Light

We are told to let our light shine, and if it does, we won't need to tell anybody it does. Lighthouses don't fire cannons to call attention to their shining- they just shine.

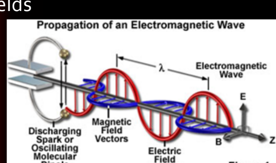
-- Dwight L. Moody
American Evangelist

Electromagnetic Waves

- Recall:
  - **Electromagnetic Waves** do **NOT** require matter to transport energy
  - Only type of wave that can travel thru space

How are Electromagnetic Waves Produced?

- By Accelerating a Charge
  - Any object that carries charge and moves with a non-zero acceleration radiates EM *waves*
  - EM waves consist of changing electric and magnetic fields

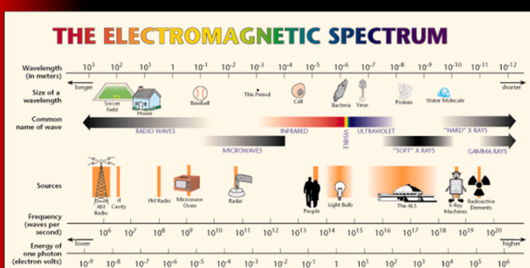


Electromagnetic Waves

- How many ways can a charge be accelerated?
  - Infinite
  - This allows for an infinite number of EM wave frequencies
    - We classify/group EM waves based on their frequencies and/or usage

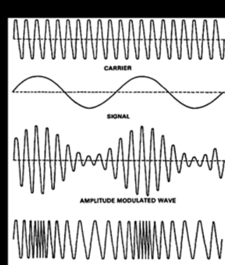
Electromagnetic Waves

- Electromagnetic Spectrum

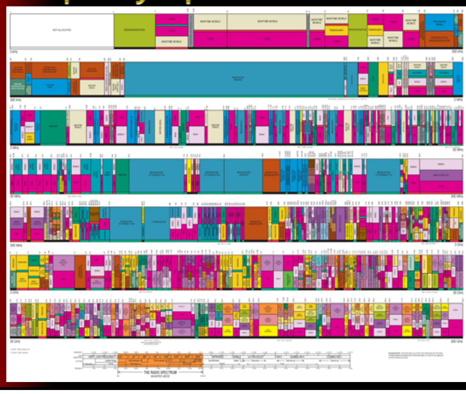


Radio & Microwaves

- Longest wavelengths & lowest frequencies of the EMS
  - Include AM, FM and Television frequencies
    - AM – Amplitude modulation: same frequency waves just a change in the amplitude. (535 – 1700 KHz)
      - Long ranged, poor quality, easily susceptible to interference effects
    - FM – Frequency Modulation: slight changes in frequency with same amplitude. (88 – 108 MHz)
      - Short ranged, better quality, not hardly susceptible to interference effects



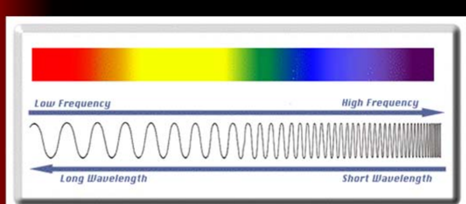
Frequency Spectrum of the US



Microwave & Infrared EM Waves

- Microwave: used in microwave ovens & cellular phones
- Infrared: Fast Food Heat Lamps, night time surveillance tool.

Visible Light



Low Energy High Energy

Visible Light

Color	Wavelength
violet	380–420 nm
indigo	420–450 nm
blue	450–495 nm
green	495–570 nm
yellow	570–590 nm
orange	590–620 nm
red	620–750 nm

Length Conversion

$1\ nm = 1 \times 10^{-9}\ m$
(nanometer)

Time Conversion

$1\ THz = 1 \times 10^{12}\ Hz$
(TeraHertz)

Color	Frequency
violet	790–714 THz
indigo	714–667 THz
blue	667–606 THz
green	606–526 THz
yellow	526–508 THz
orange	508–484 THz
red	484–400 THz

UV, X-ray & Gamma Rays

- Ultra-Violet Rays: EM waves just beyond the visible spectrum
  - UVA (400-320 nm) – most penetrating (*tanning beds, black lights*)
  - UVB (320-290 nm) – most damaging to skin, reflects off water/snow (*sun*)
- X-rays: used extensively in medicine to see "into" the body
- Gamma Rays: used in medicine to treat cancer or destructive radiation from nuclear explosions.



