9:1a Introduction to Light

Consider the questions we have answered over the last month.

- What are the characteristics that define a wave?
- How do waves interact with their environment?
- How do we know if a specific phenomenon is a wave?
- What evidence do we have that sound is a wave?

If everything has gone well you now know the answers to the above questions. But why did we ask these questions in the first place?

The answer lies with light.

It comes down to this! What exactly is light? Is it a wave or is it particle and how do we know?

These are questions that were asked by Isaac Newton and many others going back centuries. The answers to these questions slowly evolved over time.

Our goal here will be to see if we can account for the behaviors of light by using a wave model.

Before answering that question, however, we need to determine exactly what is we mean when we say “light”.

For most of us this word conjures up the different colors of light that we, as humans, can see.

The visual range of human sight extends from a shortest wavelength of approximately 400 nm to a maximum wavelength of about 760nm. The detection of these colors depends upon sensory detectors in the back of the eye.

9:1b Introduction to Light – Human Vision

There are two different types of light detectors in the back of the eye:

- **cones** – which can detect color, but which are not particularly sensitive to light intensity.
- **rods** – which are very sensitive to low levels of light, but which cannot discriminate between colors. The maximum sensitivity of rods occurs at approximately **λ = 498nm**.

Of the cones in the back of the eye there are three types:

- **red** – These cones detect red and make up approximately 64% of the cones present in the eye. The wavelength of greatest sensitivity for these "red" cones is about **575nm**.
- **green** – These cones detect green and make up approximately 32% of the cones present in the eye. The wavelength of greatest sensitivity for these "green" cones is about **535nm**.
- **blue** – These cones detect blue and make up only about 2% of the cones present in the eye. The wavelength of greatest sensitivity for these "blue" cones is about **445nm**.

The combination of these three types of detectors results in maximum human sensitivity to light at about **λ = 555nm**.

Since your eye has detectors that can only detect the three colors: red, blue and green, the three **primary colors** are likewise **red**, **blue** and **green**. All other colors are made by combining these three primaries together. Each of these primaries has a counterpart color called a **complementary color**.

9:1c Introduction to Light – Color Sight

The **complement** of any color is that color which when added to the first color results in white.

For example, in the case of red, its **complementary color** is cyan.

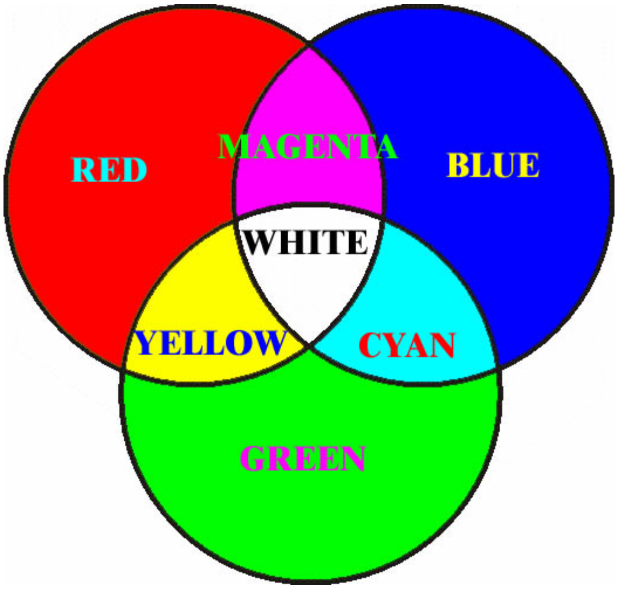
red + cyan = white

The complement of green is magenta.

green + magenta = white

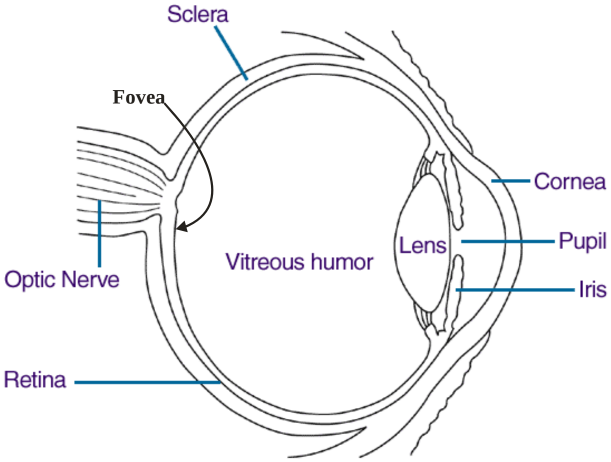
And the complement of blue is yellow.

