Quantum Technician Bootcamp

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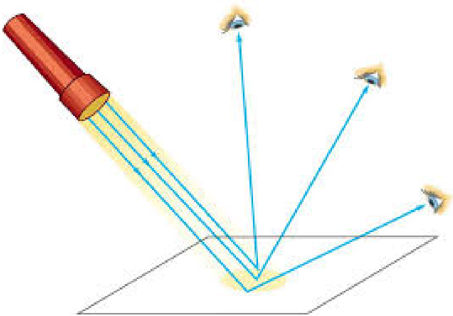
September 2025

Geometric Optics

Ray Nature of Light

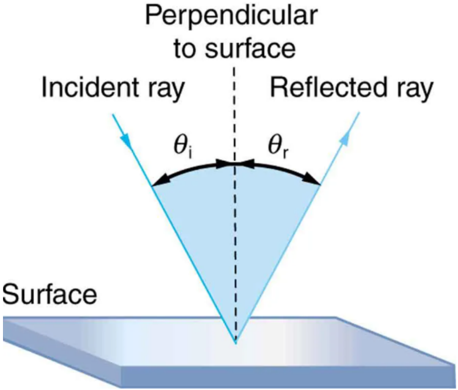
The word "ray" means a straight line that originates at some point.



The part of optics dealing with the ray aspect of light is called "geometric optics."

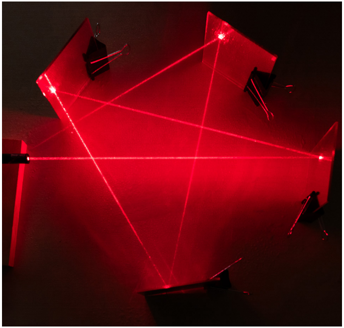
Reflection

The angle of reflection equals the angle of incidences



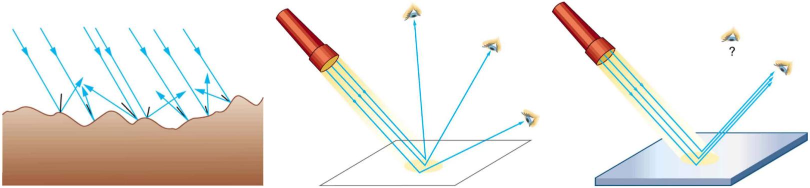
Demonstration: Handling Optics

Assignment: Laser Tag



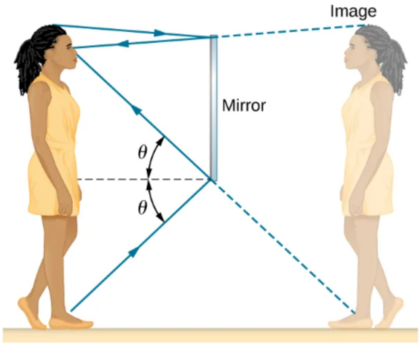
- Align a Laser and a target at opposite ends of the table.
- When obstacles are placed in the path, without adjusting laser, add mirrors to get the beam to the target.

Rough vs Smooth Surfaces



Mirrors and Virtual Images

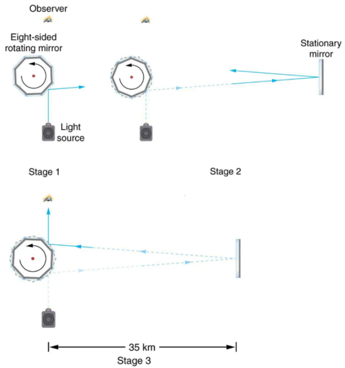
When we see ourselves in a mirror, it appears that our image is actually behind the mirror.



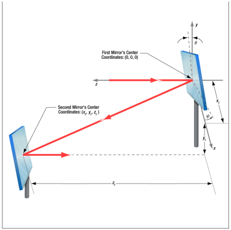
Speed of Light

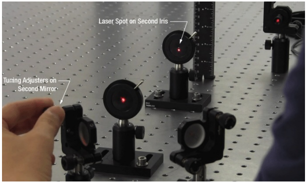
- In 1676, Danish astronomer Ole Roemer noted the change in orbital period of Jupiter's moons depending of if the earth was moving towards or away from Jupiter. He as able to calculate speed of light to be $2.26x10^8(\frac{m}{s})$.
- In 1887, American physicist Albert Michelson used a rotating mirror to get a more precise measurement of the speed of light.
- Today, the speed of light is known as:

$$c = 2.99792458 10^8(\frac{m}{s}).$$



Assignment: Two Mirror Walk





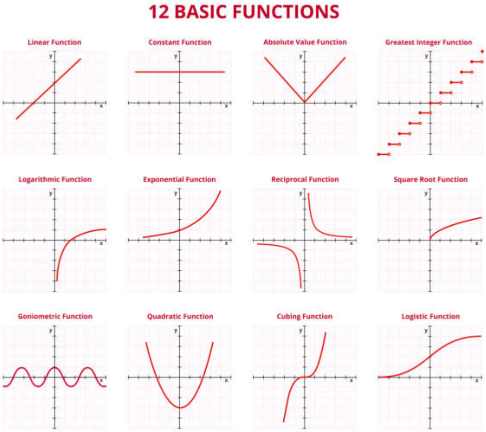
1. Setup: Laser, 45° mirror, second 45° mirror, two irises, target.
2. Adjust first mirror to center beam on center iris 1
3. Open iris 1, adjust second mirror to center beam on iris 2
4. Iterate steps 2 and 3 until the beam passes through the center of both iris and hits target.

Math Interlude: Trigonometry

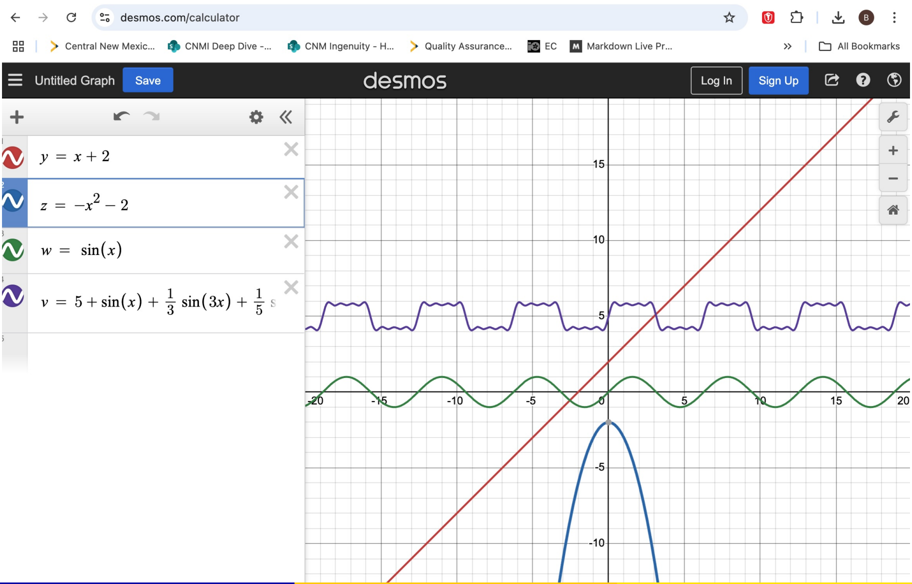
Algebraic Functions

An algebraic function provides a "y-value" for every "x-value"