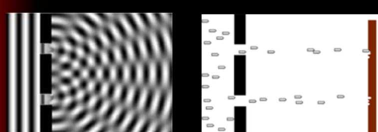

The Nature of Light (EM Waves)

- Is light a wave or particle?
  - A wave right, why would we even ask?
    - Wave Interference Effects
    - Speed of Light
    - Boundary/Edge Effects
    - Polarization

Wave Interference Effects

Light passes through each other without "colliding" like particles would

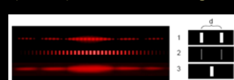
Wave Interference Effects



Water waves pass through a double slit and display constructive and destructive interference

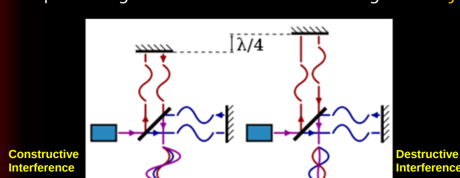
Particles should stop completely except those traveling straight through the hole.

Observed →



Speed of Light

- A single color of light with a known frequency (f), is split to follow two paths and then recombined.
- By adjusting the path length and observing the interference pattern, the wavelength of the light (λ) can be determined.
- The speed of light can then be calculated using the $v = \lambda f$.



Speed of Light

- This method is very, very accurate. In a vacuum, the speed of light is:

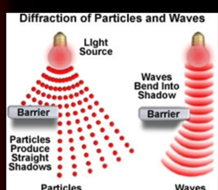
  299,792,458 ± 3.5×10^{-9} m/s (*670 million mph*)

  or

  3×10^{8} m/s *written as the symbol c*

- This is the speed of **ALL** electromagnetic waves in a vacuum!
- When light or **ANY** other EM wave encounters a medium, its speed **decreases**!

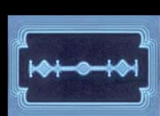
Boundary/Edge Effects



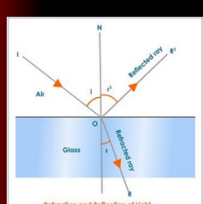
Waves bend or diffract around corners/barriers
(*would produce **blurry** image*)

Particles would stop completely except those traveling straight and not encountering the barrier
(*would produce **sharp** image*)

Observed →



Boundary/Edge Effects



When light hits the boundary between two media (*like air and glass*) part of the light is transmitted and refracts, while part of it is reflected.

When a particle hits a boundary, it will collide and stop or scatter off the surface .
(*could not see into other media*)

Observed →

Boundary/Edge Effects

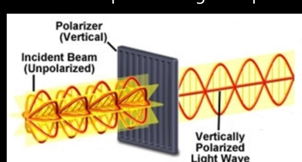
Invisibility Cloaks

This cloak works by steering microwave light around an object.

Materials that bend light in this way do **NOT** exist naturally and have to be *engineered* with the necessary optical properties.

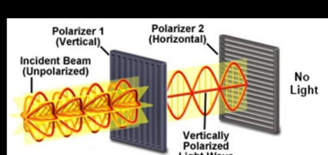
Polarization

- A polarizer can be considered a specialized type of molecular **Venetian blind** having tiny rows of slats that are oriented in a single direction within the polarizing material.
- Only light rays oriented parallel to the polarizing direction are able to pass through the polarizer.

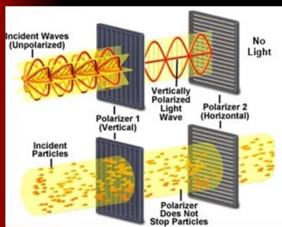


Polarization

- When a second polarizer is placed in line and rotated at a small angle, the amount of light passing through the second is decreased.
- If the second polarizer is rotated perpendicular to that of the first polarizer, then none of the light passes through.

