King Saud University
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Nature of Light

General Physics II
PHYS 111

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Outline

- Is light a wave or a particle?
- Wave Theory of Light
- Speed of light
- Frequency
- Properties of Light
- Type of Wave
- Wave Nature of Light
- Rectilinear Propagation of Light
- Energy of a Photon

Outline

- The Momentum of Photon
- Electromagnetic Spectrum
- Color of light
- Doppler Effect
- Doppler Shift
- Unpolarized light beam
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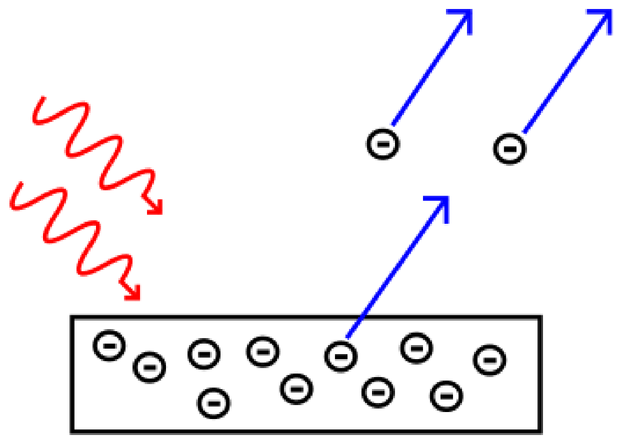
- Questions

Is light a wave or a particle?

- In the early 19th century, the English scientist Thomas **Young** carried out the famous double-slit experiment which demonstrated that a beam of light, when split into two beams and then recombined, will show interference effects that can only be explained by assuming that light is **a wavelike disturbance**.
- By 1820, Augustin Fresnel had put this theory on a sound mathematical basis, but the exact nature of the waves remained unclear until the 1860's when James Clerk **Maxwell** developed his **electromagnetic theory**.

Is light a wave or a particle?

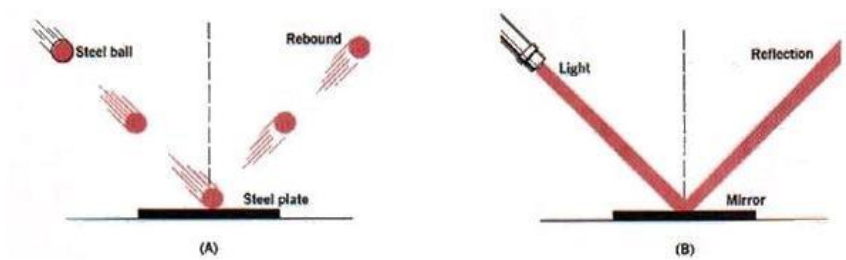
- However, **Einstein**'s 1905 explanation of the photoelectric effect (The photoelectric effect is the observation that many metals emit electrons when light shines upon them. Electrons emitted in this manner may be called photoelectrons.) showed that light also exhibits **a particle-like nature**. The photon is the smallest possible packet (quantum) of light; it has zero mass but a definite energy



Photoelectric effect

Wave Theory of Light

- **Newton** proposed that light consists of a stream of small **particle**s, because it
  - travels in straight lines at great speeds
  - is reflected from mirrors in a predictable way



- Thomas **Young** showed that light is a **wave**, because it
  - undergoes diffraction and interference

Speed of light

- Until around 1700, it was still debated whether the speed of light was infinite (traveled instantaneously from point to point)