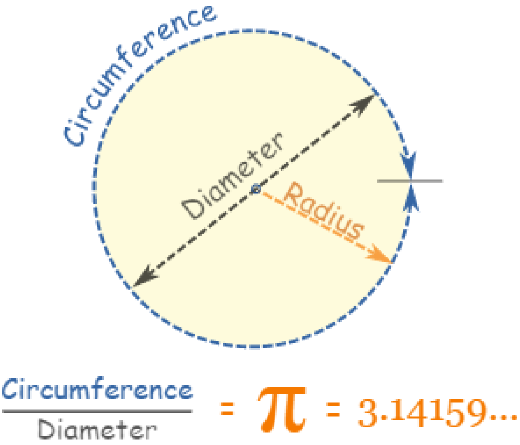
- Linear: $y = x + 2$
- Quadratic: $y = x^2$
- Periodic: $y = sin(x)$



More Desmos Fun

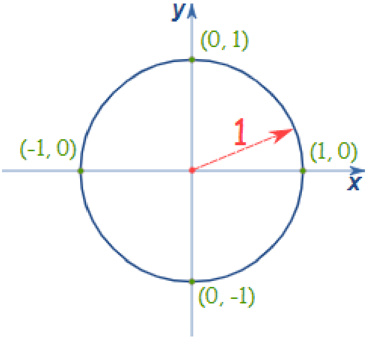


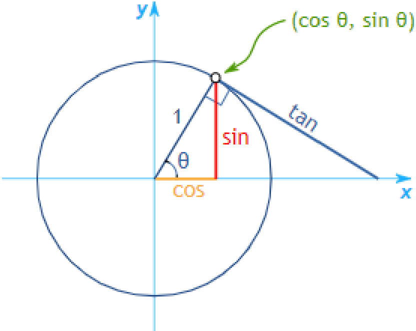
Pi (π)


Circumference
Diameter
Radius
Circumference
Diameter
= π = 3.14159...

Unit Circle and Trigonometric Functions

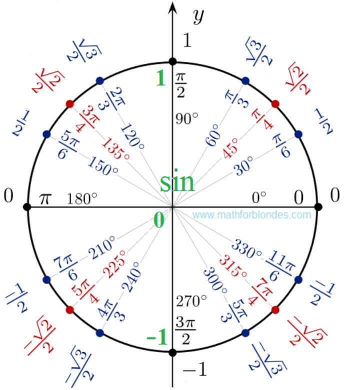
The Unit Circle is a circle with a radius of 1.

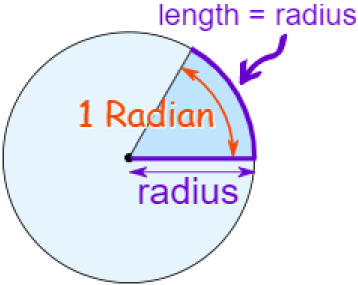




The Unit Circle can be used to map out the trigonometric values of sine, cosine, and tangent.

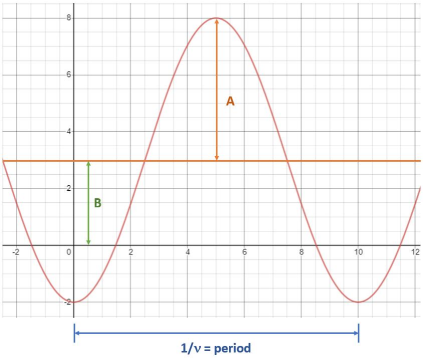
Unit Circle and the Value of *sin*(θ)





- *sin*(θ) is the y-value of the point on the Unit Circle at angle θ.
- In our trig functions, θ is measured in radians (rad), not degrees.
- 360 degrees $= 2\pi$ radians.

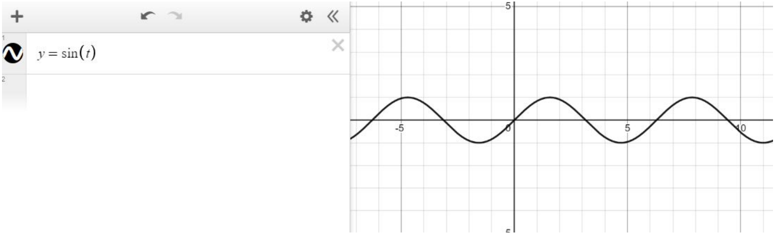
Sine Waves

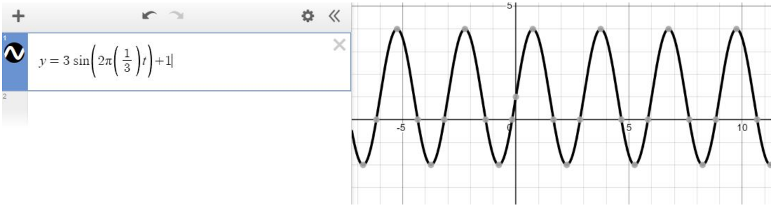


$$y = A * sin(2 * \pi * \nu * t) + B$$

where A = amplitude, B = offset, ν = frequency = $\frac{1}{period}$, and t = time in seconds.

Using Desmos (desmos.com/calculator)

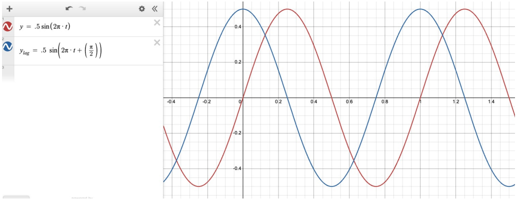




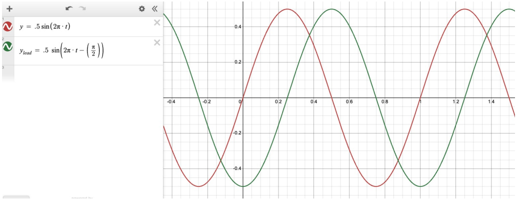
Phase Shift

The sine wave can be shifted relative to each other by adding in a phase shift (ϕ), which will shift the wave to the left or right.