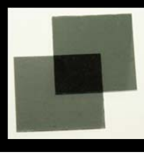


Polarization

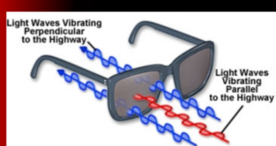


Some particles would continue traveling straight and pass through the second polarizer.

Observed →



Polarization

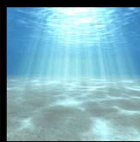


Horizontally-polarized light waves are what cause glare. The lenses of polarized sunglasses are coated with a special film in order to reduce glare.

The Nature of Light

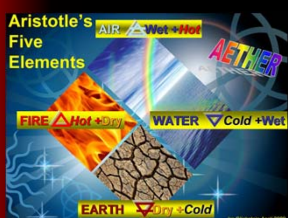
- Case closed. Light is a wave!
- Not so fast… What about these?
  - Medium Independent
  - Light "rays"
  - Particle diffraction
  - Photoelectric effect

Medium Independent



Light can travel through solids, liquids, gases or even the vacuum of space!

Medium Independent



← Remember This?

Modern scientists postulated that all space was filled with an 'ether' that light waves could move through.

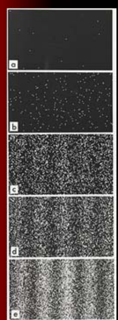
Problem! All tests have failed to prove its existence!

Light "Rays"

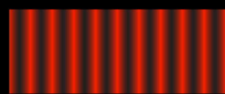
Light travels in straight lines from a source, called rays. It's what produces shadows. (*Rays don't bend around objects*)

Particles travel in straight lines, not waves.

Particle Diffraction



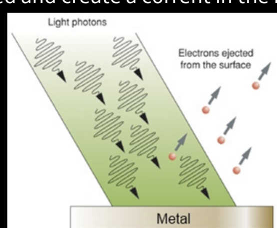
Electron (*a particle*) diffraction pattern build up through a double slit over time.



Light diffraction pattern through a double slit.

Photoelectric Effect

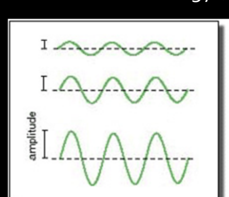
- When light shines on a piece of metal, electrons are freed and create a current in the metal.



- However, not all colors of light affect metals in this way.

Photoelectric Effect

- Waves can have any amount of energy you want
  - big waves have a lot of energy, small waves have very little.
- If light is a wave, then the brightness of the light represents the amount of energy (*amplitude*).



Photoelectric Effect

- Different colors of light are defined by the amount of energy they have.

  In General:

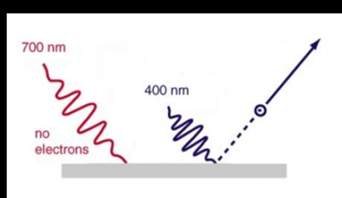
  Blue Light > Red Light

  However, a wave theory allows for:

  Dim Blue Light = Bright Red Light

Photoelectric Effect

- However, no matter how bright a red light you shine on the metal, it will **NOT** produce a current, but the dimmest blue light **WILL**.



Photoelectric Effect

- Solution
  - Light is a Particle (photon) which carries a discrete (*fixed*) amount of energy based on its color (*frequency*).

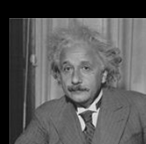
$$E = hf \quad or \quad E = \frac{hc}{\lambda} \qquad using \quad v = c = \lambda f$$

h = Planck's Constant

$$h = 6.626x10^{-34}\ J \cdot s$$

or

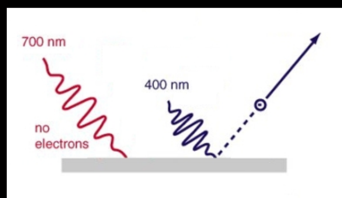
$$h = 4.136x10^{-15}\ eV \cdot s$$



Energy conversion: $1\,eV = 1.602\,x\,10^{-19}\ J$
(electron-volt)

Photoelectric Effect

- Red light may not carry enough energy to dislodge electrons in a particular metal, but blue light could.