- In 1676, Olaus Romer used the eclipses of Jupiter's moons to establish the finite speed of light and make a rough measurement

$$c = 3.00 \times 10^8 \text{ m/s} = 186{,}000 \text{ mi/s}$$

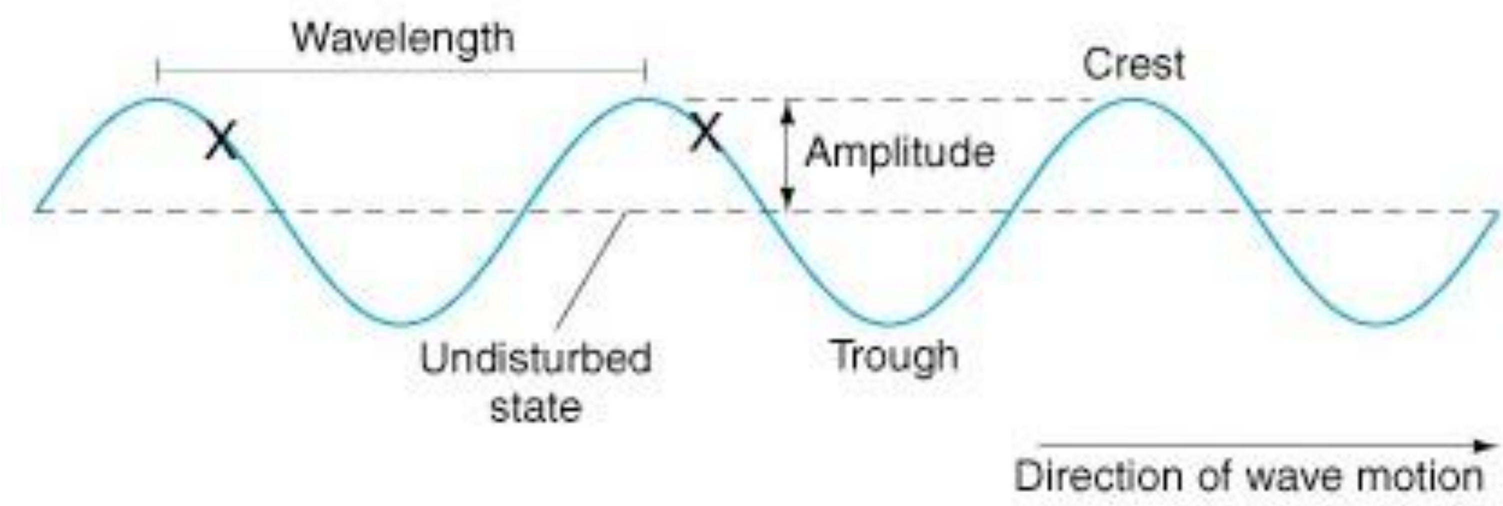
Properties of Light

- Crest and trough
- **Amplitude** - maximum excursion from its undisturbed or relaxed position.
- Waves travel at a **speed**, V.
- The number of crests that pass at a specific point in space is called a wave's **frequency f or ν** , and is recorded in units of Hertz.
- **Period τ** - the time it takes for one complete cycle, measured in seconds. This is known as **τ**.
- **Wavelength** λ- the distance a wave travels during one complete oscillation.

$$\mathbf{f = 1/\tau}$$

$$\mathbf{(\lambda) = V\tau \text{ or } V/f}$$

Properties of Light



Frequency

- Wavelength & speed of light are related by the frequency

f - frequency of light (Hz)