Blue lags Red:

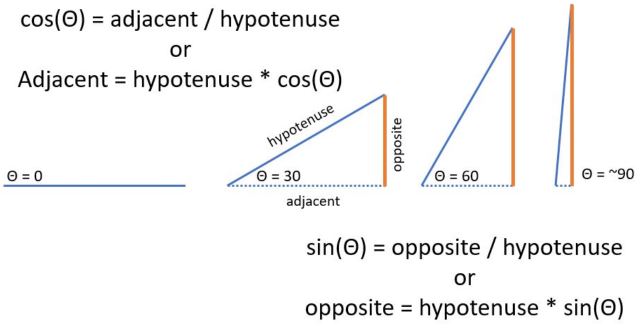


Green leads Red:

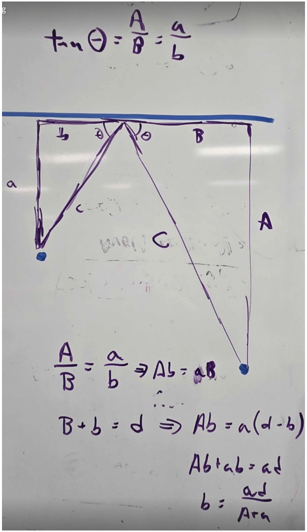


SOH CAH TOA

- sin = opposite over hypotenuse
- cos = adjacent over hypotenuse
- tan = opposite over adjacent



Assignment: Calculating Angles: Laser Billards

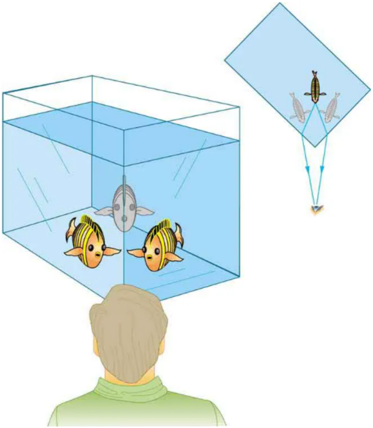


- Setup a mirror line on the optical table.
- Place the laser and target two different distances from the line.
- Calculate the location of the mirror, place the mirror there.
- Calculate the angle of the laser, adjust laser angle.
- Turn on laser and see how close on target the calculations are.

Return to Geometric Optics

Refraction

The changing of a light ray's direction (loosely called bending) when it passes through variations in matter is called refraction.



Index of Refraction

The speed of flight depends strongly on the type of material. We define the index of refraction (n) as

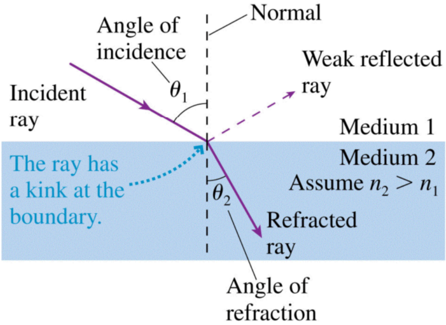
$$n = \frac{c}{v}$$

where v is the speed of light in the material and c is the speed of light in a vacuum.

Medium	***n***
Vacuum	1.00 exactly
Air (actual)	1.0003
Air (accepted)	1.00
Water	1.33
Ethyl alcohol	1.36
Oil	1.46
Glass (typical)	1.50
Polystyrene plastic	1.59
Cubic zirconia	2.18
Diamond	2.41
Silicon (infrared)	3.50

Law of Refraction - Snell's Law

The law of refraction is also called Snell's law after the Dutch mathematician Willebrord Snell (1591–1626).



Snell's Law: $n_1 \sin\theta_1 = n_2 \sin\theta_2$

Finding Index of Refraction

Snells Law:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{1}$$

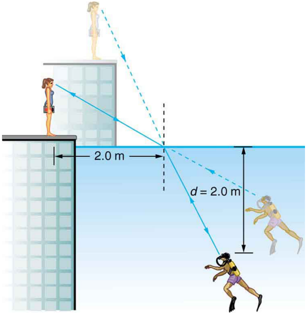
Rearranging to isolate n_2:

$$n_2 = n_1 \frac{\sin\theta_1}{\sin\theta_2} \tag{2}$$

For example, if the initial medium is air, $\theta_1 = 30^\circ$ and $\theta_2 = 22^\circ$

$$n_2 = (1.00) \cdot \frac{\sin 30^\circ}{\sin 22^\circ} = \frac{0.500}{0.375} = 1.33 \tag{3}$$

Assignment: Measuring Refraction



- Some assignment on refraction
- Acrylic, water, what else?
- Different color lasers (red, green, and if we get blue in time)

Total Internal Reflection

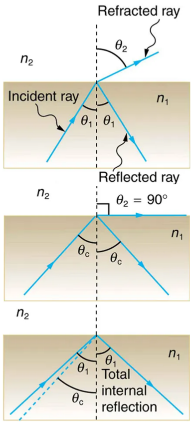
Good mirrors reflect $> 90\%$ of the light; however, total reflection can be produced via refraction.

If the index of refraction of the second medium is less than that of the first medium, the rays are refracted away from the perpendicular.

- Since $n_1 > n_2$, the angle of refraction is greater than the angel of incidence: $\theta_2 > \theta_1$.
- Increasing θ_1 causes θ_2 to increase.
- The critical angle (θ_c) is defined to be the incident angle (θ_1) that produces a $\theta_2 = 90°$

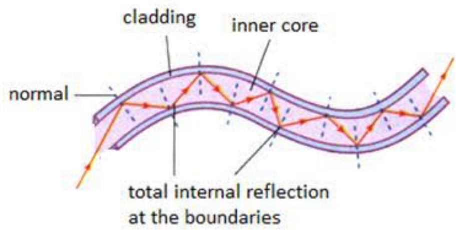
The critical angle is given by:

$$\theta_c = sin^{-1}(\frac{n_2}{n_1}), \quad \text{for} \ \ n_1 > n_2 \tag{4}$$



Fiber Optic Cable

The fiber optic cable takes advantage of the core having a high index of refraction than the cladding.



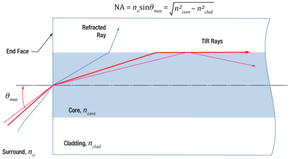
Fiber: Acceptance Angle

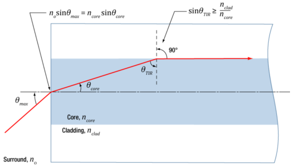
For multi-mode fibers, the numerical appeture (NA) provides a good estimate of the maximum acceptance angle.

- The cutoff angle is the maximum acceptance angle (θ_{max}), which is related to NA:

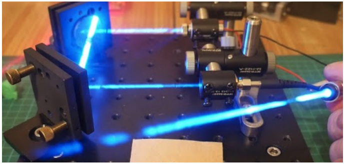
$$NA = n_0 sin(\theta_{max}) = \sqrt{n_{core}^2 + n_{clad}^2}$$

- Rays with an angle of incidence $\leq \theta_{max}$ are totally internally reflected (TIR) at the fiber core/cladding boundary.
- Rays with an angle of incidence $> \theta_{max}$ refract at and pass through the boundary.





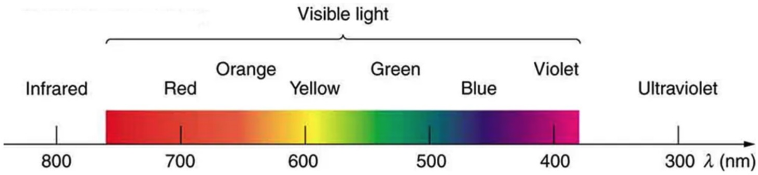
Assignment: Fiber Coupling



- Use the two mirror walk to align a HeNe laser beam to a fiber.
- Improve the quality of the coupling by maximizin the power meter reading.
- How can you improve the coupling?

Dispersion

Dispersion is defined to be the spreading of white light into its full spectrum of wavelengths.