Photoelectric Effect

Example

- **How much energy does red light (700 nm) carry in eV? Blue light (400 nm)?**

- Changing the brightness in the particle model does **NOT** change the amount of energy a light particle carries, only the number of particles present.

Photoelectric Effect

Example

- **What is the frequency (in THz) of a certain yellow light if it carries 2.11 eV worth of energy?**

Color	Frequency
violet	790–714 THz
indigo	714–667 THz
blue	667–606 THz
green	606–526 THz
yellow	526–508 THz
orange	508–484 THz
red	484–400 THz

Photoelectric Effect

- The particle model of light not only explained the photoelectric effect completely, but it also accurately predicted frequencies of light that would eject electrons in all types of metals.

The Verdict?

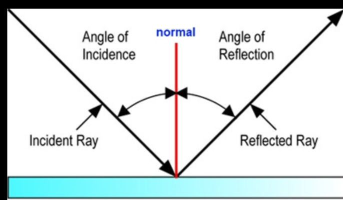
- So what is light then, a wave or a particle?
- Answer…
  - Both? (*the model used depends on the application*)
  - Other?

Light interacting with Matter

- Recall:
  When waves encounter matter, a barrier or change in medium type, they can be:
  - Absorbed
    - Taken in by matter, resulting in temp increase or broken atomic or molecular bonds
  - Transmitted (Refraction)
    - Passes through
  - Reflected (Reflection)
    - Bounces back

Reflection

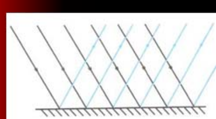
Law of Reflection



Angle of Incidence = Angle of Reflection
(Angle in = Angle out)

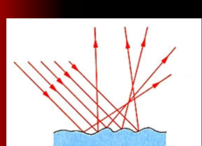
Reflection

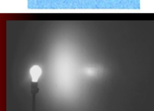
- Types of Reflection
  - Regular Reflection *(Perfect Copy)*



Reflection

- Types of Reflection
  - Diffuse Reflection *(Fuzzy Copy)*



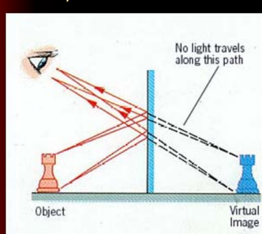


Reflection

- Applications
  - Mirrors
  - Fiber Optics

Reflection

- Mirrors
  - When you look in the mirror, the objects seem to be behind the mirror. The law of reflection shows why.

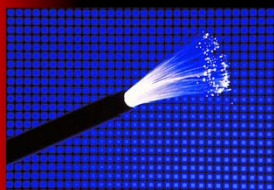


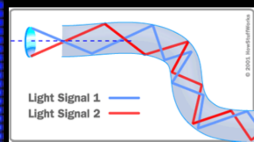
Reflection

- Multiple Mirrors

Reflection

- Fiber Optics (Internal Reflection)





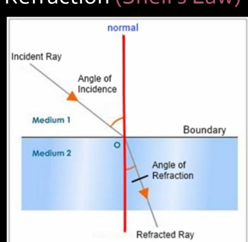
DEMO

Reflection

- Optical Illusion (Internal Reflection)

Refraction

Law of Refraction (Snell's Law)



Light bends as it passes from one medium to another due to a speed change

Refraction

- Can we predict the direction of the bending of a wave and by how much?
  YES!
- Observation
  - If the new medium is denser, the incoming wave bends ***toward*** the normal line
  - If the new medium is less dense, the incoming wave bends ***away from*** the normal line

