The Nature of Light and Matter 1
Light

ASTR 101

4/2/2018

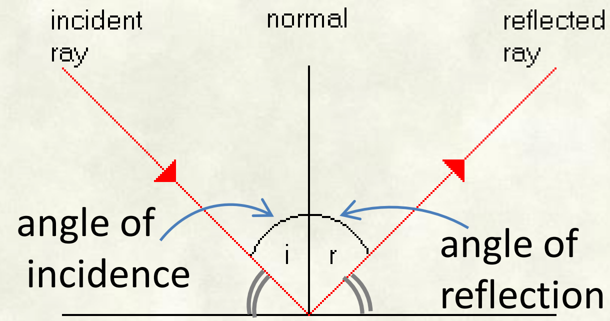
Properties of light: reflection refraction, dispersion
Rainbows
Nature of light: wave and corpuscular theory
Electromagnetic spectrum

The Nature of Light

Basic properties:

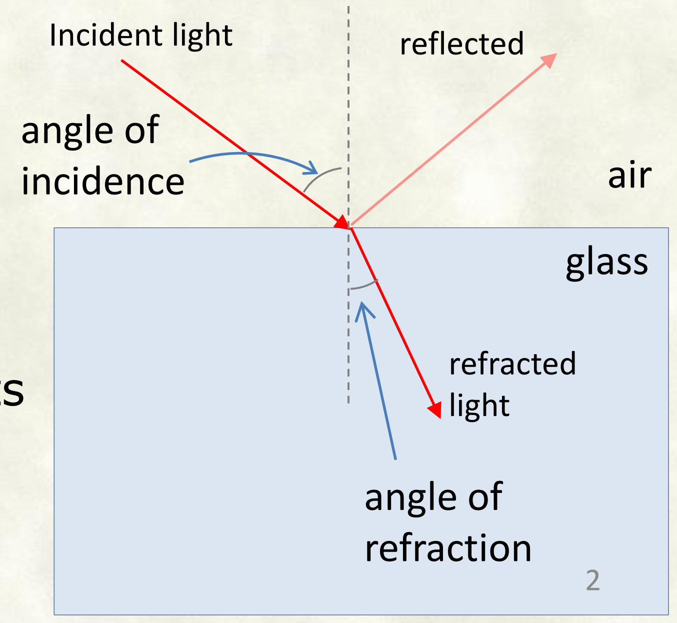
- Light travels in a straight line.
- Most surfaces reflect light.
  - Amount of reflection depends on the medium.
    - Glass 4%, water 2%, aluminum 87%, silver 98%
  - When light reflects from a smooth surface,

    incident angle = reflected angle



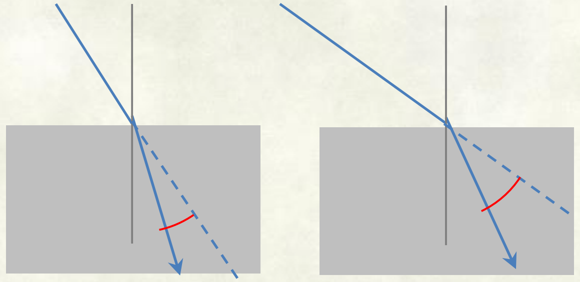
- When light travels from one transparent medium to another:
  - small fraction of light reflects.
  - light that passes through changes its direction. (called **refraction**)
- e.g. When travelling from a media like air to a media like water or glass light a ray refracts towards the normal,

  ⇒ angle of refraction is smaller than the angle of incidence.

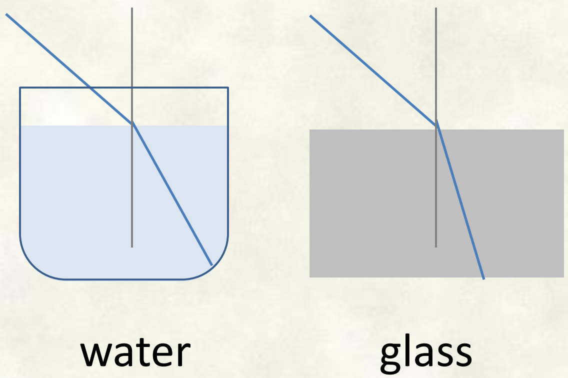


Amount of bending (refraction) depends on many factors:

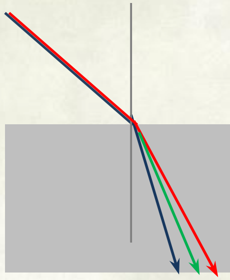
- Angle of incidence: larger the angle of incidence more the deviation from initial direction.



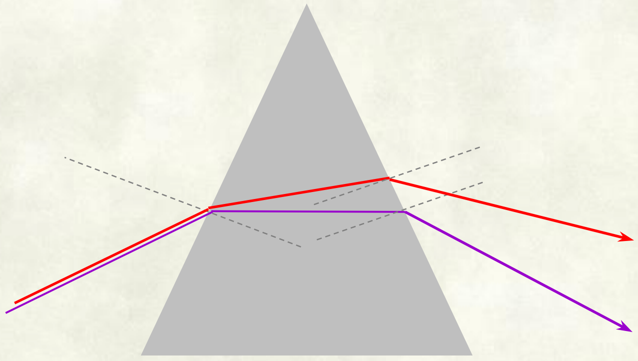
- The medium: some material refracts light more than other.
  - The refractive power, (ie. amount of bending) of the medium is given by the refractive index. Higher the number more it refracts light.
  - Water 1.3, ordinary glass 1.5, air 1.0003, diamond 2.4



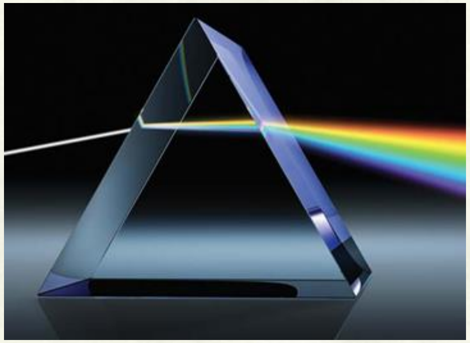
- Color:
  - Blue light is refracted (bent) more than red light.
  - Refraction of different colored light by different amounts is called the **dispersion** of light.



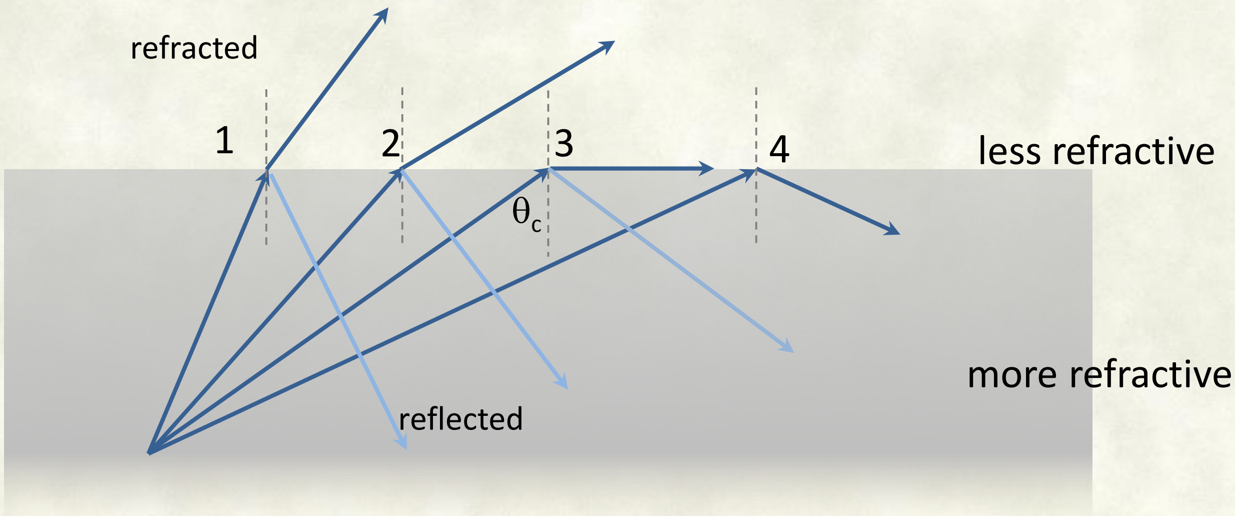
- White light is a mixture of a continuous spectrum of colors, from red to magenta.