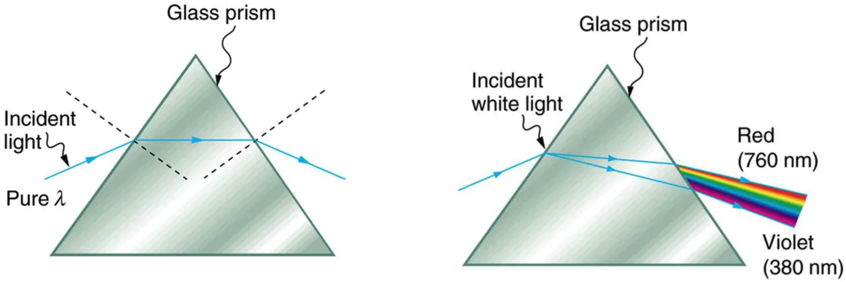
- The angle of refraction depends on the index of refraction.
- The index of refraction (n) depends on the properties of the medium.
- However, for a given medium, n also depends on the optical wavelength.

Index of Refraction by Wavelength

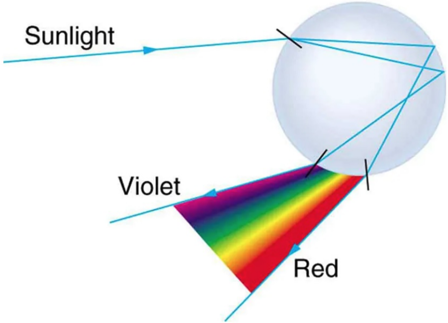
Index of refraction (n) by wavelength (λ):

Medium	**Red (660 nm)**	**Orange (610 nm)**	**Yellow (580 nm)**	**Green (550 nm)**	**Blue (470 nm)**	**Violet (410 nm)**
Water	1.331	1.332	1.333	1.335	1.338	1.342
Diamond	2.410	2.415	2.417	2.426	2.444	2.458
Glass, crown	1.512	1.514	1.518	1.519	1.524	1.530
Glass, flint	1.662	1.665	1.667	1.674	1.684	1.698
Polystyrene	1.488	1.490	1.492	1.493	1.499	1.506
Quartz, fused	1.455	1.456	1.458	1.459	1.462	1.468

Glass Prism

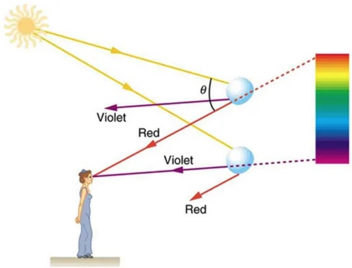

Glass prism
Incident
light
Pure λ
Glass prism
Incident
white light
Red
(760 nm)
Violet
(380 nm)

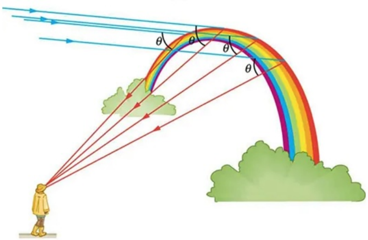
Rainbow



Rainbows are produced by a combination of refraction and reflection. You may have noticed that you see a rainbow only when you look away from the sun. Light enters a drop of water and is reflected from the back of the drop. The light is refracted both as it enters and as it leaves the drop. Since the index of refraction of water varies with wavelength, the light is dispersed, and a rainbow is observed.

Rainbow as an Arc



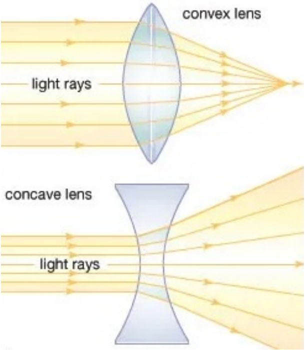


Lens

Lens

With the Law of Refraction, we can explore the properties of lens and how images are formed.

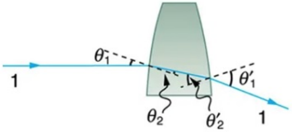
- The word lens comes from the Latin word for lentil bean, the shape of which is similar to a convex lens.
- Convex Lens: all light rays that enter parallel to the axis cross one another at a single point on the opposite side of the lens, i.e., they converge.
- Concave Lens: all light rays that enter parallel to the axis diverge (bend away) from the lens axis.

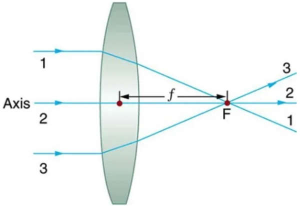


Convex Lens

With the Law of Refraction, we can explore the properties of lens and how images are formed.

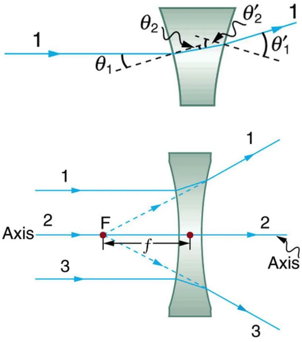
- A ray of light bends (refracts) at both interface, and for convex lens converge.
- The point at which the rays crossed is defined as the Focal point (F) of the lens.
- The distance from the center of the lens to its focal point is called the focal length (f).
- The Power of the lens, measuring in Diopters ($P = \frac{1}{f}$) where f is measured in meters.



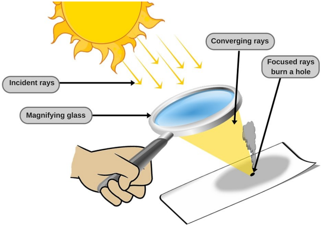


Concave Lens

- A concave lens is a diverging lens, it causes light rays to bend away from the axis.
- In the case of all rays entering parallel to its axis, the light appears to originate at the same point F.
- The distance from the center of the lens to its focal point is called the focal length (f) and is defined to be negative.



Assigment: Find the Focal Length



- Using some random lens, use the overhead lighting to find the focal length
- Repeat on optical table using laser
- Clean lens before putting away

Thin Lens

A thin lens is defined to be one whose thickness allows rays to refract but does not allow properties such as dispersion and aberrations.

Ray Tracing

1. A ray entering a converging lens parallel to its axis passes through the focal point F of the lens on the other side.
2. A ray entering a diverging lens parallel to its axis seems to come from the focal point F.
3. A ray passing through the center of either a converging or a diverging lens does not change direction.
4. A ray entering a converging lens through its focal point exits parallel to its axis.
5. A ray that enters a diverging lens by heading toward the focal point on the opposite side exits parallel to the axis.