Refraction

- Observation
  - As light goes from one medium to another, the frequency of the wave REMAINS UNCHANGED!
    (However, speed and wavelength **CAN** change)
  - Frequency is an intrinsic property of a wave (*like mass*)
  - Wavelength is an environmentally dependent property (*like weight*)
- The official model for refraction is:

$$\frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2}$$

with *v = speed of light in medium*
λ = wavelength of light in medium

Refraction

- Another model for the Law of Refraction is:

$$\frac{n_2}{n_1} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2}$$

with *n = index of refraction of medium*

- Index of Refraction (*optical density*)
  - *A measure of how much light will bend in a medium*

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

Large values of *n* bend more

Refraction

- Values of *n* for some common substances

Material	Index	Crown glasses	1.52-1.62
Vacuum	1.00000	Spectacle crown, C-1	1.523
Air at STP	1.00029	Sodium chloride	1.54
Ice	1.31	Polystyrene	1.55-1.59
Water at 20 C	1.33	Carbon disulfide	1.63
Acetone	1.36	Flint glasses	1.57-1.75
Ethyl alcohol	1.36	Heavy flint glass	1.65
Sugar solution(30%)	1.38	Extra dense flint, EDF-3	1.7200
Fluorite	1.433	Methylene iodide	1.74
Fused quartz	1.46	Sapphire	1.77
Glycerin	1.473	Heaviest flint glass	1.89
Sugar solution (80%)	1.49	Diamond	2.417

Refraction

- Observation
  - If $n_i < n_f$, the incoming wave bends ***toward*** the normal line
  - If $n_i > n_f$, the incoming wave bends ***away from*** the normal line
  - If $n_i = n_f$, the incoming wave ***does NOT bend*** at all

Refraction

Example

What is the speed of light in water (n = 1.33)?

Refraction

Example

A red light ray (656 nm) passes from air (1.00) to water (1.33). What is the wavelength of the light ray in the water? Is it still red?

Color	Wavelength
violet	380–420 nm
indigo	420–450 nm
blue	450–495 nm
green	495–570 nm
yellow	570–590 nm
orange	590–620 nm
red	620–750 nm

Frequency determines color, not wavelength in media!

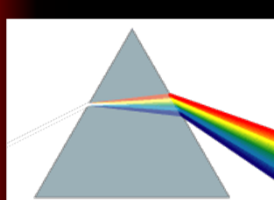
(in a vacuum [or air], you can use either)

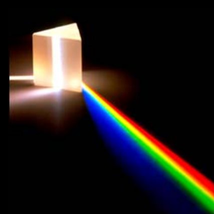
Refraction

- Applications
  - Prisms
  - Mirages
  - Optics

Refraction

- Prism
  - Recall that as light travels between media, its speed and wavelength change, but not its frequency.





Refraction

- Prism
  - Recall

$$\frac{n_f}{n_i} = \frac{\lambda_i}{\lambda_f}$$

  - Rearranging

$$n_f = n_i\left(\frac{\lambda_i}{\lambda_f}\right)$$

$$n_f \propto \frac{1}{\lambda_f}$$

→ Different colors (*wavelengths*) of light see a ***different*** index of refraction

Refraction

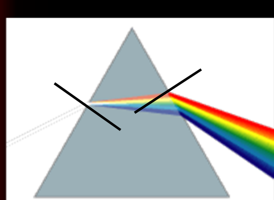
- Prism

Material	Blue (486.1 nm)	Yellow (589.3 nm)	Red (656.3 nm)
Crown Glass	1.524	1.517	1.515
Flint Glass	1.639	1.627	1.622
Water	1.337	1.333	1.331
Cargille Oil	1.530	1.520	1.516
Carbon Disulfide	1.652	1.628	1.618

$$n_f \propto \frac{1}{\lambda_f}$$

Refraction

- Prism
  - Since each color sees a different index of refraction, each color will bend differently.