c - speed of light

λ - wavelength of light

- This is actually true for any wave $\nu = c/\lambda$

ν - frequency of wave

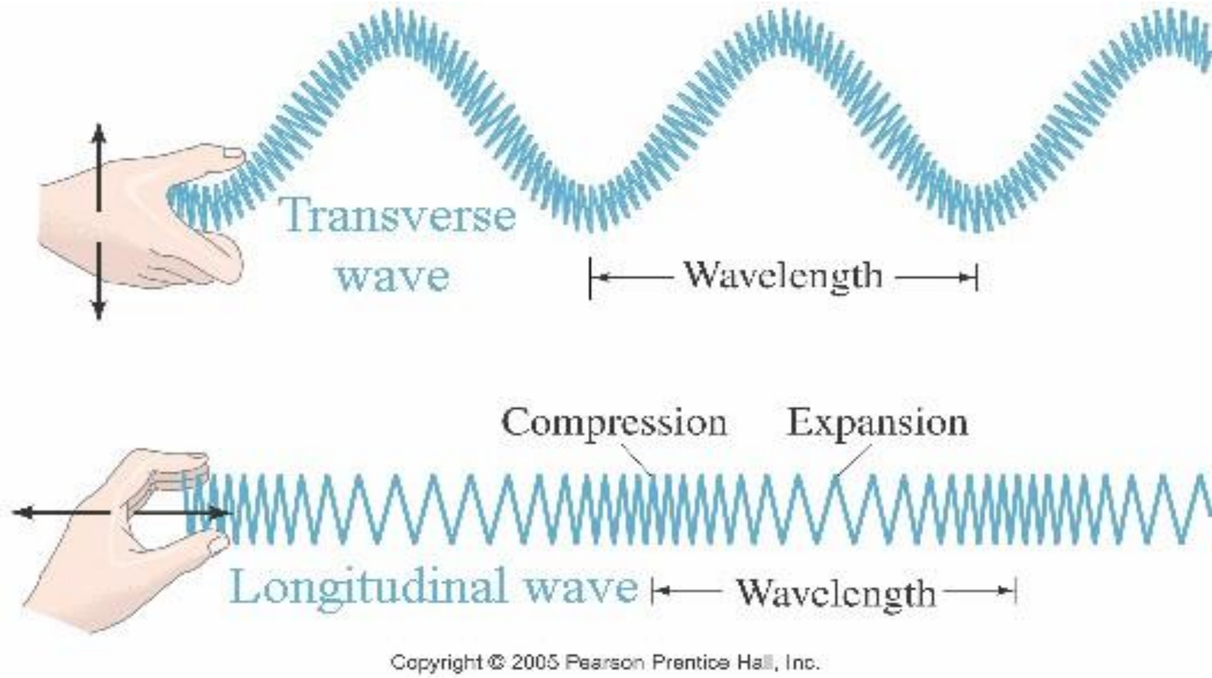
c - speed of wave

λ - wavelength

Type of Wave

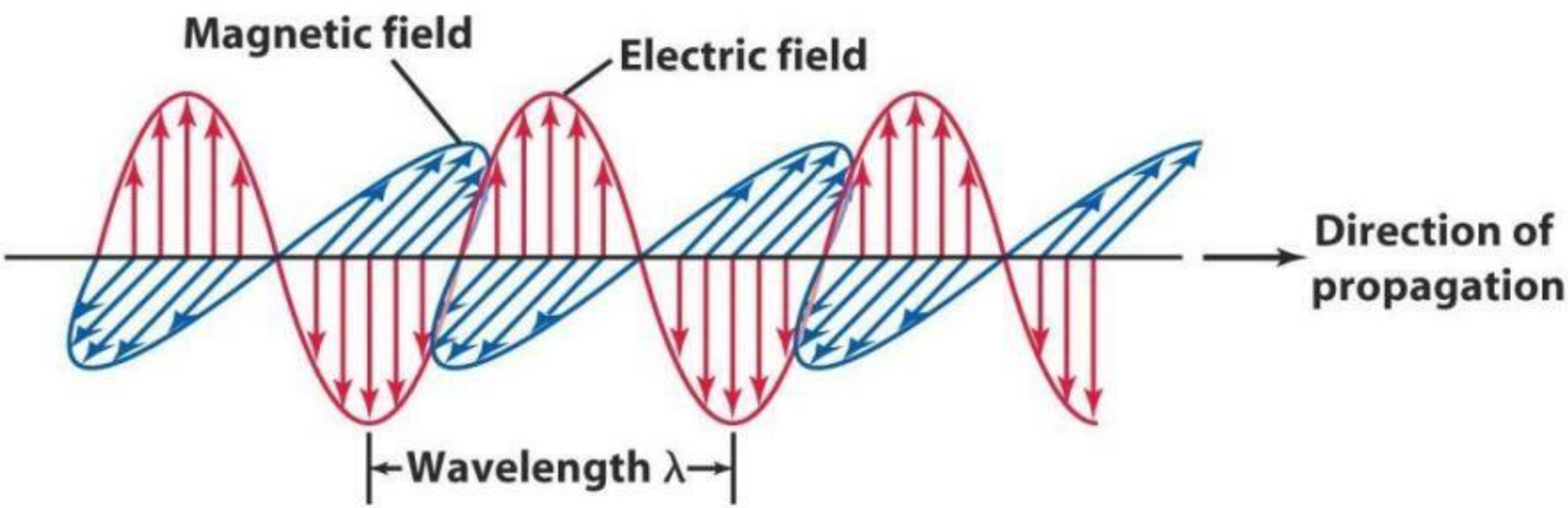
- **Transverse wave** - movement or displacement is perpendicular to the direction of the wave. i.e light wave.