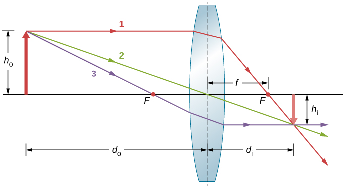
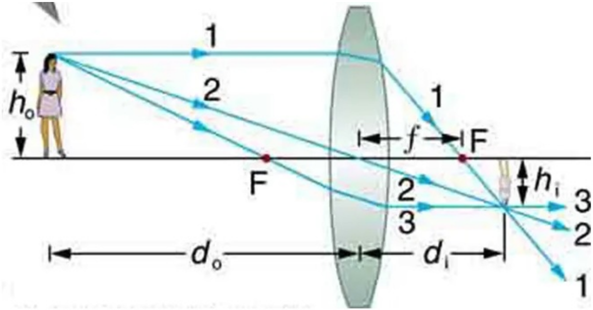


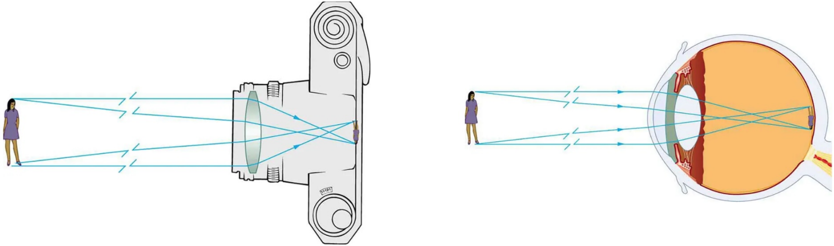
Image Formation



Thin Lens equations:

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f} \qquad \frac{h_i}{h_o} = -\frac{d_i}{d_o} = m$$

Image Formation - Real Image

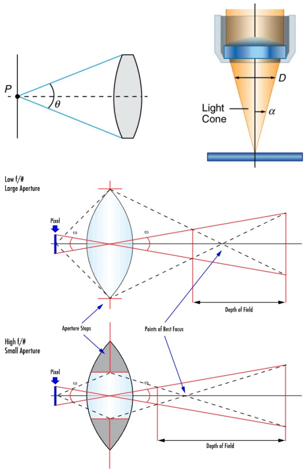


The image in which light rays from one point on the object actually cross at the location of the image and can be projected onto a screen, a piece of film, or the retina of an eye is called a real image.

Assignment - Focus CCD Camera

- Get a Thor CCD camera from the Optical Tweezer kit
- Select lens tube, adjustable lens tube, and lens
- Assemble and mount on table.
- Connect to ThorCam software
- Using adjustable lens tube, focus on various objects

Optical System Parameters



- Numerical Aperture (NA):

$$NA = n \cdot sin(\alpha) \text{ where } \alpha = \frac{\theta}{2}$$

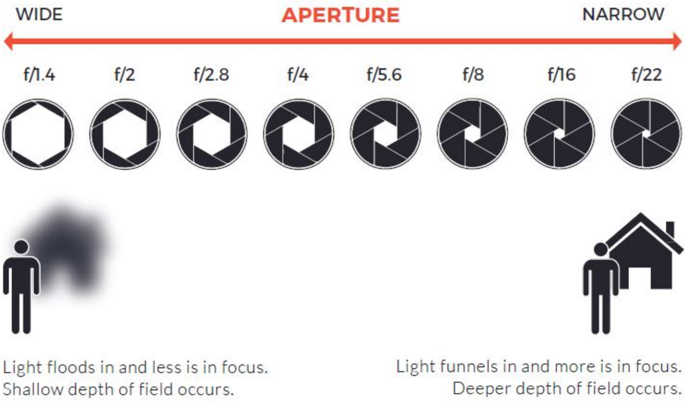
- f-number - light per unit area reaching image plane:

$$f/\# = \frac{f}{D} \approx \frac{1}{2NA}$$

- Resolution and Depth of Focus:

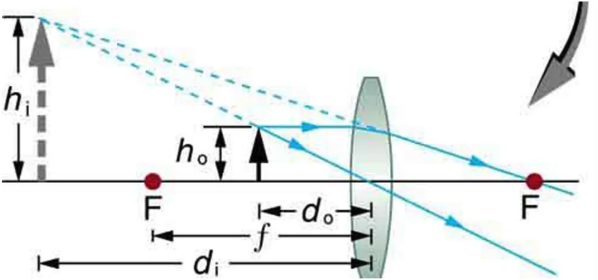
$$R = \frac{1.22\lambda}{2NA} \text{ and } DOF = \frac{\lambda n}{NA^2}$$

Aside: Camera f-step



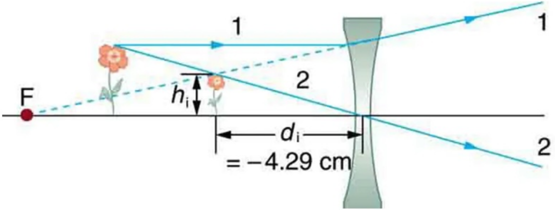
$$f/1 = \frac{f}{(\sqrt{2})^0}, f/1.4 = \frac{f}{(\sqrt{2})^1}, f/2 = \frac{f}{(\sqrt{2})^2}, f/2.8 = \frac{f}{(\sqrt{2})^3}, \ldots$$

Image Formation - Virtual Image

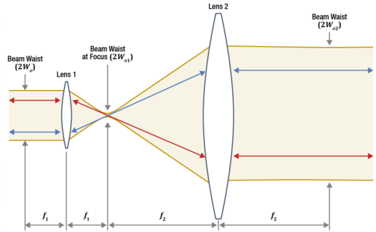


If an object is held closer to the converging lens than its focal length (f), then the rays from a common point continue to diverge after passing through the lens. They all appear to originate from a point at the location of the image, on the same side of the lens as the object. This is a virtual image.

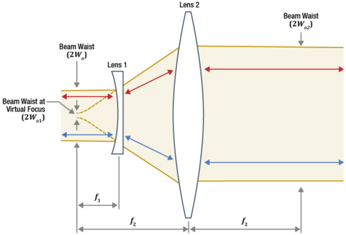
Image Formation - Concave Lens



Beam Expander/Reducer - Telescope



Galilean Design



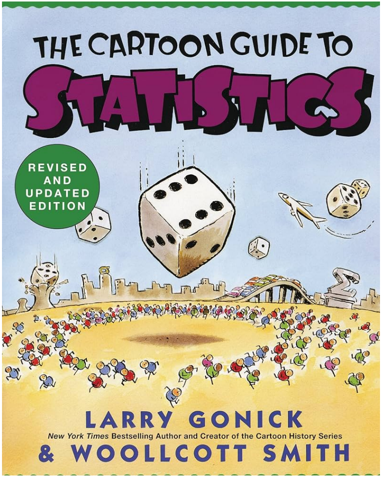
Galilean Design

Both the bean's waist $(2W_0)$ and the divergence angle (θ) are affected by by the beam expanders and reducers. If Lens 2 is the output lens, then the beam expansion ratio (m_{12}) is:

$$m_{12} = \frac{f_2}{f_1} \tag{5}$$

Math Interlude: Probability

Probability and Statistics



- Data Analysis: The gathering, display, and summary of data
- Probability: The laws of chance (inside and outside of a casino)
- Statistical Inference: the science of drawing statistical conclusions from specific data using the laws of probability

A Tale as Old as Time

Gambling is as old as mankind, so it seems that probability should be almost as old. But, the realization that one could predict an outcome to a certain degree of accuracy was unconceivable until the 16^{th} century. In order to make a profit, underwriters were in need of dependable guidelines by which a profit could be expected, while the gambler was interested in predicting the possibility of gain.