blue + yellow = white



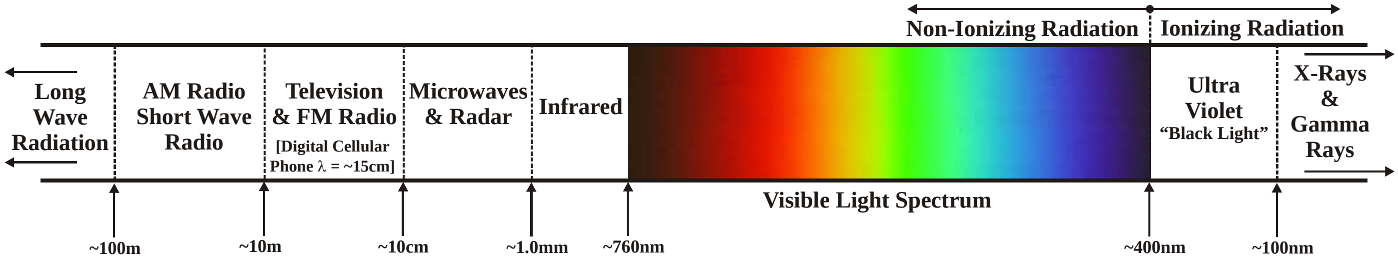
These three complementary colors are known as the **primary pigments** and are the colors used in printing any color picture in a magazine, book or computer printout.

Both the **cones** and the **rods** are located in the back of the eye along a surface called the retina. A very small area in the center of the retina where the cones are most closely packed is called the **fovea**. The fovea is filled primarily with red and green detectors with a small scattering of blue detectors.



9:1d Introduction to Light – Color Sight

The fovea is nearly devoid of any rods and so is relatively insensitive to light. The area of the retina outside of the fovea is filled with rods and a few blue detectors, both of which are more sensitive to lower levels of light. Therefore, our peripheral vision is much more sensitive to low levels of light, although the resolution is poor because the rods are larger, are not as densely packed and therefore generate a lower resolution screen than does the fovea.



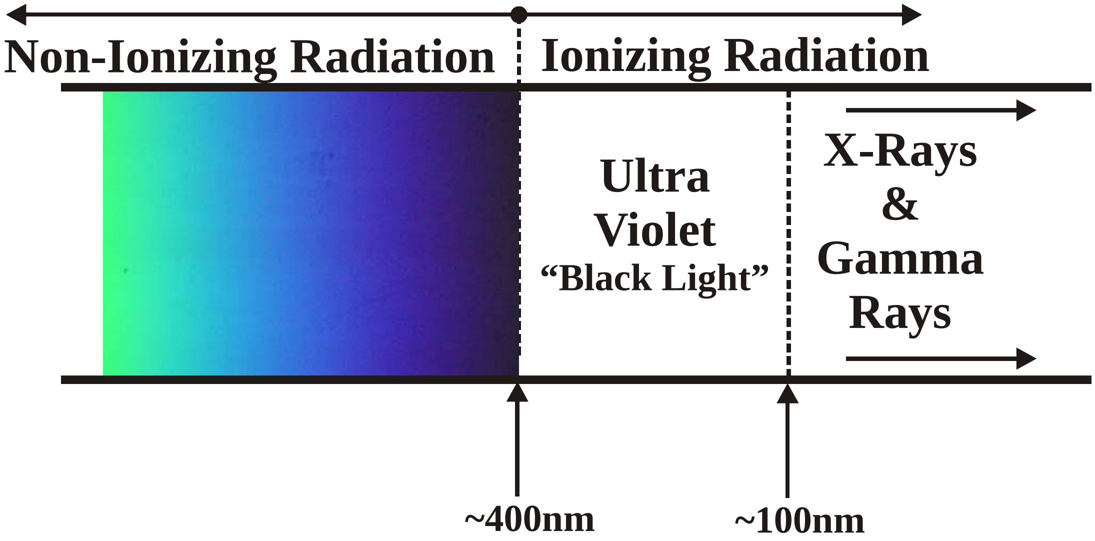
In any case, the shortest wavelength of the visible light spectrum is about 400nm while the longest visible wavelength is around 760nm. [There seems to be some disagreement about this number. Some sources report wavelengths a low as 700 nm while other sources report wavelengths as high as 780nm.]