- **Longitudinal wave** - movement or displacement is parallel to the direction of the wave. i.e sound wave.



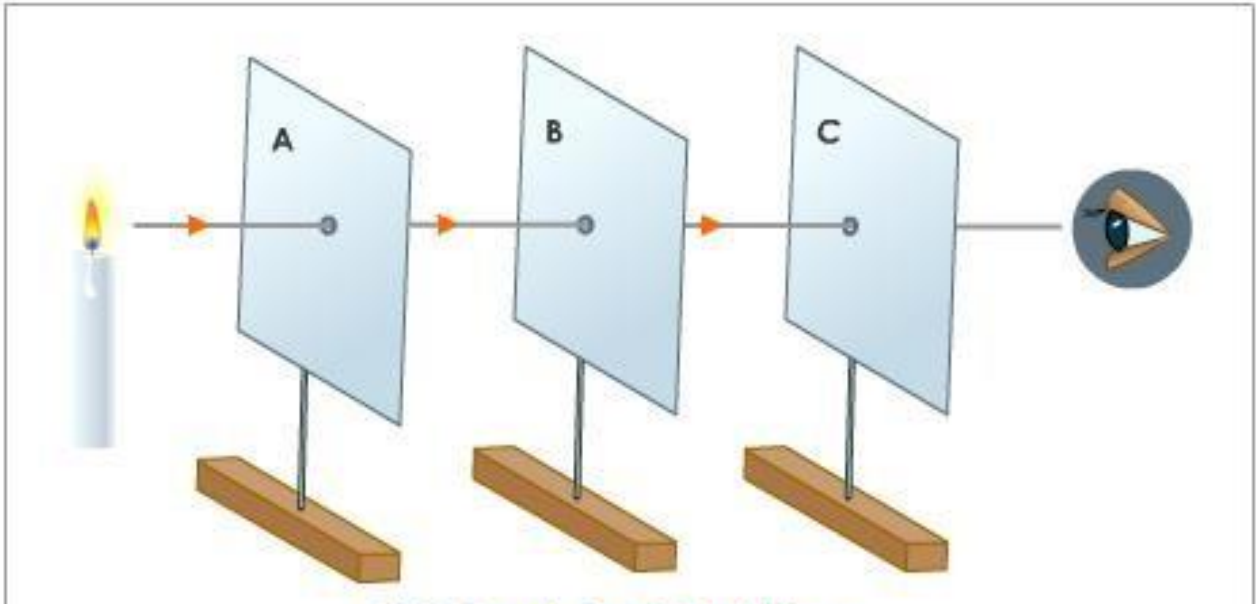
Wave Nature of Light

- In the case of light, waves are carried by electromagnetic fields
- Light = Electromagnetic Radiation



Rectilinear Propagation of Light

- take three cardboards A, B and C and make a pinhole at their centres. Place a burning candle on one side of the cardboard A and arrange the cardboards in such a way that the three pinholes and the candle flame are in a straight line. The candle flame will be visible through the pinhole of the cardboard C.



Light Travels in a Straight Line

Rectilinear Propagation of Light

- Now slightly displace any one of the cardboards and try to see the flame through the pinhole of the cardboard C. The flame will not be visible. From this it is clear that light travels in a straight line. This is one of the examples of **rectilinear propagation**.