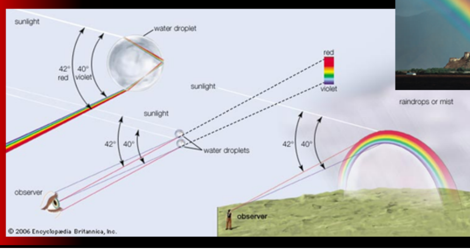


Red (*long wavelength*)
small *n*, bends only a little

Violet (*short wavelength*)
large *n*, bends a lot

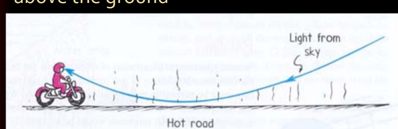
Refraction

- Rainbows
  - Light shines thru tiny droplets of water which act like little prisms



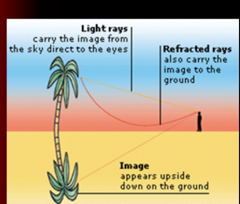
Refraction

- Mirages
  - Light bends toward the cooler, denser medium above the ground



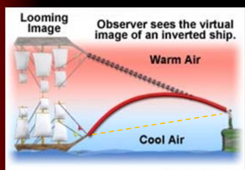
Refraction

- Mirages



Refraction

- Looming



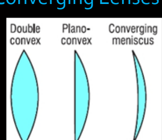
Refraction

- Optics
  - The study of light and vision
  - Lenses - a piece of glass or other transparent material, used to converge or diverge transmitted light

    2 Types of Lenses
    - Converging Lens - Focuses light to a single point
    - Diverging Lens - Spreads light out

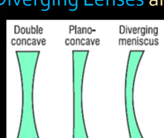
Refraction

- Converging Lenses are also called Convex Lenses



Thicker in the middle than at the edges

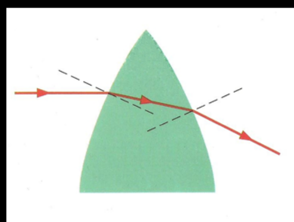
- Diverging Lenses are also called Concave Lenses



Thinner in the middle than at the edges

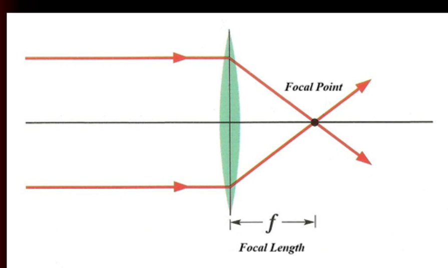
Refraction

- Converging Lenses



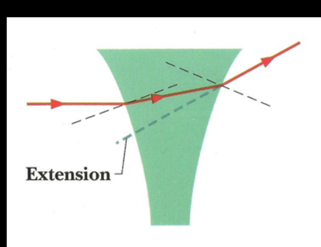
Refraction

- Converging Lenses



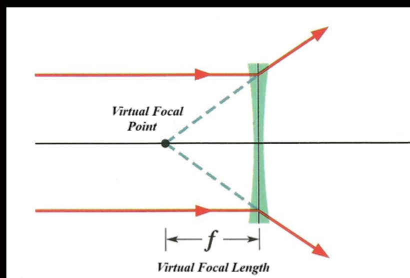
Refraction

- Diverging Lenses



Refraction

- Diverging Lenses



Refraction

Refraction & Negative Refraction

Not a normal Glass!

Light Bending through 2 media
Liquid to Glass
Glass to Air

Color

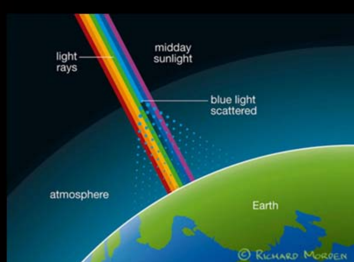
- The color of the object you see is the light that is reflected or scattered from its surface. **All other colors are absorbed by the object.**

Color

- Why is the sky blue?