In fact, of the entire electromagnetic spectrum, we are capable of seeing only a very narrow range. The vast majority of light wavelengths are not within the limited capabilities of our visual system. But nevertheless, they are still light.

Wavelengths shorter than 400 nm are distinctly different from the wavelengths greater than 400 nm in that these shorter wavelengths are significantly greater in energy content and fall into a special classification known as "ionizing" radiation.

9:1e Introduction to Light – Ionizing Radiation

Ionizing radiation is unique in that radiation of this type is capable of striping electrons from atoms and in doing so can break chemical bonds. As a result, exposure to ionizing radiation can damage living tissue.



Ultraviolet [UV] radiation is the weakest of the ionizing radiation types. It is UV light that is responsible for the damage of sunburn. This damage literally can kill living cells and has the very real potential of causing skin cancer. If there is one saving grace about UV light and its effect of living organisms, it is that it is only capable of penetrating through a few surface layers of skin and thus its damage is limited to the surface of our skin.

[According to the American Cancer Society web site there were approximately 20,000 skin cancer deaths in the past year.]

X-Ray radiation is shorter in wavelength [< ~100 nm] than UV light and contains correspondingly more energy, is able to penetrate tissue to a much greater degree and can cause significant tissue damage.

9:1f Introduction to Light – Ionizing Radiation

As in the case of UV light, X-Ray radiation is able to damage living tissue and as a result can also cause cancer. Unlike UV radiation, however, the greater penetrating ability of X-Ray radiation, as well as its greater energy content, makes X-Ray radiation significantly more hazardous that UV. Fortunately, our average exposure to this radiation type is very limited except through medical diagnosis and treatment.

The federal government sets limits on the amount of ionizing radiation that the average person is likely to encounter. Ionizing radiation exposure is measured in a unit known as the REM [**R**oentgen **E**quivalent **M**an – for more information on radiation http://web.princeton.edu/sites/ehs/radsafeguide/rsg_app_e.htm]. This unit is a measure of the damage done to living tissue by the exposure to ionizing radiation. The “mean fatal dose” of ionizing radiation for whole body exposure is in the area of 500 to 700 REM. According to federal regulations, the maximum allowed exposure for an employee in the workplace is 5.0 REM per year, with no more than 1.25 REM of that exposure occurring during any 3.0 month period. Each of us receives, on average, somewhere in the range of 300-400 millirems [for more detailed information on our exposure to background radiation sources http://healthandenergy.com/rad_chart.htm] each and every year from environmental exposure.

Medical exposure can vary dramatically depending on the medical procedure. A typical chest x-ray will deliver about 40-60 millirems while cancer treatment can result in 100’s of REMS of exposure.

9:1g Introduction to Light – Ionizing Radiation

You may wonder how a cancer patient can survive 100’s of REMS of exposure in light of the previously mentioned mean fatal dose. The key here is in the type of exposure. In radiation treatment for cancer, the ionizing radiation is typically focused on a specific portion of the body rather than the whole body. The point, of course, is to kill off the growing cancer while sparing the rest of the body. Even so, cancer patients suffer very severe radiation sickness due to the damage done by the radiation exposure.

Gamma Radiation is typically, but not always, shorter in wavelength than x-ray radiation. The real difference between these two types of radiation is not so much their wavelengths and energies, but rather in their origins. X-ray radiation is caused by accelerating electrons to extremely high velocities [usually greater than 10% the speed of light!] and then slamming them into a target. As these electron rapidly come to a halt their kinetic energy is converted into light by a process called “x-ray production” [also known as the “inverse photoelectric effect” to be discussed later]. The energy of these x-rays is determined by the velocity and kinetic energy of the incoming electrons. Gamma radiation, by contrast, results from an entirely different process. The protons and neutrons in the nucleus of an atom exist in energy levels in much the same way that electrons occupy energy levels in an atom.