Energy of a Photon

- A photon is characterized by either a wavelength, denoted by λ or equivalently an energy, denoted by E. There is an inverse relationship between the energy of a photon (E) and the wavelength of the light (λ) given by the equation:

$$E = hc/\lambda$$

- where h is Planck's constant and c is the speed of light.

$$h = 6.626 \times 10^{-34}\ \mathrm{J}$$

$$c = 2.998 \times 10^{8}\ \mathrm{m/s}$$

Energy of a Photon

- By multiplying h and c to get a single expression, hc = 1.99×10^{-25} joules-m.

- The $E = hc/\lambda$ inverse relationship means that light consisting of high energy photons (such as "blue" light) has a short wavelength. Light consisting of low energy photons (such as "red" light) has a long wavelength

The Momentum of Photon

- In empty space, the photon moves at c (the speed of light) and its energy and momentum are related by E = pc, where p is the magnitude of the momentum vector p. This derives from the following relativistic relation, with m = 0

$$E^2 = p^2c^2 + m^2c^4.$$

- The energy and momentum of a photon depend only on its frequency (ν) or inversely, its wavelength (λ):

$$\boldsymbol{p} = \hbar\boldsymbol{k},$$

$$E = \hbar\omega = h\nu = \frac{hc}{\lambda}$$

The Momentum of Photon

- where k is the wave vector (where the wave number

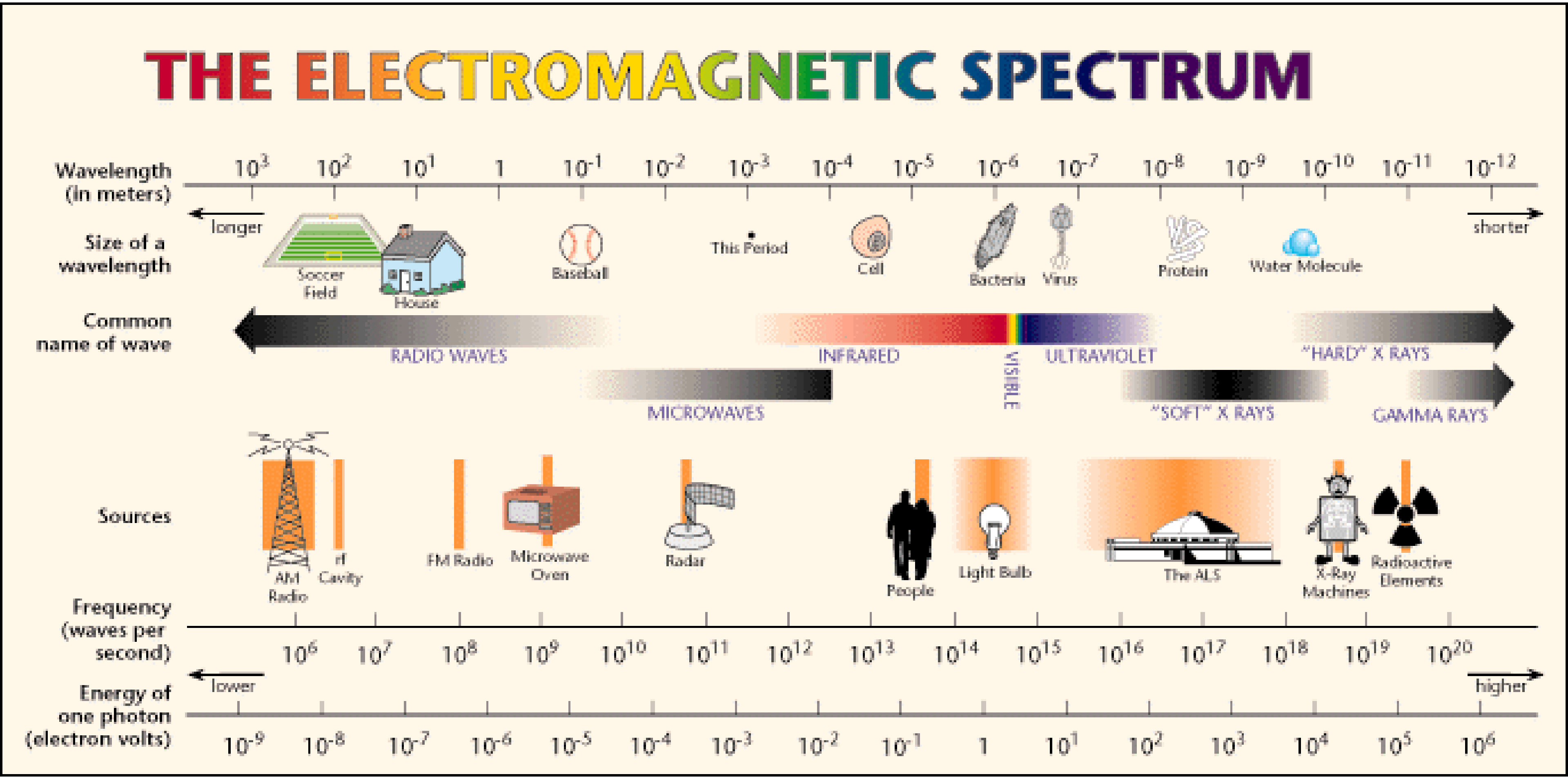
$k = |k| = 2\pi/\lambda$), $\omega = 2\pi\nu$ is the angular frequency, and $\hbar = h/2\pi$ where h is Planck constant