- When a beam of white light passes through a glass prism, due to dispersion it is separated into different colors, forming a spectrum



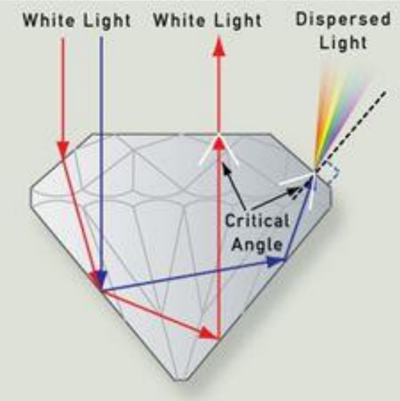
Total internal reflection

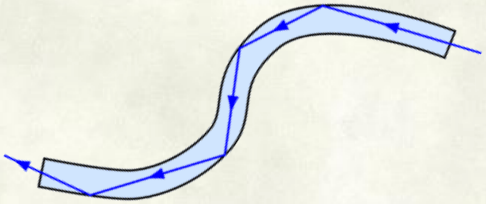


1. When light goes from a high refractive medium to a less refractive medium (from glass to air for example), at larger incident angles light completely reflects without any light passing through.
2. This phenomenon that light is totally reflected at the interface between two media is called **total internal reflection.**
3. For that to happen, the incident angle has to exceed a certain value.
4. The limiting angle this happens is called the **critical angle (θ_c).**

   for glass to air 41°, water to air 49°, diamond to air 28°
   (depends on the refractive index of the two media)

Few examples of total internal reflection (TIR)



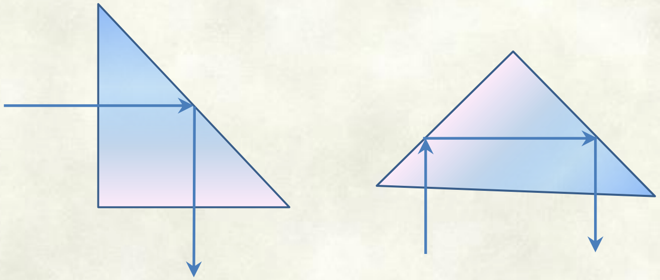


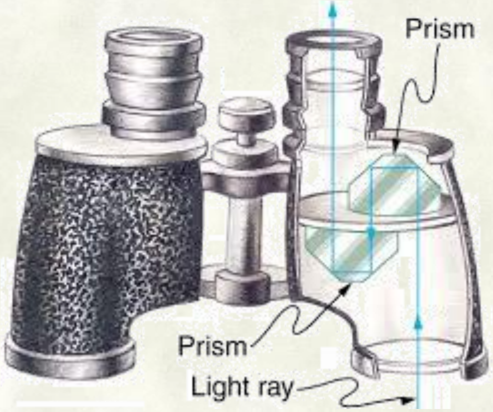
functioning of optical fibers depends on the TIR

Diamond refractive index = 2.4, TIR happens easily (θ_c=28°) ,

- Most light falling on the face of a properly cut diamond undergo several TIF inside diamond and leave it, causing it to sparkle .

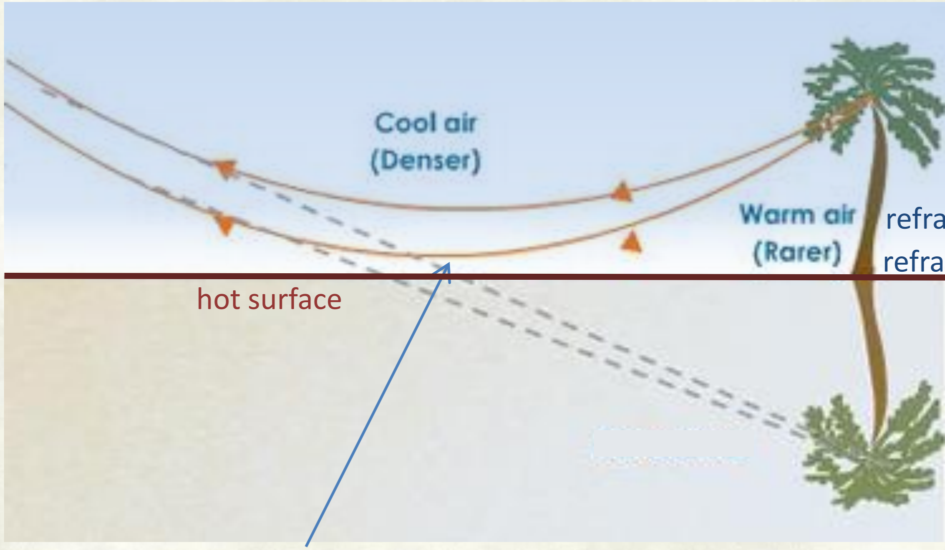
Light from a lamp under water gets TIR through water streams in a fountain





Prism binoculars use TIR in glass prisms as efficient reflectors

Formation of Mirages



refractive index higher

refractive index lower

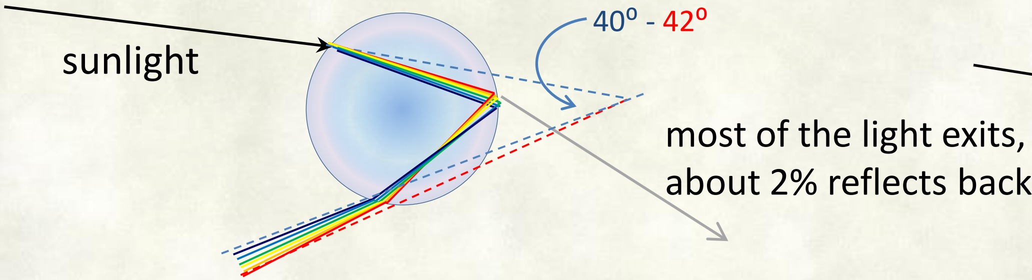
hot surface

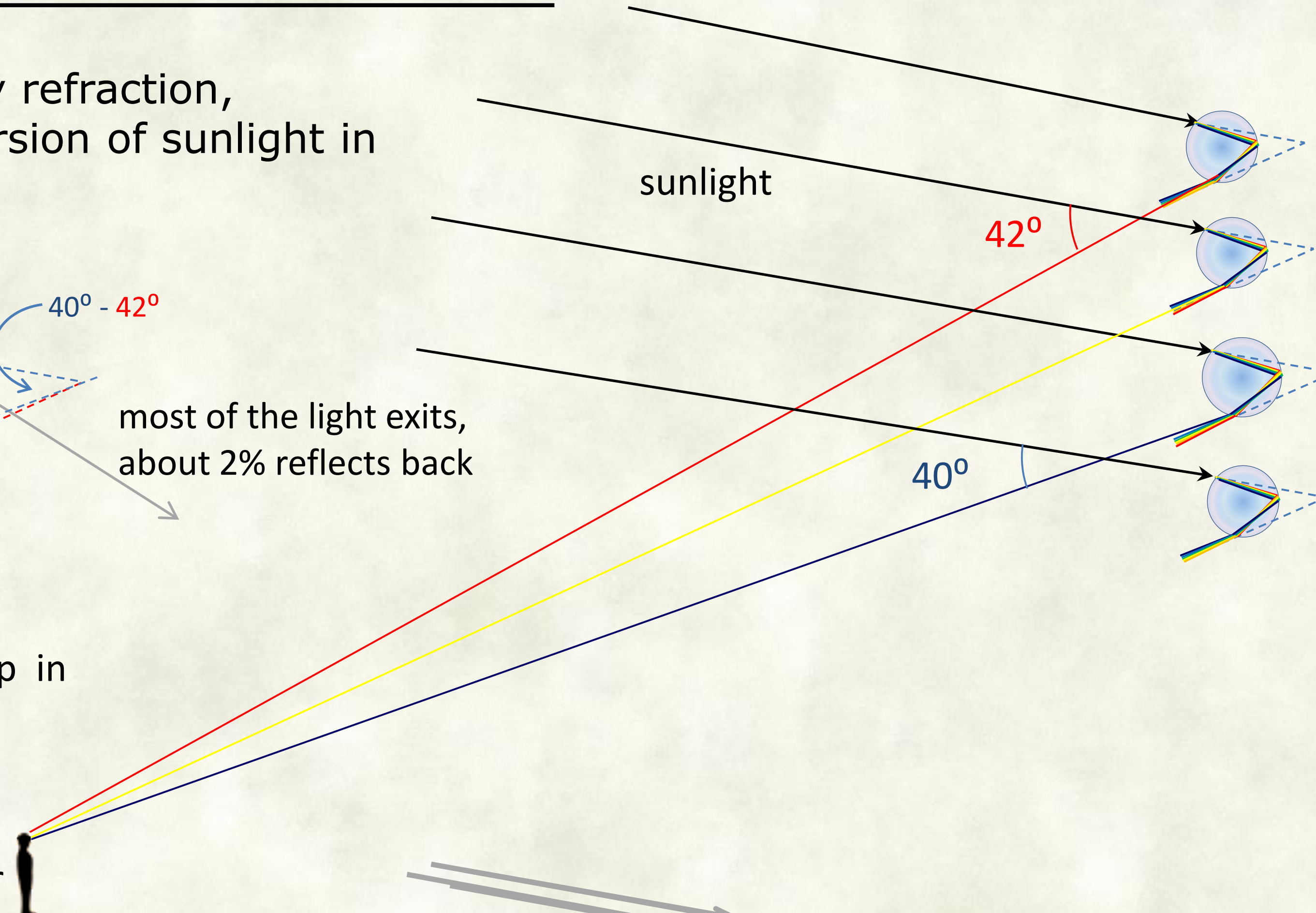
Light from distance objects bends and totally reflected as light travels from cold denser air to warm thin air.