Rich Guys Gambling

Known as the "Father of Probability", Gerolamo Cardano was an Italian mathematician, physician, and gambler who first talked about probability. Cardano's fascination with games of chance led him to write the first book dedicated to probability, "Liber de Ludo Aleae" (Book on Games of Chance), published in 1564. Cardano introduced concepts like odds and probabilities in this work, providing a framework for analyzing the likelihood of different outcomes in dice rolls and other games.

Probability

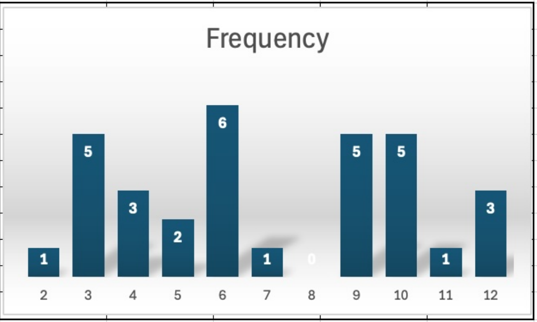
The probability of an event expresses the likelihood of the event outcome

$$P(event) = \frac{\text{\# of favorable outcomes}}{\text{\# of all possibly outcomes}}$$

Frequency Tables and Histograms

Roll two dice and add them together, repeat.

Dice Roll	Frequency
2	1
3	5
4	3
5	2
6	6
7	1
8	0
9	5
10	5
11	1
12	3



Assignment: Tenzi

Role two dice 12 times, after each role:

- Record the sum
- Record the running average (total up to this point divided by number of roles)

After the twelfth role:

- Create a histogram of the sums
- Create a line chart of the running averages

Summary Statistics

- Mean (or average): add the totals and divide by number of samples

$$\bar{x} = \frac{x_1 + x_2 + x_3 + \ldots + x_n}{n}$$

or

$$\bar{x} = \frac{\sum_{i=1}^{n}(x_i)}{n}$$

- Median: middle sample in the ordered distribution
  - Odd: median is the value of middle sample
  - Even: median is the average of the two middle samples
- Mode: the value the appears most often

Dice Roll	Frequency	Total
2	1	2
3	5	15
4	3	12
5	2	10
6	6	36
7	1	7
8	0	0
9	5	45
10	5	50
11	1	11
12	3	36
SUM	**32**	**224**

$$\text{average} = \bar{x} = 7$$
$$\text{median} = 6$$
$$\text{mode} = 6$$

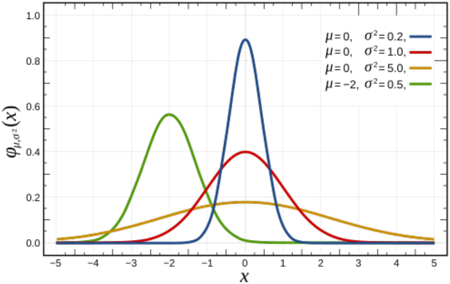
Summary Statistics: Variation

1-8								9-16								17-24								25-32							
2	3	3	3	3	3	4	4	4	5	5	6	6	6	6	6	6	7	9	9	9	9	9	10	10	10	10	10	11	12	12	12

- Interquartile Range (IRQ): Spread of the middle 50% of the data
  - Find the median
  - Find the first quartile (Q1): median of the lower half.
  - Find the third quartile (Q3): median of the upper half.
  - IRQ = Q3 - Q1 = 6
- Standard Deviations (σ):

$$\sigma = \sqrt{\frac{\sum_{i=0}^{n}(x_i - \bar{x})^2}{n}} = 3.06$$

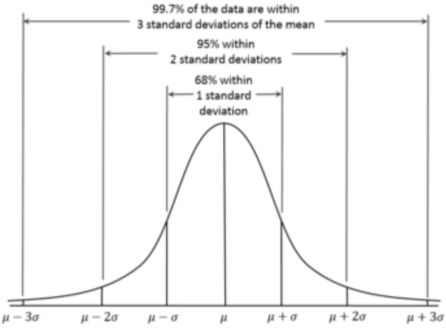
Gaussian Distribution



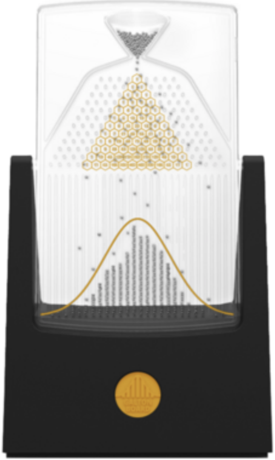
Probability Distribution Function $f(x)$:

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-(x-\bar{x})^2}{2\sigma^2}}$$

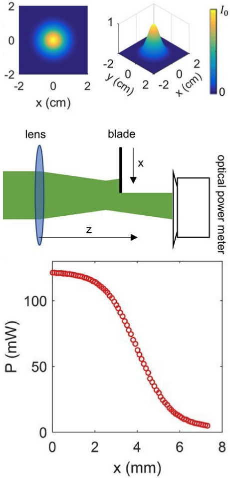
Gaussian Distribution: 3σ



Galton Baord



Assignment: Measuring Bean Profile



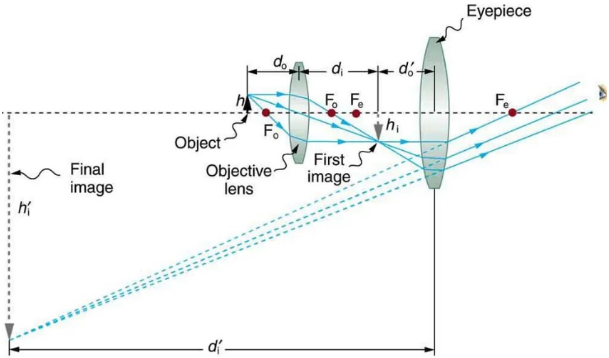
The laser beam has a Gaussian profile.

1. Direct a laser beam at a power meter, setting the correct wavelength
2. Moving the knife edge across the beam path, record the drop in power vs distance.
3. Setup a telescope to expand the beam size by 2-5 times.
4. Repeat the knife edge process.
5. Plot the results of both sets of measurements on paper and in excel.

Python Excursion

Optical Tweezers

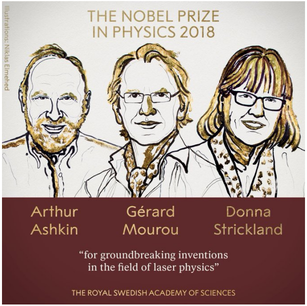
Microscope



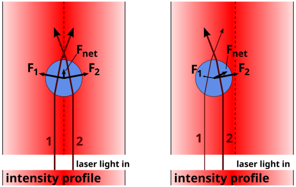
$$m = m_o \cdot m_e = (-\frac{d_i}{d_o}) \cdot (-\frac{d_i'}{d_o'})$$

Optical Tweezers - Collimated Laser

- Ashkin's award was being given for his ability to "realize an old dream of science fiction – using the radiation pressure of light to move physical objects" aka the Tractor Beam.
- In 1987 Ashkin and his team were able to send a laser through a microscope's objective lens and trapping particles varying in size from a tens of nanometres up to tens of micrometres

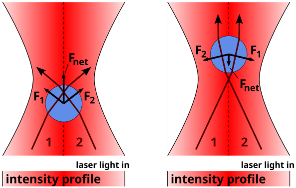


Optical Tweezers - Collimated Laser



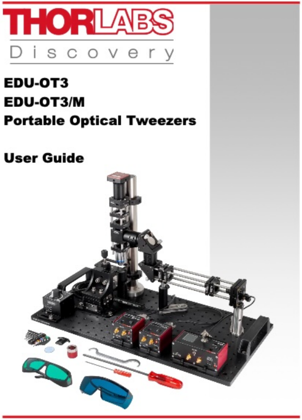
When the bead is displaced from the beam center (right image), the larger momentum change of the more intense rays cause a net force to be applied back toward the center of the laser. When the bead is laterally centered on the beam (left image), the resulting lateral force is zero. But an unfocused laser still causes a force pointing away from the laser.