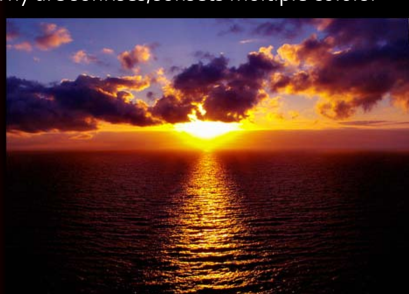
Color

- Blue wavelengths are being scattered by air molecules in the atmosphere



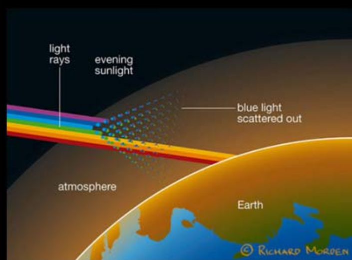
Color

- Why are sunrises/sunsets multiple colors?



Color

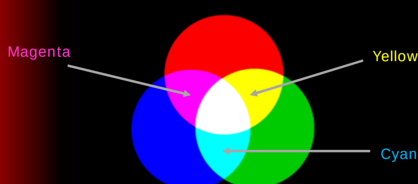
- Most short wavelengths are being scattered by air molecules and air borne particles (*i.e. dust*)



Color

primary colors - the 3 colors of light that can combine to form all other colors

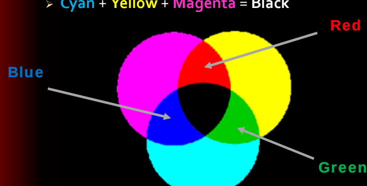
- Red, Blue, Green
  - Red + Blue = Magenta (*secondary color*)
  - Red + Green = Yellow (*secondary color*)
  - Green + Blue = Cyan (*secondary color*)
  - Red + Green + Blue = White



Color

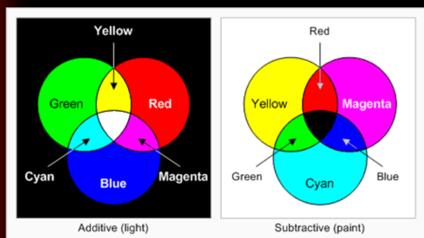
Pigment – substance that colors other materials like paints, inks, etc.

- **Primary Pigments** are **Cyan**, **Yellow** & **Magenta**
  - Cyan + Yellow = Green
  - Yellow + Magenta = Red
  - Cyan + Magenta = Blue
  - Cyan + Yellow + Magenta = Black

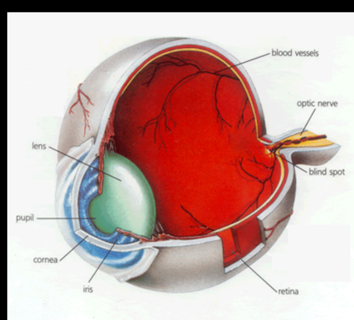


Color

- Three primary colors = Three secondary pigments
- Three primary pigments = Three secondary colors



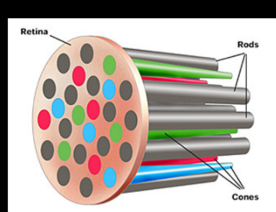
Human Vision



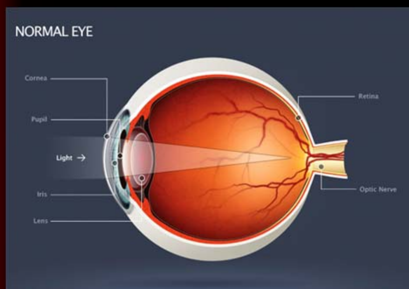
Human Vision

- Retina
  contains the rods & cones that are sensitive to light
- Rods (*about 1 billion*)
  sensitive to brightness, light and dark & movement
- Cones (*about 3 million*)
  detect color

  3 types of cones: sensitive to red, blue & green light.