- Cold air is denser than warm air, therefore has a greater refractivity.
- On a sunny day air near the ground is warmer and less refractive than the air higher up.
- As light travels at a shallow angle along a boundary between air of different temperatures, the light rays bend towards the colder (upper) air and gets totally reflected.

Formation of Rainbows

Rainbows are formed by refraction, reflection and the dispersion of sunlight in raindrops.

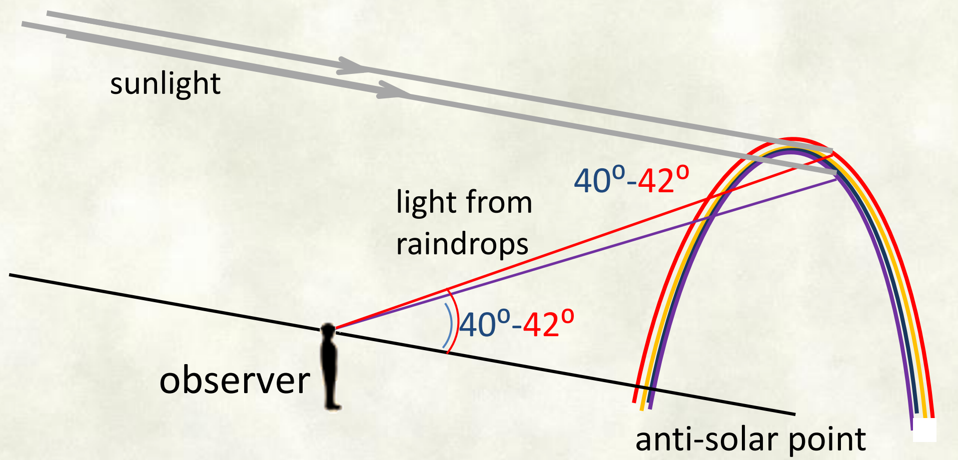




After two refractions and a reflection light exits a raindrop in slightly different directions depending on the color

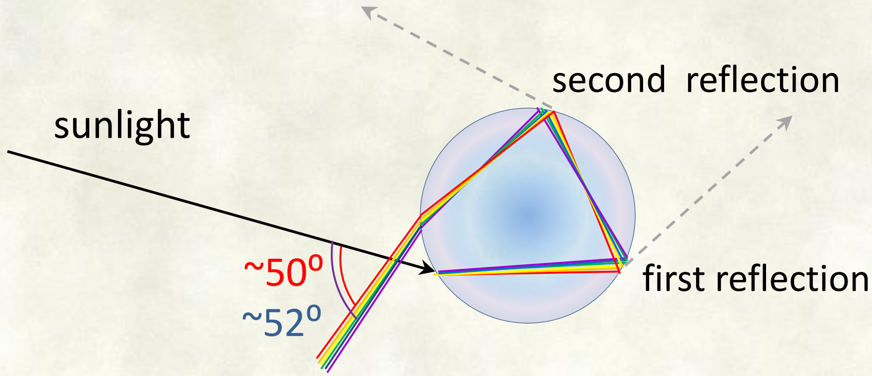
Angle between incident and refracted light is largest and brightest around 42° for red and 40° for blue.

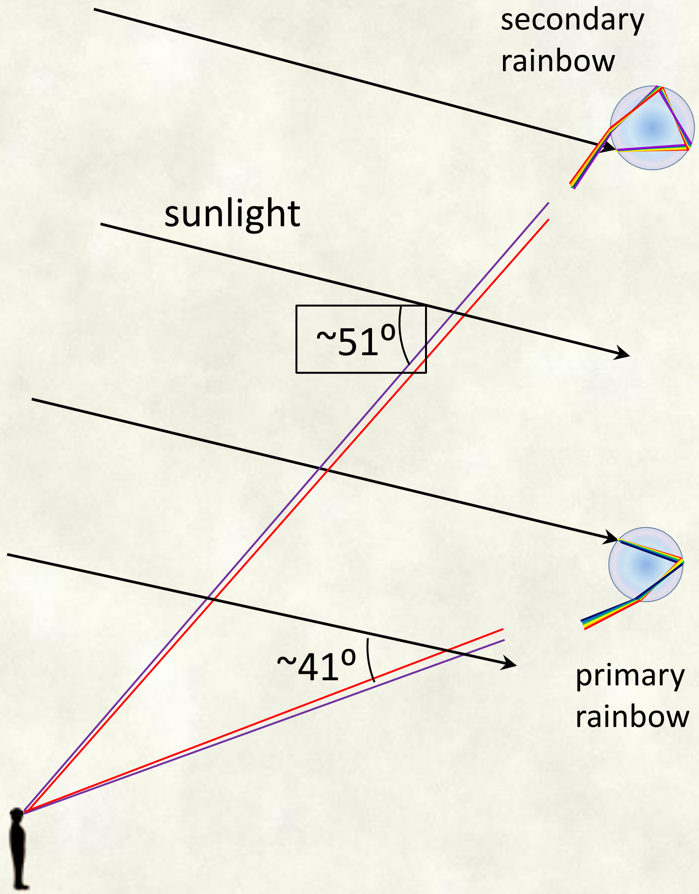
⇒ inner ring of the rainbow is blue and outer ring is red



Secondary rainbow

- Light could reflect more than once inside a raindrop, producing higher order rainbows.





- When light reflects twice inside a water droplets, a secondary rainbow is formed.
  - Due to extra reflection (only 2% of the light reflected) secondary rainbow is fainter.

http://apod.nasa.gov/apod/ap140930.html

Rainbows can form a complete circle, but the horizon only allows us to see half of the rainbow circle. From a mountain top or an airplane more of the rainbow can be seen

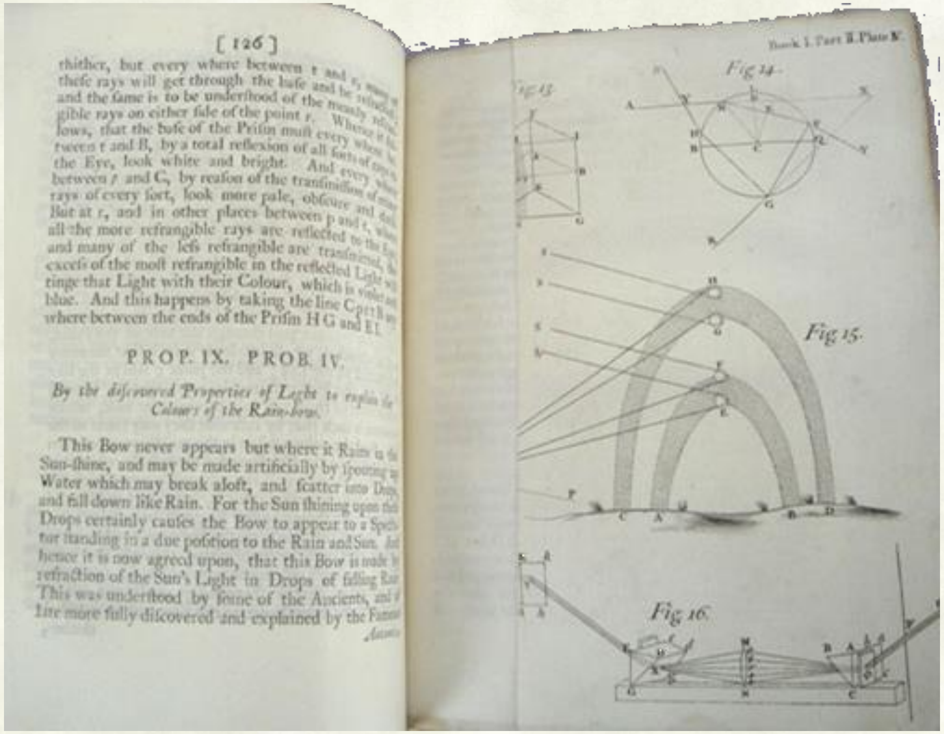
A rainbows can form whenever there are water droplets (mist) in air, and sunlight.