Optical Tweezers - Focused Laser



In addition to keeping the bead in the center of the laser, a focused laser also keeps the bead in a fixed axial position: The momentum change of the focused rays causes a force towards the laser focus, both when the bead is in front (left image) or behind (right image) the laser focus. So, the bead will stay slightly behind the focus, where this force compensates the scattering force.

Assignment: Optical Tweezers

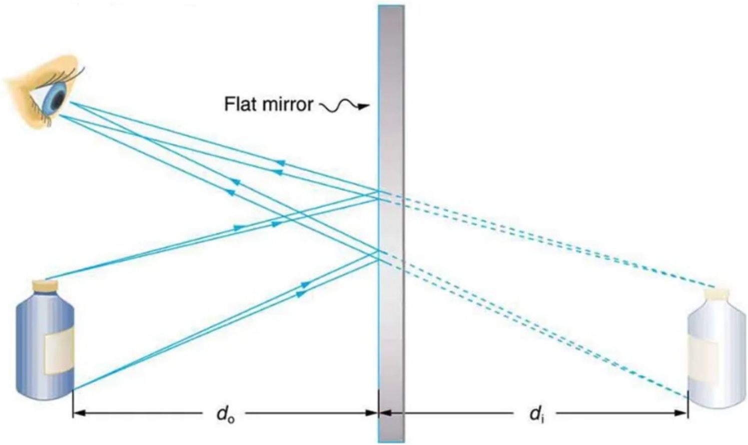


Over the next few days, we will take a few hours at a time to work on EDU-OT3

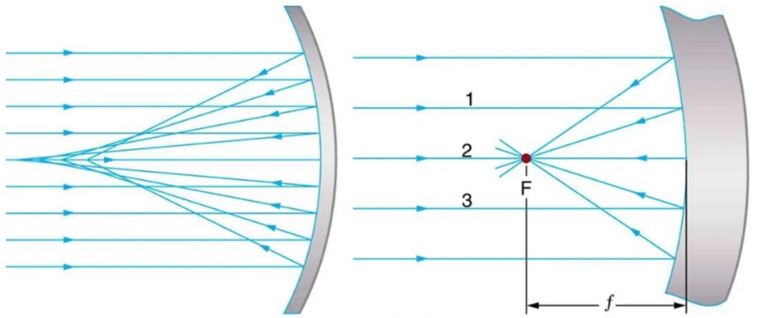
- Carefully get the parts for the Optical Tweezers from the cabinets
- Please don't write in the lab manuals, document progress in your notebooks.
- Follow assembly instructions
  - Take your time, alignment is critical
  - Take notes on the handouts on any documentation changes you feel are needed
- Once constructed, follow the experiment instructions.

Mirrors

Flat Mirror



Concave Spherical Mirrors - Thin Lens Equivalent



For a mirror that is large compared to the radius of curvature, the reflected rays do not cross at the same point. A parabolic mirror, the rays would indeed cross at a single point. However, parabolic mirrors are expensive. So, using a mirror that is small compared to the radius of curvature, leads to a well-defined focal point F, with $f = \frac{R}{2}$.

Convex Mirrors

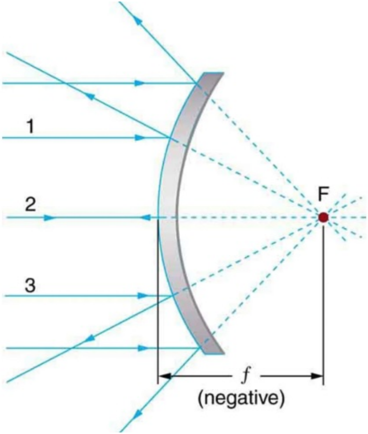


Image Formation - Concave Mirrors

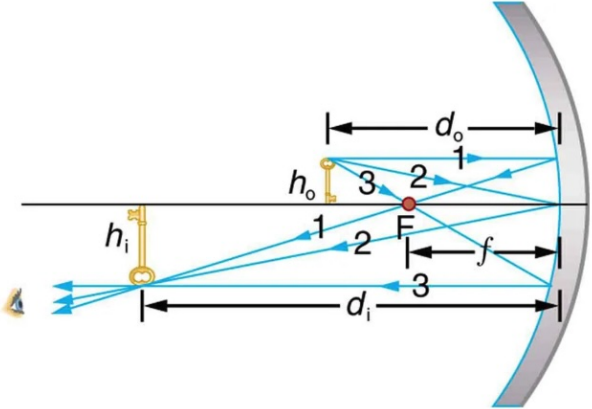


Image Formation - Concave Mirrors

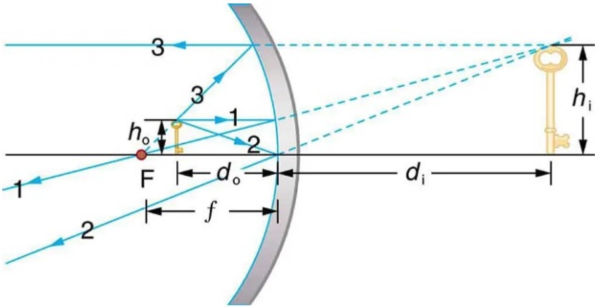
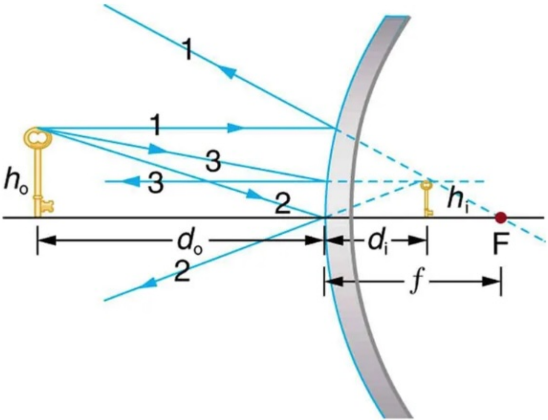
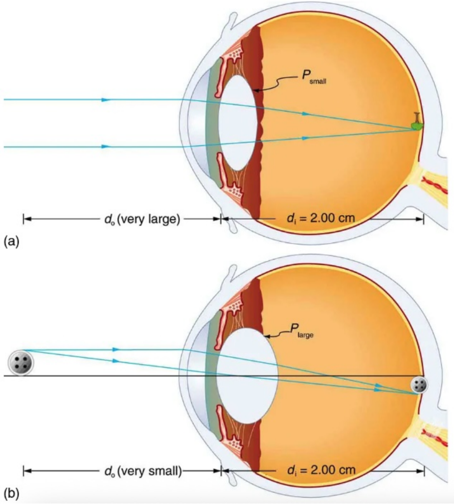


