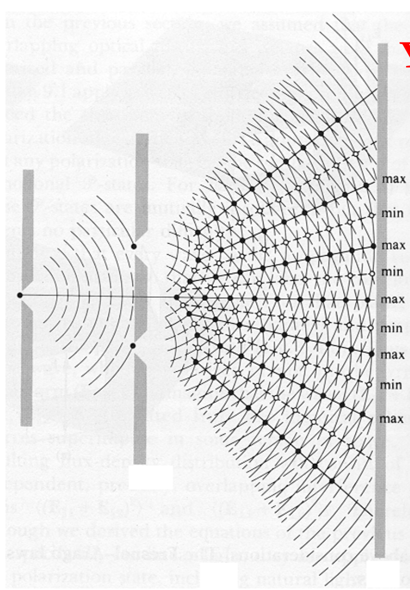
You need to learn the concepts and formulae highlighted in red. The rest of the text is for your intellectual enjoyment, but is not a requirement for homework or exams.

Chapter 4
THE NATURE OF LIGHT

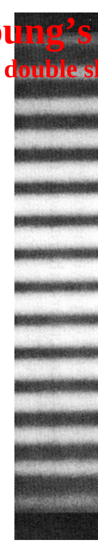
We all have experience of light, its colors, variations in intensity, its reflection, refraction, focusing, and its characteristic of traveling along a straight line in a homogenous medium. We have, however, no intuitive feeling for the physical nature of light, what it is made of, how it works. In this chapter we will discuss the dual nature of light, according to which light behaves as both waves and particles. We will also discuss the electromagnetic spectrum, the speed of light in different media, and polarization.

Light is composed of waves: there is therefore something similar to the crests and troughs of waves on the surface of water, or of waves traveling on strings. These are the ***electric and magnetic fields***: they both oscillate in the plane perpendicular to the travel direction. We all have some familiarity with these fields: the magnetic field is what makes a magnet attract a piece of iron, the electric field is responsible for the attraction of small pieces of paper to a comb that has been rubbed on wool (or dry hair).

Since these fields oscillate in light waves, there must be an alternation of places with a strong upward electric field, places with a strong downward field and places where the electric field is zero. The pattern is similar to the one we see for waves on a string: light moves with a velocity of propagation v, and just like in all other waves, there is an amplitude, a frequency and a wavelength.
Young's experiments proved for the first time that light is composed of waves. In this experiment (see diagram on the right), light coming from one slit diffracts and propagates in circular wavefronts as if the slit were a point source. If these encounter a second screen with two slits, they will be diffracted again, as from two point source, perfectly in phase, because both sources originated from a single wave. The waves from the two slits ***interfere constructively and destructively*** to generate the pattern



Young's experiment
double slit diffraction



Why would particles accumulate in certain regions not in others?

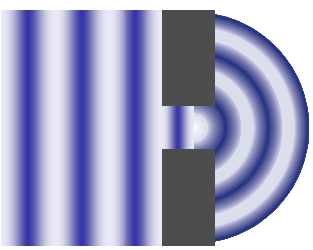
shown in the photo (right, dark and light stripes). Where interference is constructive the image is white, where destructive black. This result could not be generated by particles, therefore, Young and everyone else concluded that was that light is composed of waves.

You might understand ***interference*** of light waves better if you think of something similar, such as waves on a pond. The amplitude is the height of the wave. If the waves cancel (a crest and trough superimpose), no wave remains (flat pond) and there is no light in that position (dark band in the photo). If the waves add we get a big wave and lots of light.

The dual Nature of Light

(The text that follows, in blue italic-face, was written by Yoshinao Hirai, UW-Madison. It is reproduced here with permission of the author)
Everyone thought light was a particle before the 19th century. It became a wave in the 19th century, then a particle again in the 20th century. Now, it is both. Our understanding of light came with a twist - a twist that changed our physical world into a quantum world. Different experiments could point to either a wave or a particle nature of light. Scientists then concluded that both wave and particle behaviors describe the nature of light. Everybody now calls it the dual nature of light.

It's diffraction, interference, reflection, refraction, and all that: wave nature of light
Imagine that you take a bath or go to a pool. You know that you just can't stop waves by hands – waves just go around your hands. There is no doubt that waves on water diffract and get around an obstacle. Waves also go through a small opening and seem to diverge from there.

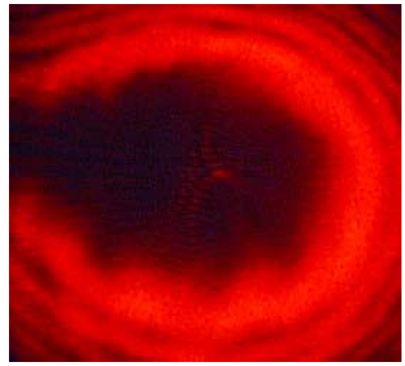


When wakes from two boats combine, standing waves could form. You made standing waves on slinky, remember? They are interference patterns. Nodes result from destructive interference and antinodes result from constructive interference.

