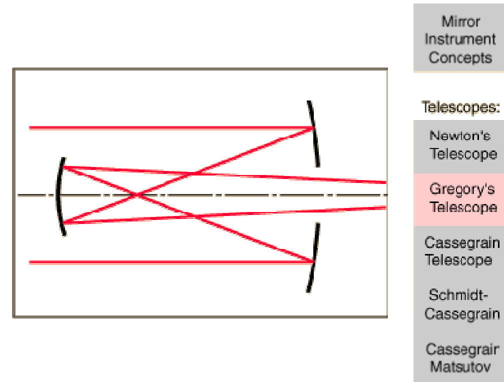
$$M = M_N \bullet \bullet \bullet \bullet \; M_2 \, M_1$$

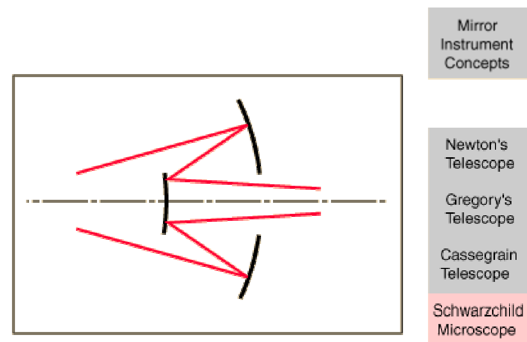
Show opticlab and oslo software

Catoptric Systems





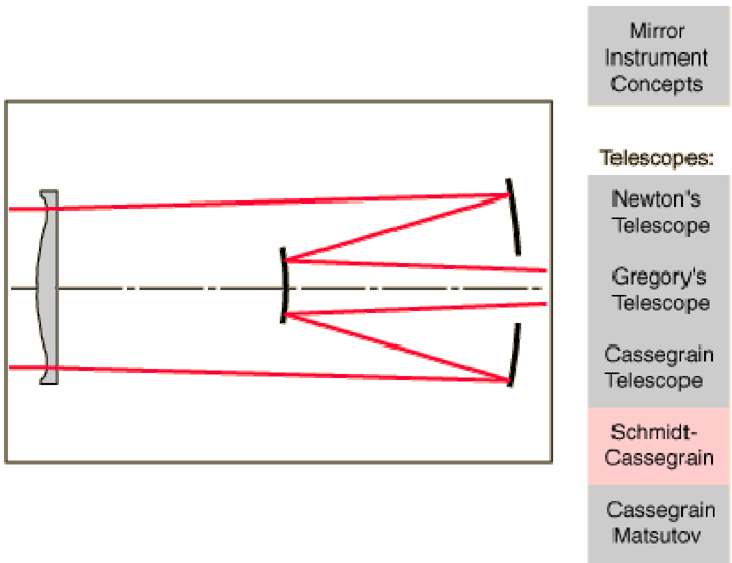


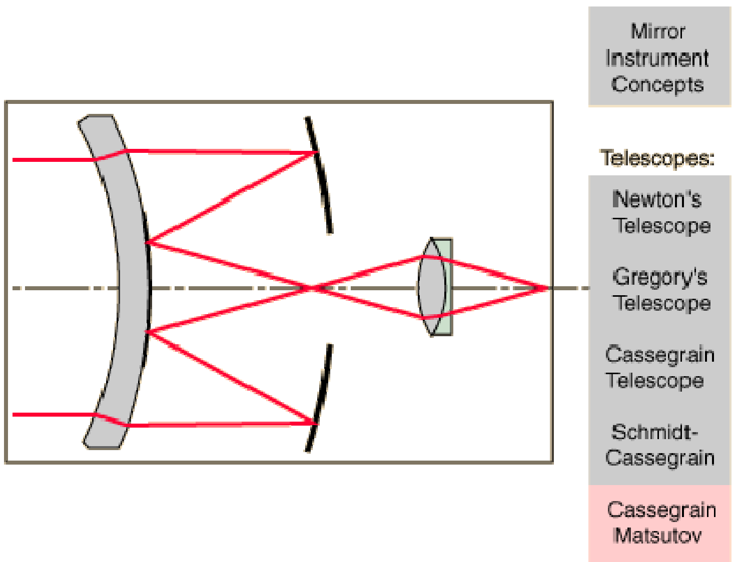


hyperphyics

Catoptric systems are those which use only mirrors for image formation. They contrast with catadioptric systems which use both mirrors and lenses and with pure dioptric systems which use only lenses.