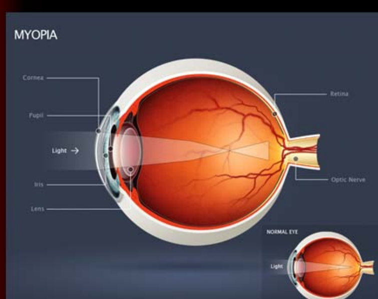


Human Vision



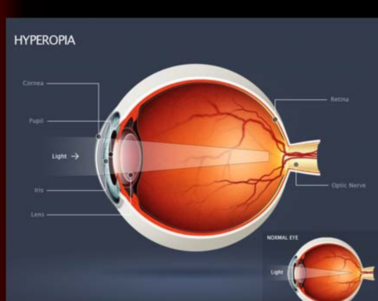
Light focuses at a single point on the retina.

Human Vision



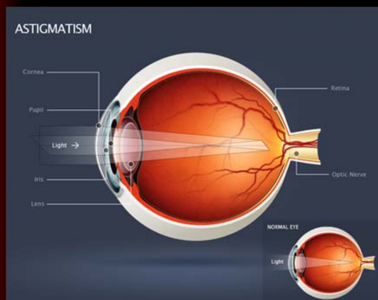
Light focuses at a single point in front of the retina.

Human Vision



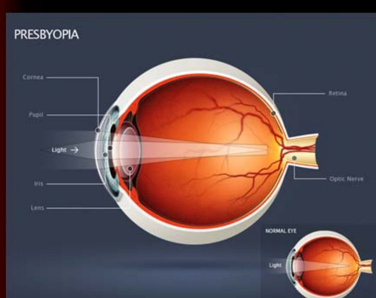
Light focuses at a single point behind the retina.

Human Vision



Light focuses at a multiple points on the retina.

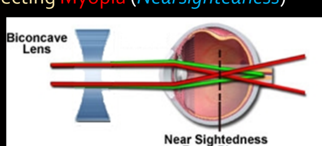
Human Vision



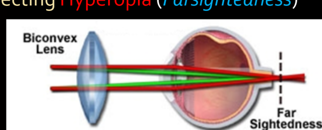
Lens loses some of its elasticity.

Human Vision

- Correcting Myopia (*Nearsightedness*)



- Correcting Hyperopia (*Farsightedness*)



Human Vision

Glasses


Before


After

Human Vision

Hubble Telescope Image: M100 Galaxy Core


Before

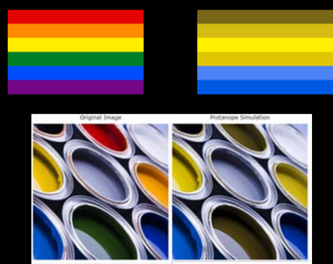

After

Color Blindness

- The inability to see or perceive color in the usual way
  - Two Major Types:
    - Red-Green
      - Protanopia
      - Deuteranopia
    - Blue-Yellow
      - Tritanopia

Color Blindness

- Red-Green
  - Protanopia



Color Blindness

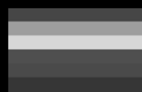
- Red-Green
  - Deuteranopia

Color Blindness

- Blue-Yellow
  - Tritanopia

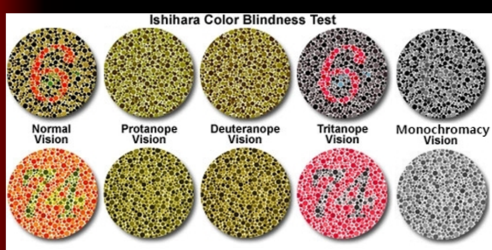
Color Blindness

- Total Color Blindness (*Monochromacy*)
  - Achromatopsia

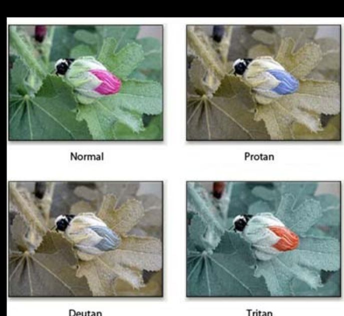


Color Blindness

Color Blind Test Chart



Color Blindness



Color Blindness

Normal

As water reflects a face,
so a man's heart reflects the man.

Proverbs 27:19