Is this real ?

- Real or fake?

https://www.reddit.com/r/earthporn/comments/2zz5cb/full_double_rainbow_from_my_backyard_in_redding

real or fake?



[126]

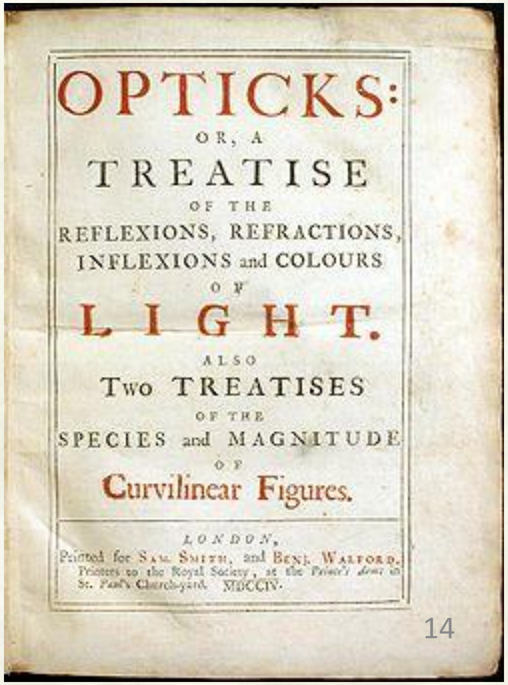
thither, but every where between t and r, ...
these rays will get through the base and be refracted ...
and the same is to be understood of the mean ...
gible rays on either side of the point r. Whence it fol-
lows, that the base of the Prism must every where be-
tween t and B, by a total reflexion of all sorts of rays ...
the Eye, look white and bright. And every where
between p and C, by reason of the transmission of ...
rays of every sort, look more pale, obscure and ...
But at r, and in other places between p and t, where
all the more refrangible rays are reflected to the ...
and many of the less refrangible are transmitted, ...
excess of the most refrangible in the reflected Light ...
tinge that Light with their Colour, which is violet ...
blue. And this happens by taking the line C ...
where between the ends of the Prism H G and E I.

PROP. IX. PROB. IV.

By the discovered Properties of Light to explain the Colours of the Rain-bow.

This Bow never appears but where it Rains in the
Sun-shine, and may be made artificially by spouting up
Water which may break aloft, and scatter into Drops,
and fall down like Rain. For the Sun shining upon these
Drops certainly causes the Bow to appear to a Specta-
tor standing in a due position to the Rain and Sun. And
hence it is now agreed upon, that this Bow is made by
refraction of the Sun's Light in Drops of falling Rain.
This was understood by some of the Ancients, and of
late more fully discovered and explained by the Famous
...

Nature of color was first reveled by Newton through a series of experiments. He was the first to understand the color of the rainbow. They were published in 1704 in the book *Opticks*



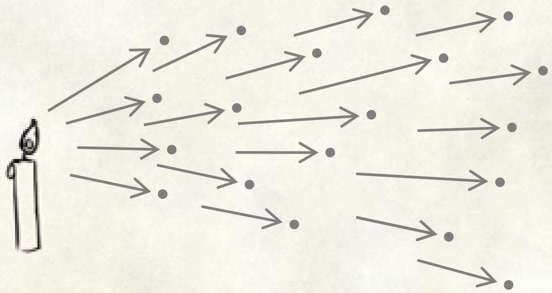
OPTICKS:
OR, A
TREATISE
OF THE
REFLEXIONS, REFRACTIONS,
INFLEXIONS and COLOURS
OF
LIGHT.
ALSO
Two TREATISES
OF THE
SPECIES and MAGNITUDE
OF
Curvilinear Figures.

LONDON,
Printed for Sam. Smith, and Benj. Walford,
Printers to the Royal Society, at the Prince's Arms in
St. Paul's Church-yard. MDCCIV.

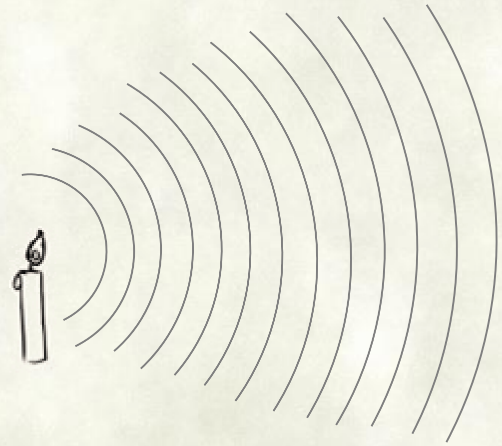
(Shape of the rainbow was first explained by Rene Descartes in 1637, but he could not explain the color)

What is light?

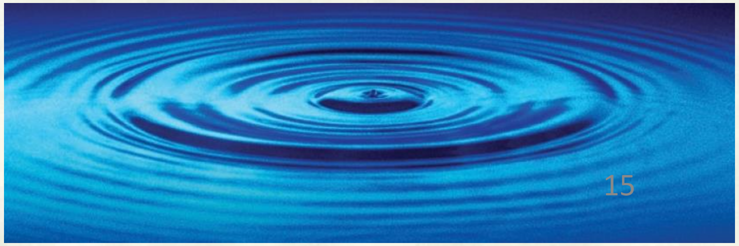
- Newton proposed the corpuscular theory of light. That light is made up of little particles - called corpuscles.
  - A light source (lamp, light bulb) emits corpuscles.
  - They travel in straight lines in all direction from the source and bounce off (reflects) when they illuminate an object.
  - Corpuscular theory was able to explain many properties of light (reflection, refraction, color).
- In 1768 Christian Huygens proposed the wave theory of light.
  - According to the wave theory, light is a wave propagating from the light source.



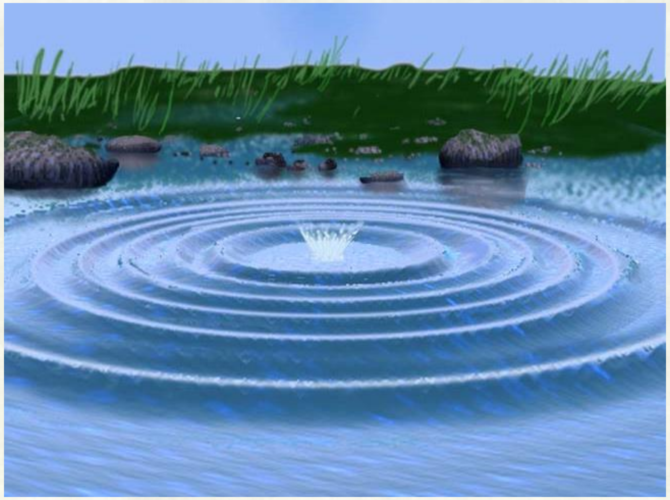
According to Newton light is *corpuscles* emitted from the light source

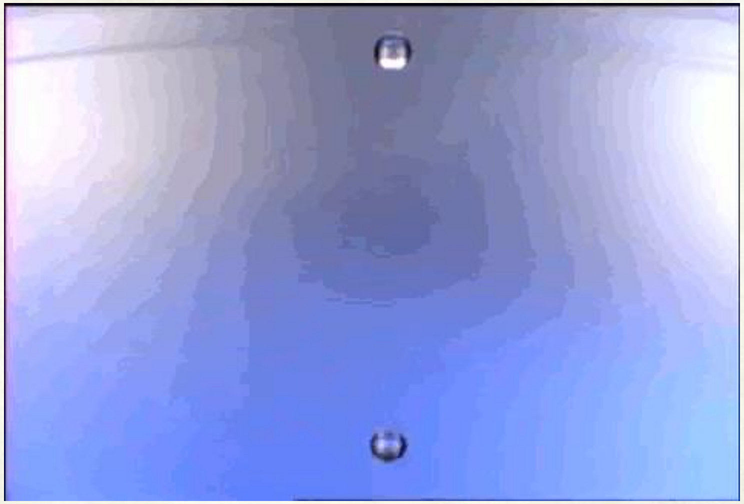


According to Huygens light is a wave generated by the light source, like water ripples on a pond formed when a stone is dropped



Wave motion



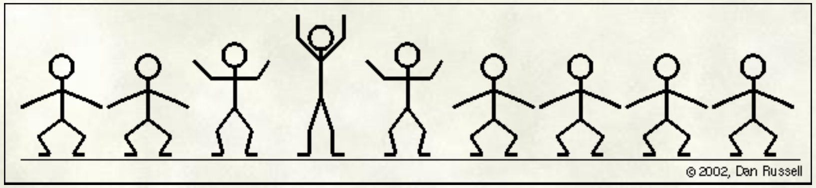


- A wave is a disturbance propagating (moving) in a medium.