- Since p points in the direction of the photon's propagation, the magnitude of the momentum is

$$p = \hbar k = \frac{h\nu}{c} = \frac{h}{\lambda}.$$

- The unit of momentum of a photon is kg · m/s.

Electromagnetic Spectrum



Electromagnetic Spectrum

- The electromagnetic (EM) spectrum is the range of all types of EM radiation.
- Radiation is energy that travels and spreads out as it goes – the visible light that comes from a lamp in your house and the radio waves that come from a radio station are two types of electromagnetic radiation.
- The other types of EM radiation that make up the electromagnetic spectrum are microwaves, infrared light, ultraviolet light, X-rays and gamma-rays.

Electromagnetic Spectrum

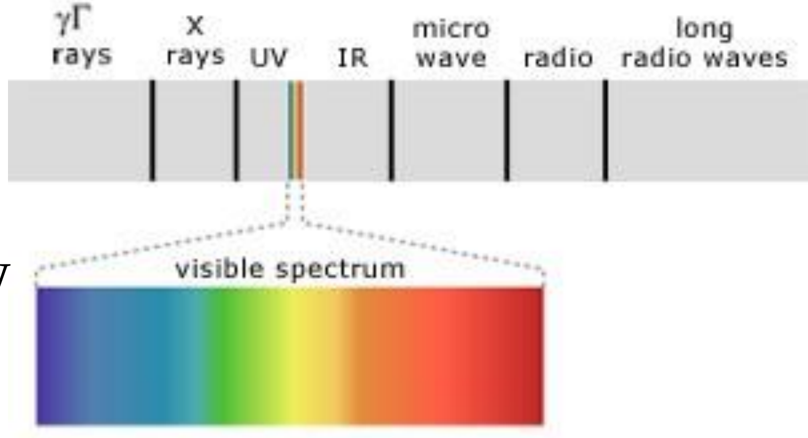
- **Radio**: Your radio captures radio waves emitted by radio stations, bringing your favorite tunes. Radio waves are also emitted by stars and gases in space.
- **Microwave**: Microwave radiation will cook your popcorn in just a few minutes, but is also used by astronomers to learn about the structure of nearby galaxies.
- **Infrared**: Night vision goggles pick up the infrared light emitted by our skin and objects with heat. In space, infrared light helps us map the dust between stars.