Catadioptric Systems





hyperphyics

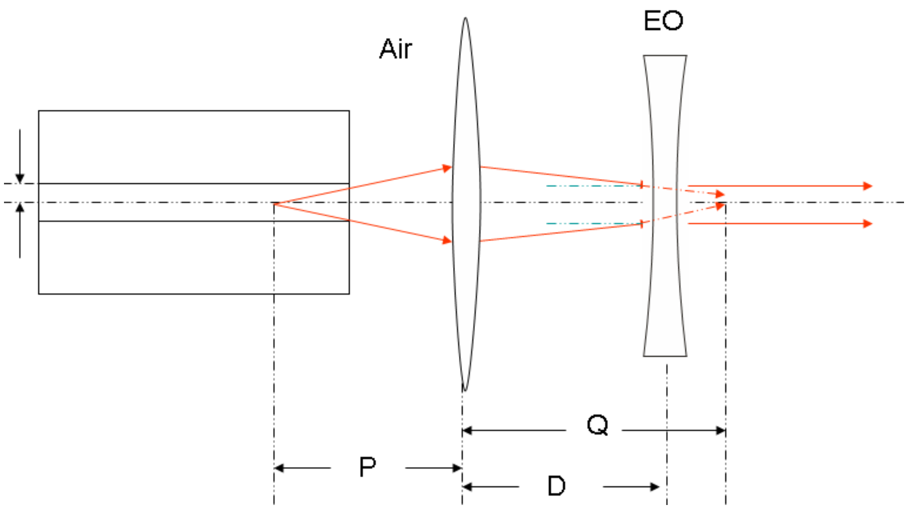
Catadioptric systems are those which make use of both lenses and mirrors for image formation. This constrasts with catoptric systems which use only mirrors and dioptric systems which use only lenses. (i.e. Nikon 500mm mirror lens)

Take home project

- Design a mirror system to focus, diverge or collimate an incident beam or create some interesting magic tricks or illusion or something you can think of that using ray tracing technique.

Collimator

Figure 13, 2-D path of light via Convex-Concave lens combination



Assuming both of the lenses are thin lenses, the govern equations for this collimator are:

$$\frac{1}{P}+\frac{1}{Q}=\frac{1}{f_1}=(n-1)(\frac{1}{R_1}-\frac{1}{R_2}) \quad \langle R_1:+\ R_2:-\rangle$$

$$Q-D=f_2=\frac{1}{(n-1)(\frac{1}{R_3}-\frac{1}{R_4})} \quad \langle R_3:-\ R_4:+\rangle$$

There are two more design rules to follow:

1. **H/2>Rcone** , where H the height of the lens, Rcone the radius of the diverged beam
2. **H/W is relatively big to qualify thin lens,** where H the height of the lens, w is the thickness of the lens

‘ Then, by defining the P , D and one of the focal length(or radius), the other focal length will be determined.

Another approach to address the problem is by using ray-transfer matrics. The detail was addressed as following:

W.Wang

$$M = \begin{pmatrix} 1 & 0 \\ -\frac{1}{f_2} & 1 \end{pmatrix} * \begin{pmatrix} 1 & d_2 \\ 0 & 1 \end{pmatrix} * \begin{pmatrix} 1 & 0 \\ -\frac{1}{f_1} & 1 \end{pmatrix} * \begin{pmatrix} 1 & d_1 \\ 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} 1 & d_2 \\ -\frac{1}{f_2} & 1-\frac{d_2}{f_2} \end{pmatrix} * \begin{pmatrix} 1 & 0 \\ -\frac{1}{f_1} & 1 \end{pmatrix} * \begin{pmatrix} 1 & d_1 \\ 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} 1-\frac{d_2}{f_1} & d_2 \\ -\frac{1}{f_2}-\frac{1}{f_1}(1-\frac{d_2}{f_2}) & 1-\frac{d_2}{f_2} \end{pmatrix} * \begin{pmatrix} 1 & d_1 \\ 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} 1-\frac{d_2}{f_1} & d_2 + d_1(1-\frac{d_2}{f_1}) \\ -\frac{1}{f_2}-\frac{1}{f_1}(1-\frac{d_2}{f_2}) & 1-\frac{d_2}{f_2}-\frac{d_1}{f_2}-\frac{d_1}{f_1}(1-\frac{d_2}{f_2}) \end{pmatrix}$$

$$\begin{bmatrix} y_2 \\ \theta_2 \end{bmatrix} = M * \begin{bmatrix} y_1 \\ \theta_1 \end{bmatrix} = \begin{pmatrix} 1-\frac{d_2}{f_1} & d_2 + d_1(1-\frac{d_2}{f_1}) \\ -\frac{1}{f_2}-\frac{1}{f_1}(1-\frac{d_2}{f_2}) & 1-\frac{d_2}{f_2}-\frac{d_1}{f_2}-\frac{d_1}{f_1}(1-\frac{d_2}{f_2}) \end{pmatrix} * \begin{bmatrix} y_1 \\ \theta_1 \end{bmatrix}$$

$$= \begin{bmatrix} (1-\frac{d_2}{f_1}) * y_1 + (d_2 + d_1(1-\frac{d_2}{f_1}))\theta_1 \\ (-\frac{1}{f_2}-\frac{1}{f_1}(1-\frac{d_2}{f_2}))y_1 + \theta_1(1-\frac{d_2}{f_2}-\frac{d_1}{f_2}-\frac{d_1}{f_1}(1-\frac{d_2}{f_2})) \end{bmatrix}$$

W.Wang

To be collimated beam, θ 2 must equal 0 for any input angle θ 1, which means:
Let y1=0

$$\theta_1(1-\frac{d_2}{f_2}-\frac{d_1}{f_2}-\frac{d_1}{f_1}(1-\frac{d_2}{f_2})=0$$

$$\Rightarrow 1-\frac{d_2}{f_2}-\frac{d_1}{f_2}-\frac{d_1}{f_1}(1-\frac{d_2}{f_2})=0$$

$$\Rightarrow f_1 f_2 - f_1 d_2 - f_1 d_1 - f_2 d_1 + d_1 d_2 = 0$$

$$f=\frac{1}{(n-1)(\frac{1}{R_1}-\frac{1}{R_2})}$$