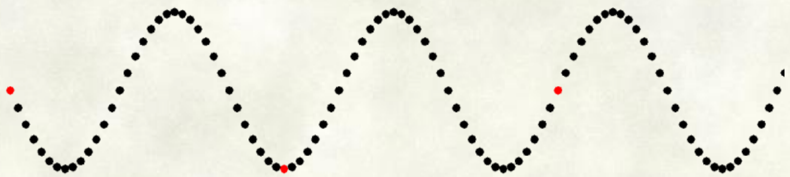
  Example: Waves on the surface of water

Waves along a rope

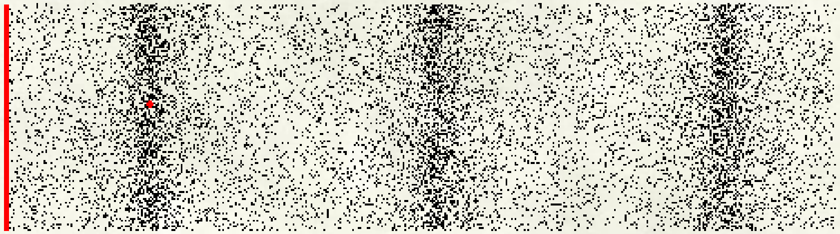
Stadium waves (medium is people)



Wave motion



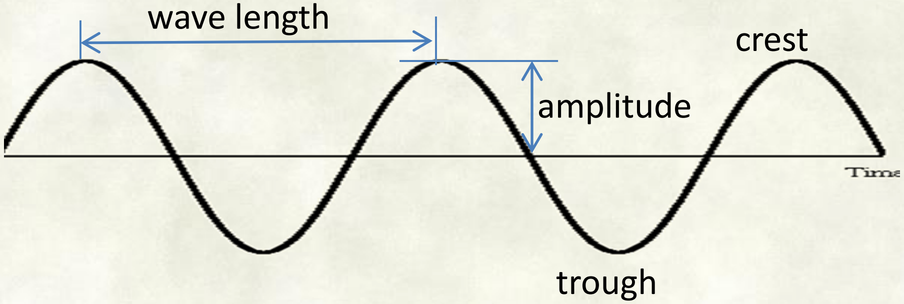
- It appears like a ripple is moving:
  - but particles in the medium only do a local cyclic movement.
  - only the disturbance (wave) is moving.

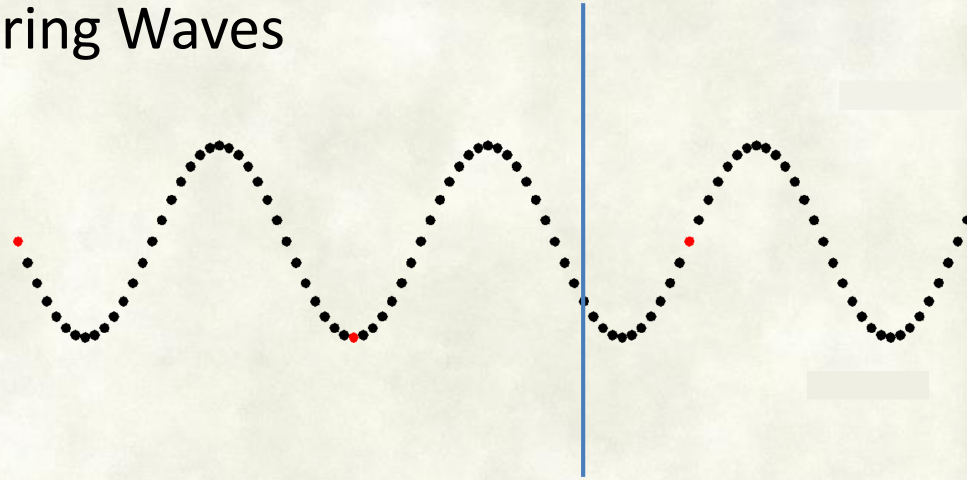


- Waves carry energy in the form of a disturbance, but not the matter in the media.
- Variation causing the wave could be any property:
  - position of particles as in above examples
  - density, pressure
  - value of some field, like the magnetic or electric field as in the case of light, radio waves…
  - Epidemic, fashion

Animations: www.phy.olemiss.edu/~perera/animations/waves.html

Measuring Waves





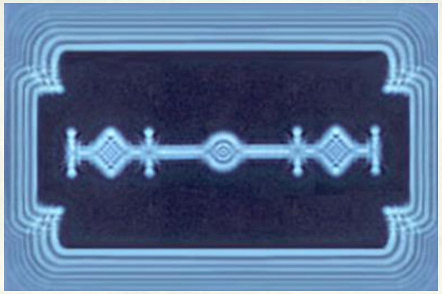
- **Amplitude (*A*) :** the magnitude of the wave at its peak.
- **Wavelength (λ) :** the distance between two adjacent crests or troughs (or any two similar adjacent positions)
- **Period (*T*):** the time it takes for one complete wave to pass a given point (or time to complete one cycle)
- **Frequency (*f*):** number of complete waves that pass a point in unit time: $\boldsymbol{f = \frac{1}{T}}$
  - usually measured in Hertz (Hz: cycles per second).
- **Speed (*s*) :** distance the wave travels in a unit time

Obviously, speed = wave length *x* frequency

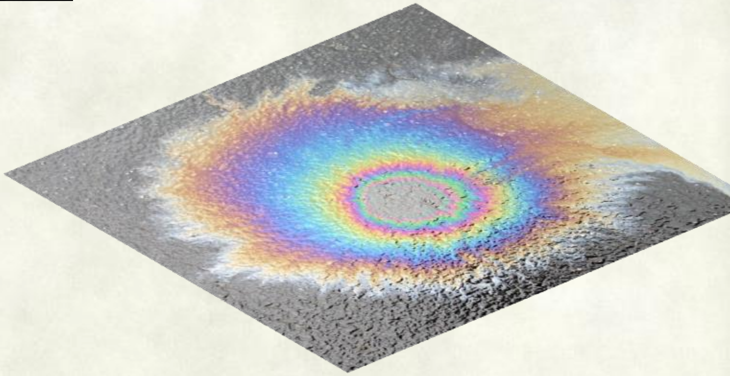
(length of one cycle) (how many of them pass a point in unit time)

$$\boldsymbol{s = \lambda f}$$

Wave Theory of Light



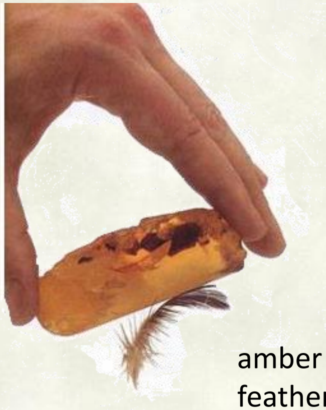
diffraction



interference

- In addition to basic properties, wave theory of light was able to explain phenomena that did not have an explanation in the corpuscular theory.
  - like diffraction, interference, polarization.
- But waves in what?
  - All known wave motion required a medium, (water waves, waves along a rope, sound waves in air…)
  - But light can travel in the empty space (vacuum), so the medium cannot be ordinary mater
- 19th century physicists came up with various explanations, finally it was realized that light is a electromagnetic wave.