Electromagnetic Spectrum

- **Visible**: Our eyes detect visible light.light bulbs, and stars all emit visible light.
- **Ultraviolet**: Ultraviolet radiation is emitted by the Sun and are the reason skin tans and burns. "Hot" objects in space emit UV radiation as well.
- **X-ray**: A dentist uses X-rays to image your teeth, and airport security uses them to see through your bag. Hot gases in the Universe also emit X-rays.
- **Gamma ray**: Doctors use gamma-ray imaging to see inside your body (medical applications)

Color of light

- As seen in the figure, light at one end of the visible spectrum has shorter wavelengths near the 400nm range of the spectrum producing a "blue" visual sensation.
- Medium wavelengths in the 500-600nm range produce a "yellow to green" sensation. Longer wavelengths produce a "reddish" sensation.
- Primaries color: Red (R), Green (G), Blue (B)



Visible light

- Light is made up of wavelengths of light, and each wavelength is a particular color. The color we see is a result of which wavelengths are reflected back to our eyes.

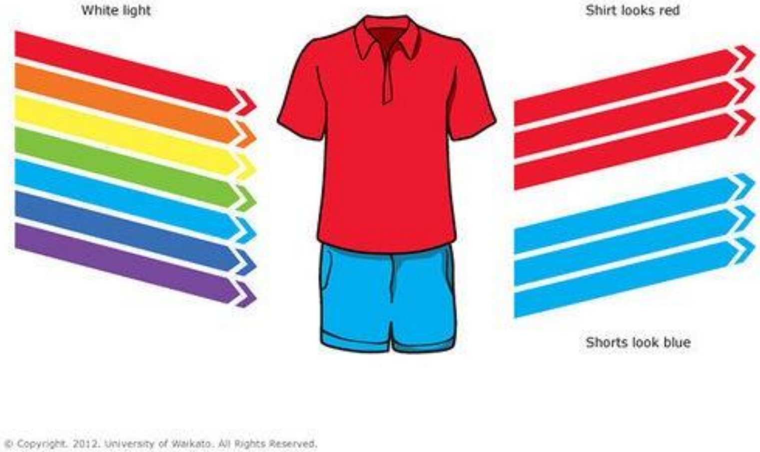
- **Visible light**
- Visible light waves consist of different wavelengths. The color of visible light depends on its wavelength. These wavelengths range from 700 nm at the red end of the spectrum to 400 nm at the violet end.
- White light is actually made of all of the colors of the rainbow because it contains all wavelengths. Light from a torch or the Sun is a good example of this.

Visible light

- Objects appear different colors because they absorb some colors (wavelengths) and reflected or transmit other colors. The colors we see are the wavelengths that are reflected or transmitted.

<u>Visible light</u>

- For example, a red shirt looks red because the dye molecules in the fabric have absorbed the wavelengths of light from the violet/blue end of the spectrum. Red light is the only light that is reflected from the shirt. If only blue light is shone onto a red shirt, the shirt would appear black, because the blue would be absorbed and there would be no red light to be reflected.
- White objects appear white because they reflect all colours. Black objects absorb all colours so no light is reflected.