So, Young's double slit experiment result surely points to the wave nature of light. In the history of science, many scientists experimentally and theoretically showed the wave nature of light. Who are the pioneers in this? Christiaan Huygens (wave theory on reflection and refraction), Willebrord Snell (Snell's law), Thomas Young (interference), Augustin Fresnel (interference and polarization), James Clerk Maxwell (wave theory on electromagnetic waves), Heinrich Hertz (creation and detection of radio waves) to name some.

It's mainly because of three musketeers: particle nature of light
Have you heard the names of Isaac Newton and Albert Einstein? They said light was a particle. At the beginning of the twentieth century, Albert Einstein and two other physicists - Max Planck (thermal radiation) and Arthur Compton (Compton effect) – concluded that light behaved like a particle. Those three received the Nobel Prize in Physics for their work related to the particle nature of light.

About Shadows



A pioneer of light, but not among the three musketeers, is Isaac Newton – the famous mathematician and physicist in the seventeenth century. He thought that the light was a particle because of the way a light beam creates sharp shadows of objects. Was he right in his idea? Well, we say the particle part is right but the shadow part is wrong. And we'll show you why the shadow part is wrong.

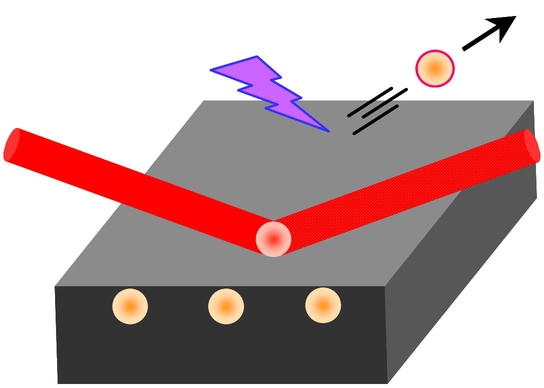
The figure on the right shows the shadow created by a pinhead under a laser beam. You see a bright central spot (inverted bull's eye) in the shadow. We didn't cheat - the pinhead is an opaque solid sphere, which doesn't allow any light to pass through. It's the result of the diffraction of light around the pinhead and constructive interference.

Thermal Radiation

The first of the three musketeers is Max Planck. Max Planck is the person who opened the door to the quantum world. He observed the intensity of light radiated by hot objects. He showed that the intensity of light at different wavelength varied in such a manner that only the emission of light having a discrete amount of energy could explain. No classical theories explained the phenomenon adequately.

Photoelectric Effect

The second of the three musketeers is Albert Einstein. But let's get this straight first. When Albert Einstein received a Nobel Prize, he was already famous for his theory of relativity. Was the prize for his work on relativity? Wrong. Was it for his work on photoelectric effect? Right!

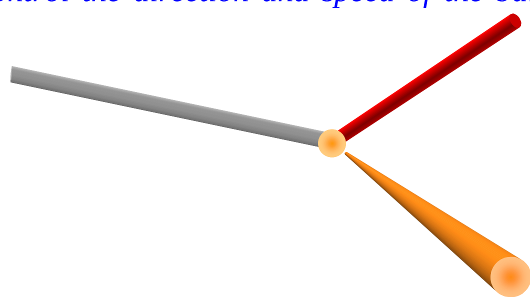


What is photoelectric effect any way? Well, it works like a soda vending machine. If you put a penny in the vending machine, you don't get a soda. Even if you put one hundred pennies, you don't get a soda… If you put in a dollar bill, a soda pops out. Now, imagine various colors of light as the money - red light being the penny and ultraviolet light being the dollar bill. If a red light illuminates a sheet of metal, nothing happens even if it's an intense red laser beam. But if a very low intensity ultraviolet light illuminates the same metal, electrons instantaneously pop out of the metal. The more intense light pops out more electrons. The light with higher frequency pops out faster electrons. This phenomenon is called a photoelectric effect.

Where is the particle part, you say? The part is the speed of electrons. The speed increases as the electron gains more kinetic energy from the light. The energy of a wave is related to its amplitude (i.e. intensity). If light interacts with an electron as a wave, an intense light would pop out a faster electron. In reality, more electrons of the same speed simply popped out with more intense light. The conclusion is that the interaction of light and matter (i.e. metal) depends on the quantum of energy, which is associated with a photon – light as a particle. Intense light simply has more photons.