Electromagnetic Waves

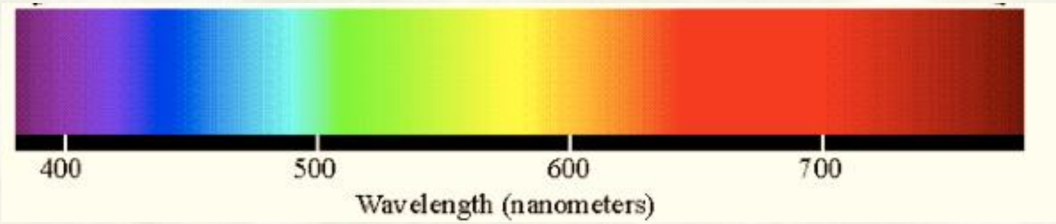


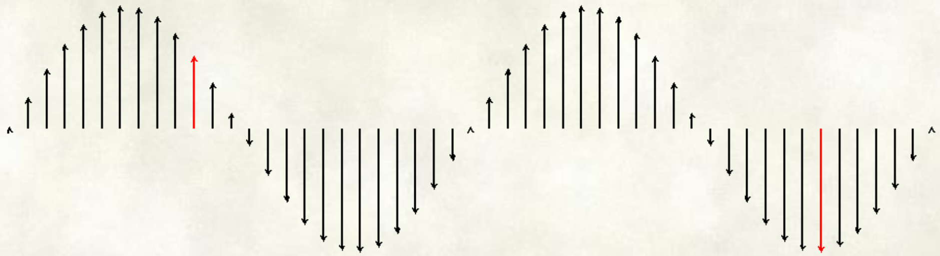
amber attracting a
feather : electricity

lodestone attracting
iron: magnetism

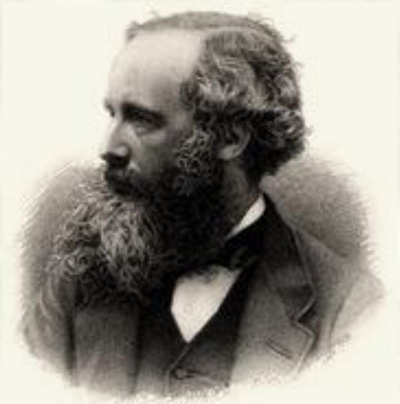
- Thales (6thc BCE) noted that amber attracts feathers and other light materials when rubbed with fur - The first historical reference to static electricity.
  - (origin of the word electricity is from "*ilektron*" the Greek name for amber)
- He also observed that *lodestone* attract iron, the magnetism.
- Knowledge about electricity and magnetism was developed as two separate phenomena until the later half of the 19th century
- In 1865, James Clerk Maxwell showed that electricity and magnetism are related, two aspects of the same entity, which he named **electromagnetism**.
  - He found that "electromagnetic waves" can exist and they travel at the same speed as light.
  - Thus he realized that light was nothing but electromagnetic waves traveling in space.

Light as an Electromagnetic Wave





(length of an arrow = value of the field there)



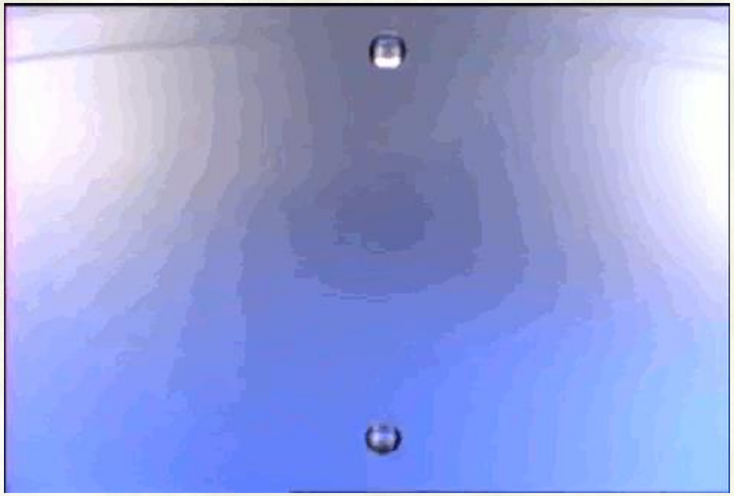
James Clerk Maxwell

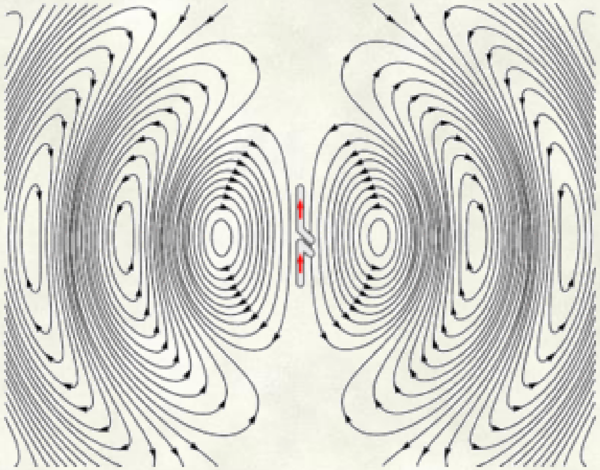
- **Electromagnetic waves** : In an EM wave, strengths of eclectic and magnetic fields are changing in a cyclic manner, propagating like a wave.
  - Intensity of light depends on the amplitude of the wave.
  - Its frequency determines the color
    - red light frequency 4.6×10^{14} Hz, blue light frequency 6.7×10^{14} Hz
    - using $s = \lambda f$ (slide 15) $\Rightarrow$ $\lambda = {}^{s}/_{f}$ (s = speed of light $3\text{x}10^{8}$ m/s)

    wave length of red light: ~650 nm, wave length of blue light: ~450 nm

    (nm: nanometer, 1 nm= $1\text{x}10^{-9}$m. thickness of paper ~60,000 nm)

Radio waves





credit: en.wikipedia.org/wiki/Radio_wave

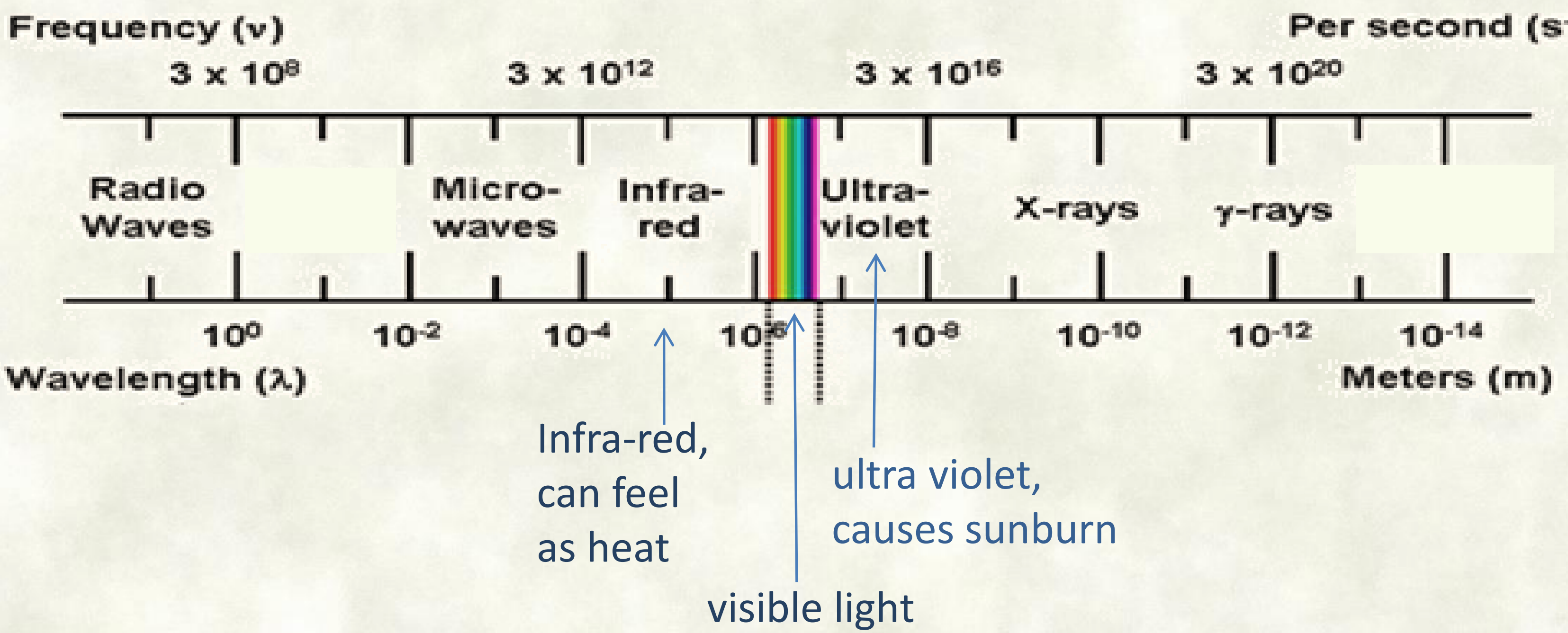
Heinrich Hertz

Just like falling water droplet create water waves oscillating electric currents produce radio waves.