Image Formation - Convex Mirrors

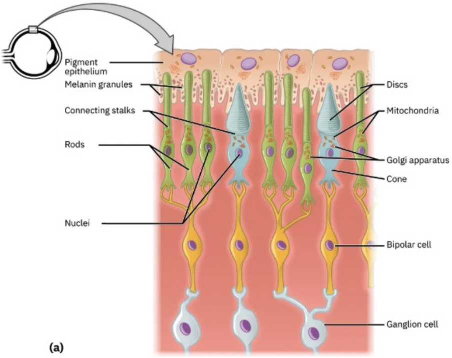


Vision

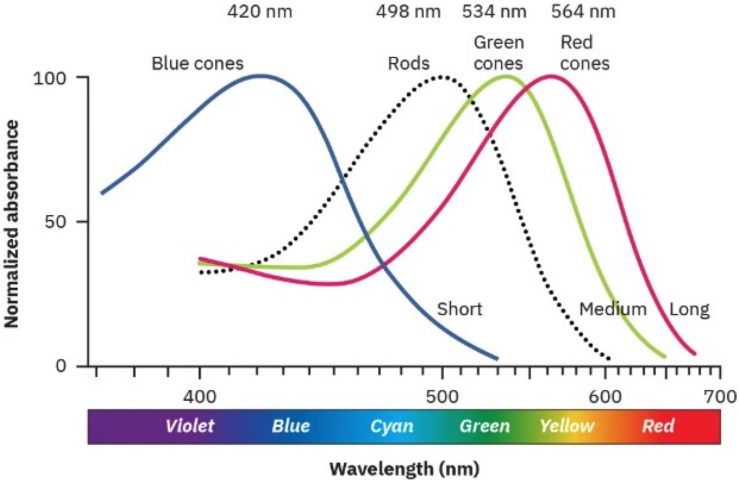
The Eye


P_{small}
d_o (very large)
d_i = 2.00 cm
(a)
P_{large}
d_o (very small)
d_i = 2.00 cm
(b)

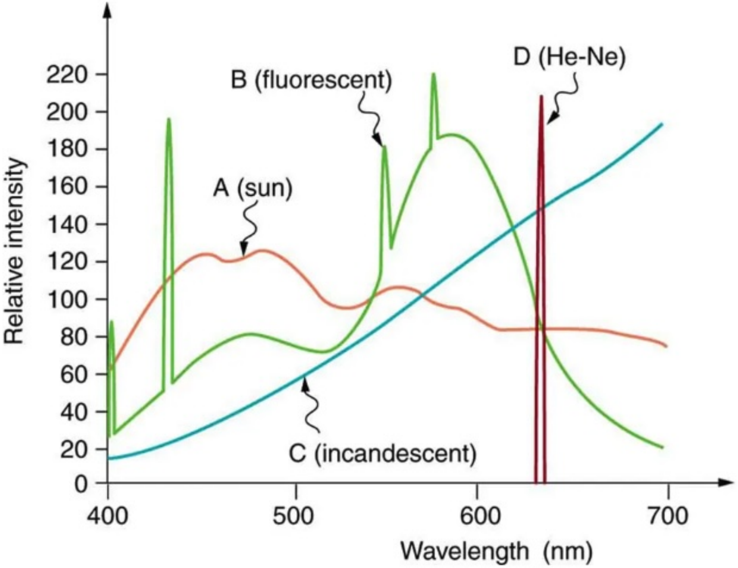
Rods and Cones and Color



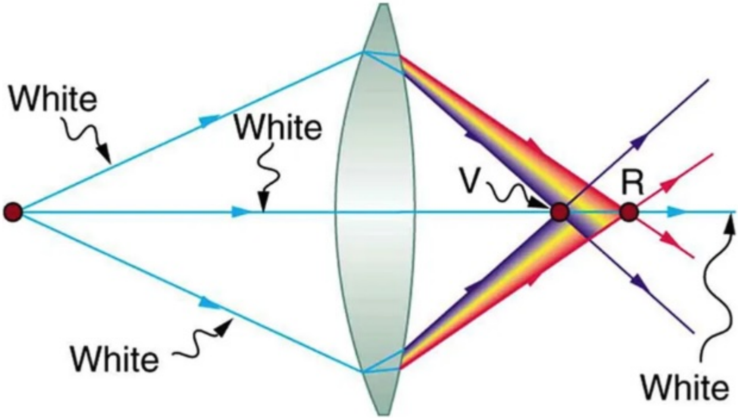
Visible Spectrum



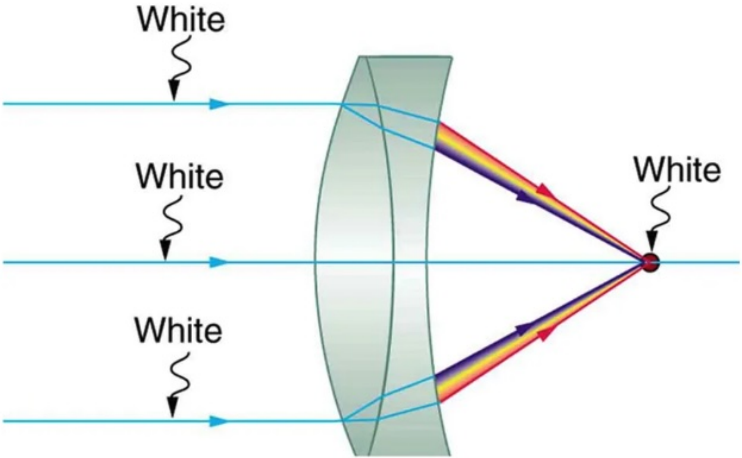
Spectrum of Light Sources



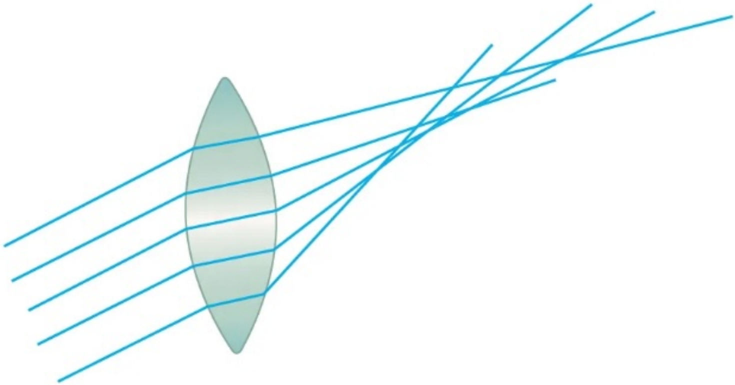
Chromatic Aberrations



Correcting Chromatic Aberrations



Coma - Off Axis Abberation



Spherical Aberrations