Compton Effect

The third of the three musketeers is Arthur Compton. Compton effect was explained first by Arthur Compton… It works like billiard. With a great luck, a novice billiard player could bring down a ball or two into holes one after another. With a great pride and technique, a professional billiard player can predict and control the direction and speed of the balls very well. Using the law of conservation of momentum and energy, scientists predict the speed and direction of the balls (and particles) accurately. In a way, Compton effect is similar to the collision of billiard balls. Compton observed how light (x-rays) was scattered by materials, carefully measuring the direction and frequency of light. He found that the scattered light detected along particular direction had lower frequency than the incident light. He beautifully explained the result as the collision of a photon (light as a particle) and an electron. If the light interacted with electron as a wave, scattered light would have the same color (f and λ) as the incident light.



Conclusion?

So, what do we conclude about the nature of light? Based on these experimental results and ideas, we now know that the light acts like a particle when it interacts with matter. To make things more intriguing, light also behaves like a wave during the propagation as the diffraction/interference experiments show.

SPEED OF LIGHT

The velocity of propagation of electromagnetic waves depends on the medium through which the waves are traveling. ***In vacuum***, or to a good approximation in air, the speed of electromagnetic waves is 300,000,000 m/sec (or 3 x 10^8 m/s). This is a very considerable speed; for comparison a fast car travels at 30 m/s, sound travels at 300 m/s and a rocket leaving earth travels at 10,000 m/s. The speed of electromagnetic waves ***in vacuum*** is usually represented by the letter c; so we write $c = 3 \times 10^8$ m/s.

In other transparent media such as water, glass or plexiglass the speed v of electromagnetic waves is smaller than the speed c of waves in vacuum. The actual value of v depends on the medium. The velocity v of light in a medium depends on the index of refraction of the medium, according to the equation:

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

The denser the medium, the larger its index of refraction, the slower light travels through that medium. For example: the index of refraction of plexiglass is n = 1.5 so the velocity of light in plexiglass is:

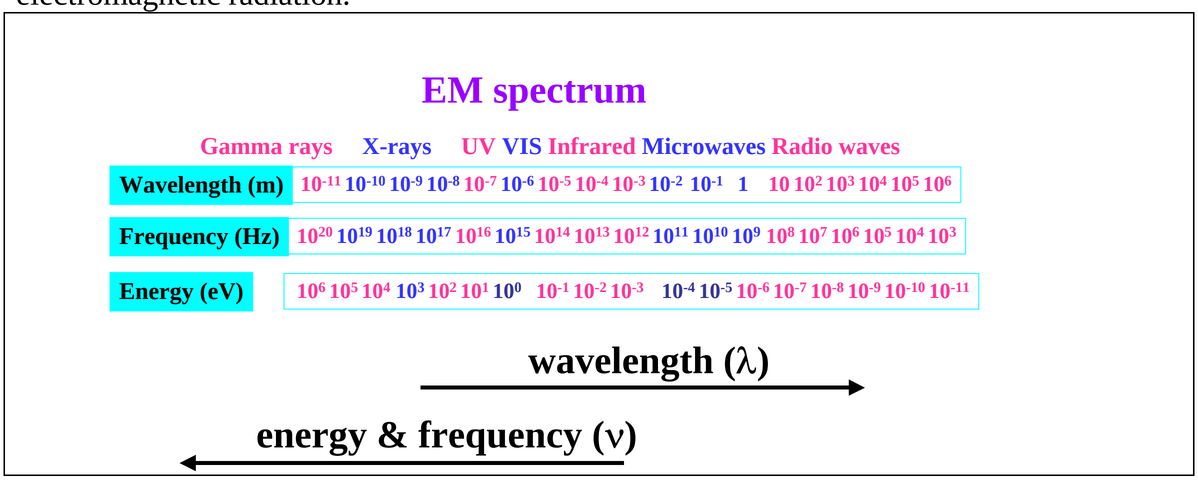
$$v = \frac{c}{n} = \frac{3x10^8}{1.5} = 2x10^8 m/s$$

The index of refraction of vacuum is n_{vac} = 1, the smallest that exists, therefore light is fastest in vacuum.