- Since frequency can be anything, can there be EM waves with other frequencies?
- Maxwell believed there should be
  - He predicted the existence of low frequency EM waves 10^4- 10^6 Hz.
  - They (radio waves) were discovered by Heinrich Hertz in 1887.
    - Radio waves are produced by oscillating electric currents (charges)
    - which generates oscillating electric and magnetic fields and propagates away from the electrical conductor (antenna)

Electromagnetic Spectrum

- Visible light is only a small portion of a wider spectrum of waves known as Electromagnetic radiation, all travelling at the speed of light in empty space (vacuum)
- Total spectrum spans from very low frequency radio waves to extremely high frequency gamma rays (γ-rays).
- Different frequency ranges have different names
    - Radio, microwave, infrared, visible, ultraviolet, x ray, γ-ray …

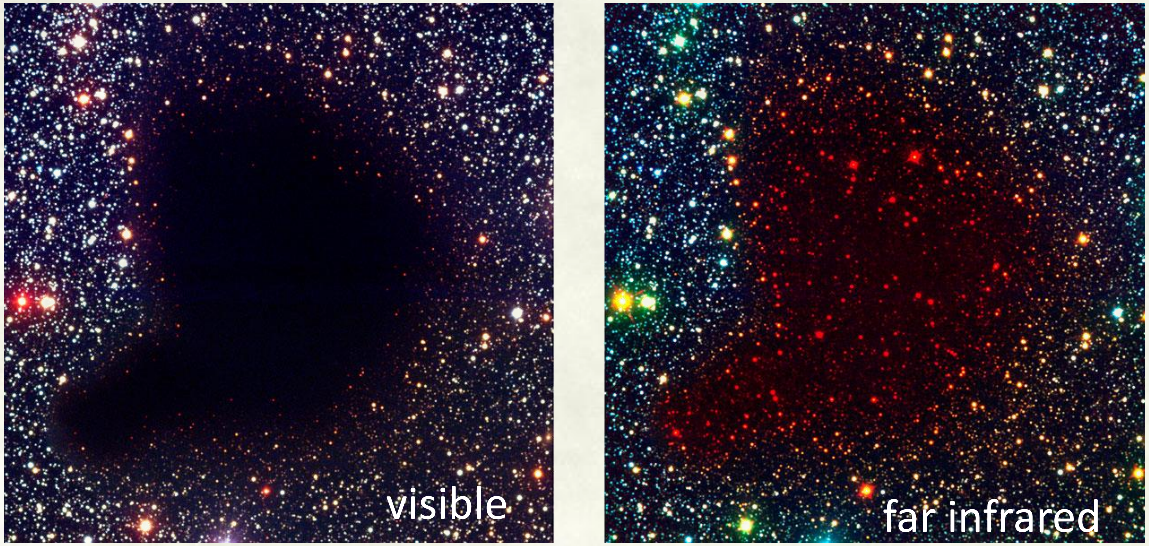


Infra-red radiation scatters less

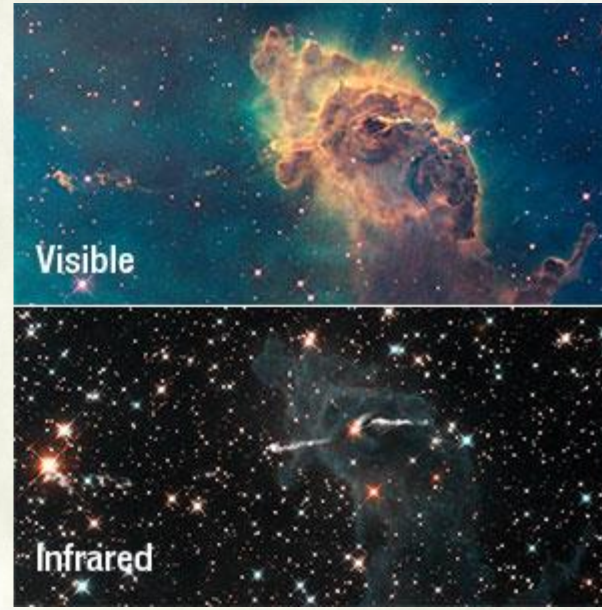
A visible light photo

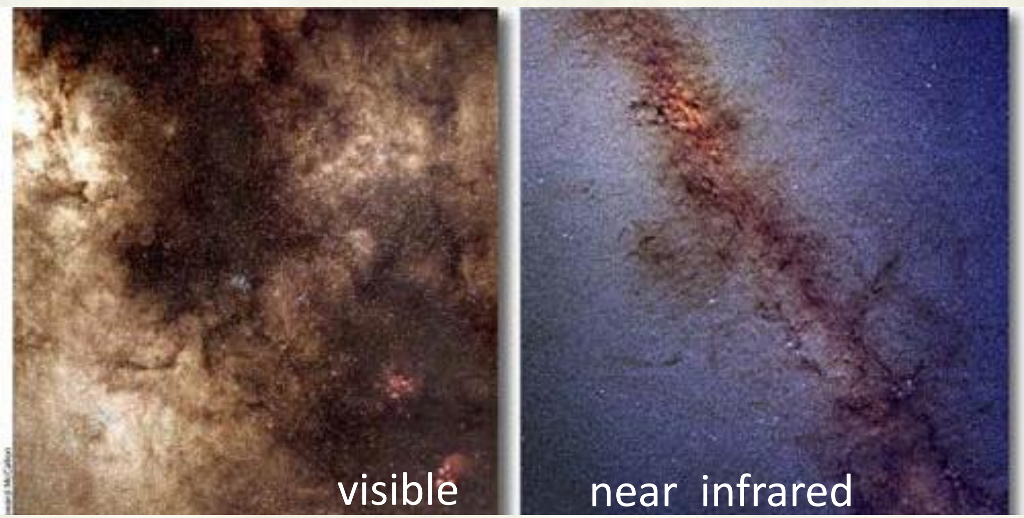
A photo taken with IR

- Amount of light scatters depend on the relative size of the wavelength of light and the size of scattering particles.
- If the wave length is larger than the size of the scattering particles it scatter less.
- That is the reason blue light scatters more in the atmosphere than red light.
  - Wave length of red light is larger in comparison to molecules and dust particles in the atmosphere.
- Infra-red radiation has wavelengths even longer than the red light, so it won't scatter by even larger particles in the atmosphere, like tiny water droplets in fog/mist.
- IR can be used to see through mist, fog or dust.

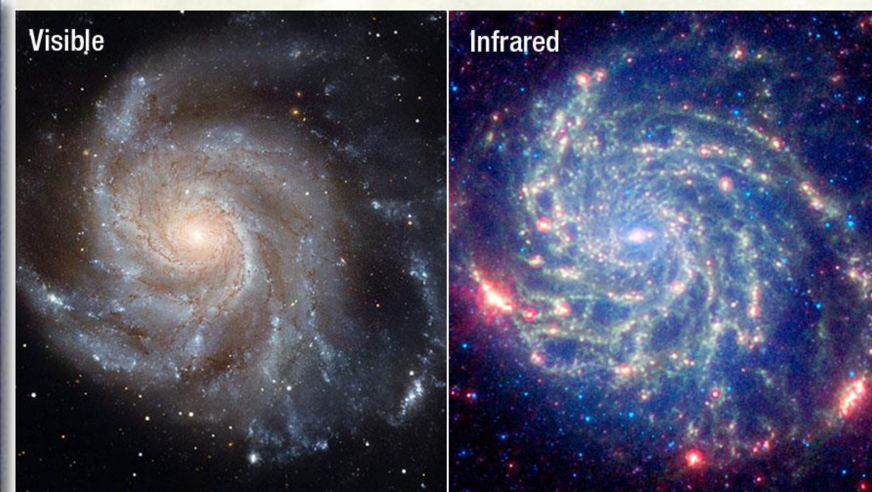


Barnard 68 dark nebula (dust cloud)