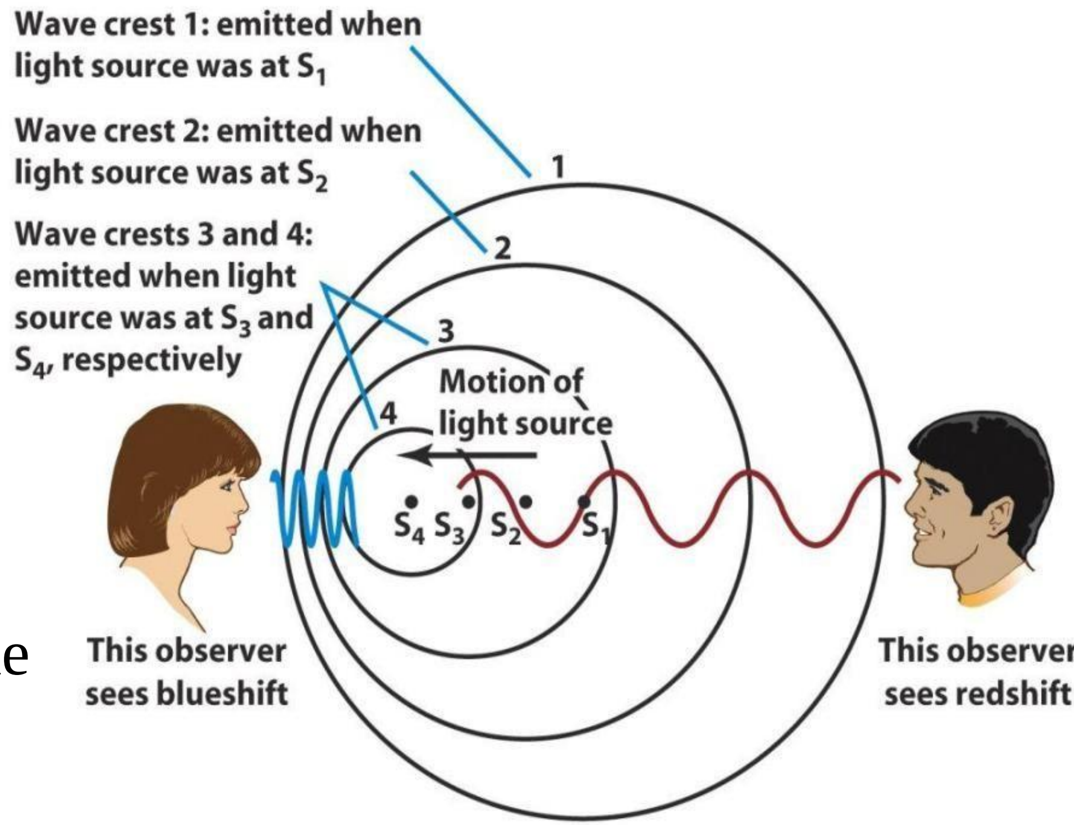


Visible light

- Electromagnetic radiation in the visible spectrum is typically generated by one of these sources:
- Incandescent sources. The most common incandescent source is a tungsten light.
- Non-incandescent sources such as fluorescent.
- The sun.

Doppler Effect

- The observed wavelength of any wave depends on the relative motion of the emitter (source) and the receiver
- If source & receiver are approaching one another, the wavelength appears shorter (blue shift)
- If source & receiver are receding from one another, the wavelength appears longer (red shift)



Doppler Shift

- The amount that the wavelength is shifted depends on the relative speed of the source and receiver

$$\frac{\Delta\lambda}{\lambda_0} = \frac{v}{c}$$

$\Delta\lambda$ - change in wavelength

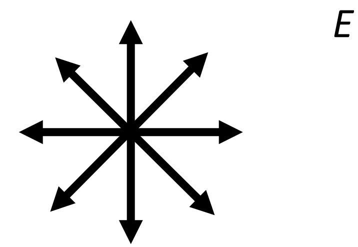
λ_0 - wavelength emitted at source

v - relative velocity of source & receiver

c - speed of light

Unpolarized light beam

- Light waves are emitted through the atomic de-excitation process in light sources, and each of them is emitted during the de-excitation of one atom. A light beam from a ordinary light source consists of a large number of electromagnetic waves and the orientations of their electric field vectors (hence also their magnetic field vectors) are random and have statistically equal distribution in all directions. Such a light beam is called an ***unpolarized*** light beam



Electric vectors of individual waves of an unpolarized light beam viewed from the direcNon of propagaNon.

Polarized light beam

- If all the waves of a light beam have their electric field vectors in the same direction at all times, giving one resultant electric field vector, then the light beam is said to be linearly polarized or plane polarized or simply polarized.

Questions

- Why are sunsets red?

Questions

- (a) Calculate the momentum of a visible photon that has a wavelength of 500 nm.

Questions

- (b) Find the energy of photon?