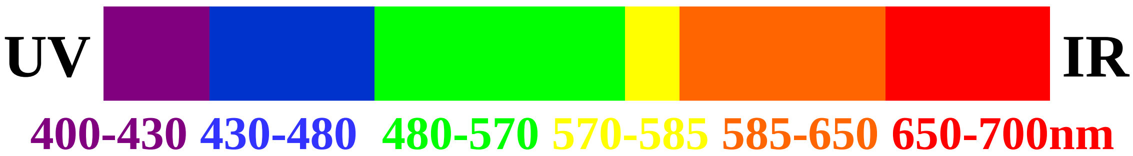
<u>ELECTROMAGNETIC SPECTRUM</u>

Electromagnetic waves can have a large range of frequencies or of wavelengths; what we call light is that narrow range of wavelengths which can be detected by our eye, from ***400 nm to 700 nm*** (*1 nm = one nanometer = 1 x 10^{-9} m*). This range of wavelengths is called ***visible range***. This is similar to the situation in sound: longitudinal waves in air can have many frequencies, but we only perceive the audible range, 30-15,000 Hz, corresponding to wavelengths between 0.02 m and 10.0 m.

Electromagnetic waves with large wavelengths (λ = 300.0 m) are called radio waves, and are what make radios work. Waves with very short wavelengths are called ultraviolet light, or if shorter still, they are called x-rays and gamma-rays. The figure in the next page shows frequency, wavelength and common name for a wide range of wavelengths of electromagnetic radiation.



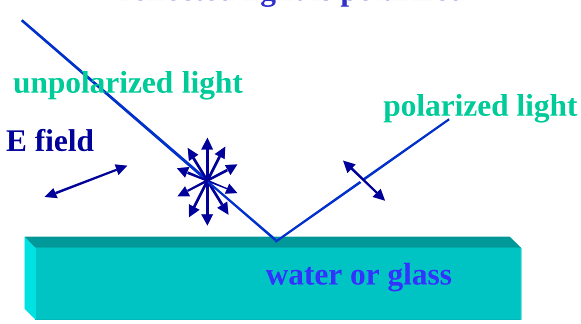
And for the visible range (VIS), different colors have different wavelengths. The serie below shows a simplified version of the spectrum, with 6 colors only, and the ranges of wavelengths associated with each color.



POLARIZATION

Let us describe one more phenomenon that can only be explained using the wave nature of light. When light propagates along one direction, the electric and magnetic fields oscillate along a second and third direction, respectively, all perpendicular to each other. The plane in which the electric field oscillates, which also contains the direction of propagation, is called ***plane of polarization***. For a simple example, imagine a rope fixed at one end, and moved at the other end. If the free end of the string is moved up and down periodically, the crests and hollows that form on the string are vertically above and below the position of the undisturbed string. In this case we can say that the waves on the string are ***vertically polarized***. If the end of the string is moved horizontally the waves are ***horizontally polarized***.

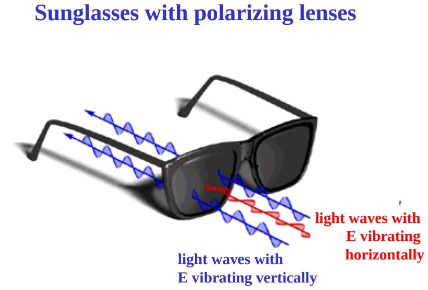
To produce an electromagnetic wave, an electric charge is moved up and down on a conductor (antenna): this generates a vertically polarized electromagnetic wave, irradiating in all horizontal directions away from the transmitting antenna. This is easily done by making an electric current flow back and forth along a vertical wire. Light from the sun or a light bulb, however, is composed of many waves with different and random planes of polarization. This is called ***unpolarized light***.



Sunlight is unpolarized, that is, it contains electric fields oscillating in all directions, in the polarization plane, perpendicular to the ray of light. When unpolarized light is ***reflected by a horizontal surface*** (mirror, water surface, car top, road, etc.) the ***reflected light is horizontally polarized***.
Polaroid filters absorb light polarized in one specific direction, and transmit the rest. These filters are prepared depositing iodine needle crystals on a polymer surface, which is then stretched, so that the iodine needles orient themselves along the direction of stretching. They then absorb light polarized in that direction only.

Sunglasses with polarizing lenses have the iodine needles oriented horizontally, and they absorb horizontally polarized light, with the electric field (E) vibrating horizontally (red in the figure on the right). Vertically

Sunglasses with polarizing lenses



polarized light is transmitted. If you combine two Polaroid filters at 90° from each other, no light is transmitted.

polarizer: enhances cloud contrast

w/o polarizer **w/ polarizer**

the filter darkens the cloud by about 1/2, but darkens the sky even more

A ***polarizer filter*** in front of a camera lens darkens the clouds in the sky, but darkens the sky even more. This happens because light scattered by smaller particles is more polarized than light scattered by larger particles. The air molecules in the sky are smaller than the ice crystals and water droplets in the clouds, therefore there is more polarized light from the sky than from the clouds. The polarizer filter, therefore, removes more light from the sky, and the contrast cloud-sky is enhanced. (Photographs are courtesy of Tiziana Parasassi).