Galactic center



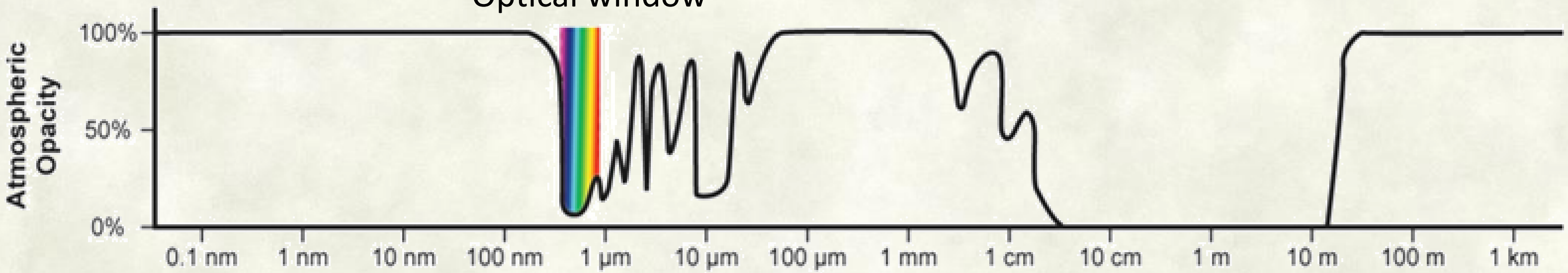
Pinwheel galaxy M101

- Infrared imaging used in astronomy to see through dust clouds

Atmospheric absorption of EM radiation

Optical window

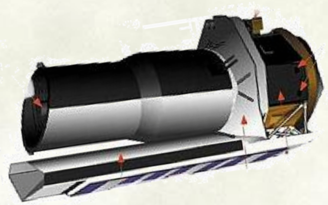
Radio window



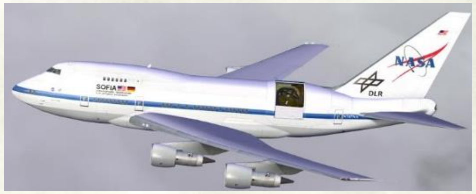
Atmospheric opacity to different wavelengths of the Electromagnetic Spectrum

- All types of electromagnetic radiation is produced by various kinds of celestial objects.
- However, atmosphere is transparent only for two wavelength regions, in the optical region and in radio wave region.
- To see with other types of EM radiation, instruments have to be placed above Earth's radiation absorbing atmosphere, in satellites, airplanes, or high altitude balloons.

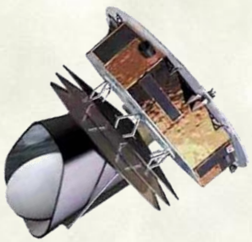
Chandra: X-ray



Spitzer : IR



SOFIA : IR

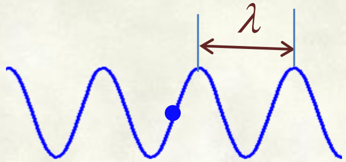


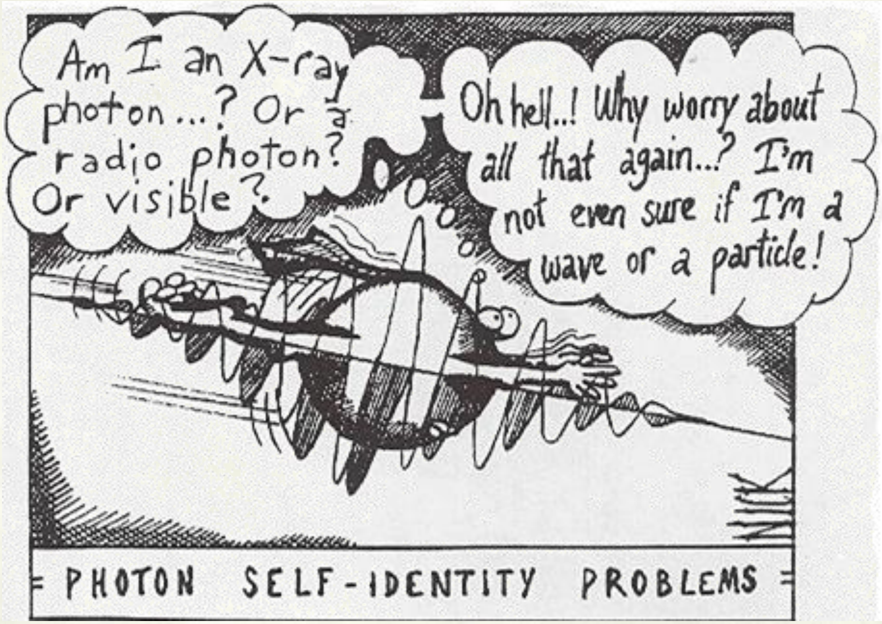
Plank : microwave

The Modern view of light

According to current understanding light has a dual nature: It is both a particle and a wave.

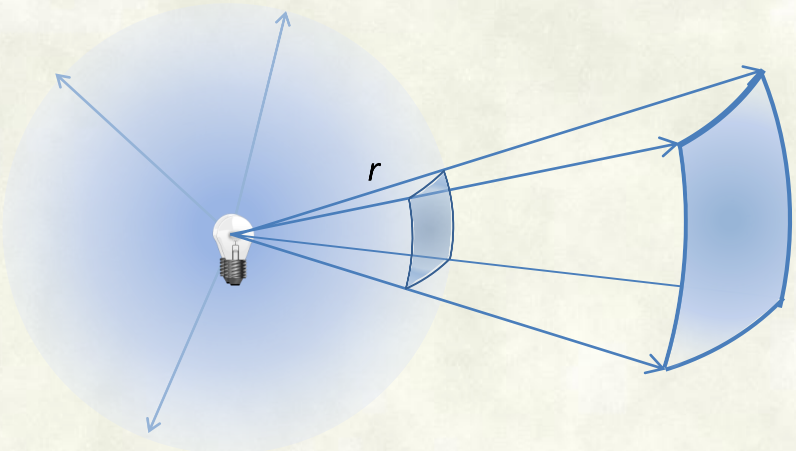
(subject of the branch of modern physics: Quantum Mechanics)

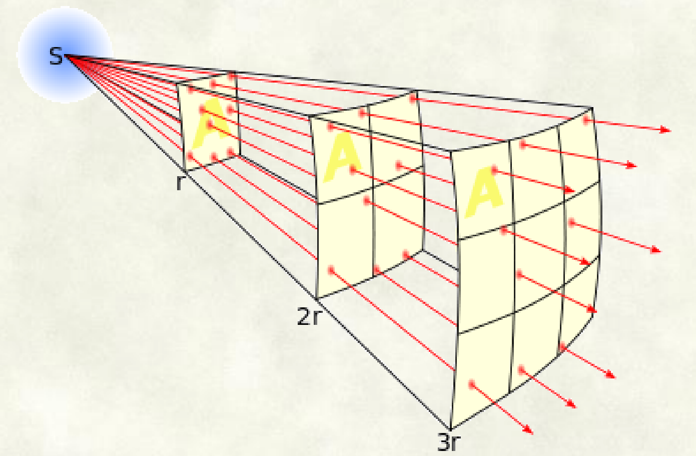




- Both particle theory and wave theory are correct. Each describes a different aspect of light.
  - When regarded as a wave it is described as an electromagnetic wave characterized by its frequency (or the wavelength) and the amplitude.
  - Also light can be considered as made of particles, called **photons**.
    - In that context light is a collection of photons, each having a specific energy depending on the frequency (color) of light.
      - energy of a photon: $E = hf$, h a constant (Planks constant), f frequency.
    - color ⇒ frequency ⇒ energy of the photon
    - Intensity ⇒ number of photons higher intensity ⇒ more photons

Inverse square law of light





Same amount of light is spread over a larger area as distance increases

- As distance to a light source increase, same amount of light is spread over a larger area, so the brightness (intensity of radiation) falls off.
- Since surface area increases with the square of the distance brightness falls off as the inverse square of the distance $(\frac{1}{r^2})$

$$\text{brightness of an object} \propto \frac{1}{r^2}$$

Review Questions

- What is refraction? Which color of light refracts the most?
- Why is the secondary rainbow fainter than the primary?
- What is the order of colors in a rainbow?
- Is it possible to touch a rainbow?
- Why do rainbows appear in the morning or late afternoon, but not around noon?
- What is meant by the wavelength of a wave?
- What is frequency? How is the period of a wave related to its frequency?
- How are frequency, wavelength and velocity related to one another?
- Why was the wave theory of light accepted over corpuscular theory in the 19^{th} century?
- Why does infrared light able to penetrate fog and dust?
- Why does infrared light able penetrate cosmic dust clouds better than visible light?
- What is the speed of radio waves?
- Why does it take some time to hear the thunder after lightning?
- What is the modern view of the nature of light?
- Why do X-ray telescopes are placed in satellites orbiting the Earth, not on the ground?
- What are the observational evidence that light can travel in a vacuum?
- What is 92.1 in the Rebel radio 92.1 FM?