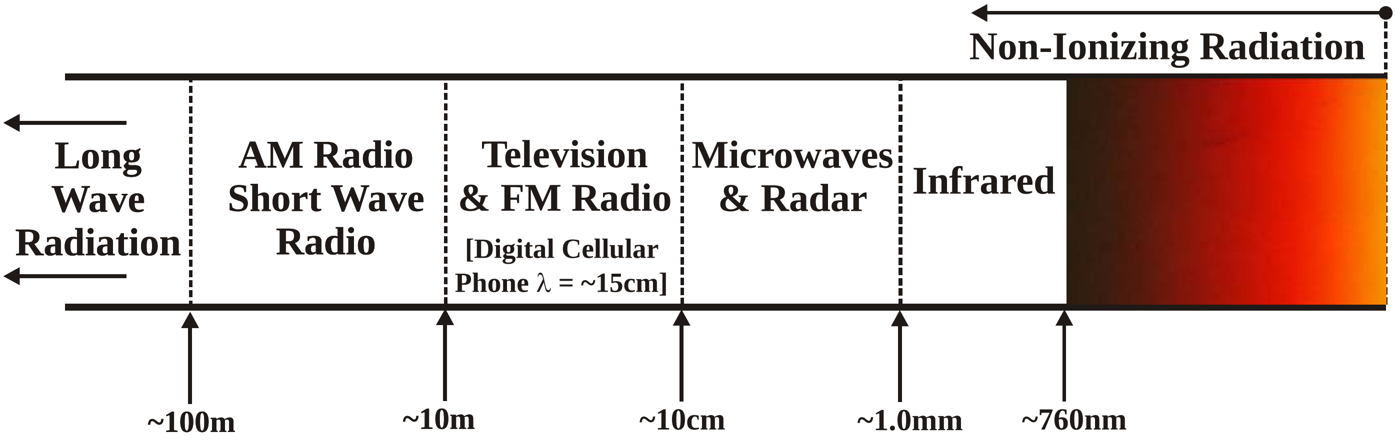
[Smoking one package of cigarettes delivers approximately 29 milliRem per pack! Consider the lifetime exposure of heavy smoking!]

9:1h Introduction to Light – Non Ionizing Radiation

If the nucleus of an atom is somehow moved into an excited state, [this can occur through certain types of radioactive decay or through violent collisions with other atoms] this nucleus can then return to its ground state and in the process emit a very energetic light wave which we call a gamma ray.

Therefore, the fundamental difference between x-rays and gamma rays is how they are generated, rather than what their energies and wavelengths happen to be.

On the other end of the optical spectrum are the **non-ionizing** forms of light. This includes visible light and all longer wavelengths, none of which can strip electrons from their atoms.



Infrared radiation is a form of light somewhat longer in wavelength than red light [“infra” red means less energetic than red]. Although we cannot see infrared with our eyes, we can detect it through our skin through which we can “feel” the warmth of infrared. Infrared light is the light responsible for the “warmth of the sun” or the warmth we feel when we stretch out before a fireplace on a cold winter’s evening.

9:1i Introduction to Light – Microwaves

Certain types of snakes, called "pit vipers" have small pits on their faces, which are capable of detecting infrared and enable them to catch their prey even in total darkness.


MICROWAVE OVEN

Microwaves and **radar** are forms of light on the order of millimeters to centimeters in length. As you are probably aware, microwaves are capable of heating food. They can do so because these waves are capable of setting up oscillations in atomic molecules. This ability can be tuned to specific frequencies and in the case of microwave ovens a frequency of 2450 MHz, which correspond to a wavelength of 12.24 cm [for more information see http://en.wikipedia.org/wiki/Microwave_oven] which has the capability of causing oscillations in the molecules of water, fat and sugar, thus heating the food without heating the dish on which the food site. Eventually, the dish warms up due to the conduction of heat from the food, but the dish is not heated directly by the microwaves. [Some dishes are specifically designed of materials that will absorb energy at these same wavelengths.]

The first microwave ovens were marketed by Amana under the name "Radar Range" because the wavelengths used in microwave ovens are comparable to that used in radar.

9:1j Introduction to Light – Television & FM Radio


TYPICAL ROOFTOP ANTENNA

Television and **FM radio** [FM radio falls between TV channels 6 and 7] are waves whose wavelengths are the only wavelengths of light that are of the same order of magnitude as our every day lives, ~0.1m through ~10m. You can get a pretty good idea of the wavelength of a wave by looking at the length of the antenna used to receive and detect that wave. Roughly speaking, the ideal length of a dipole antenna is slightly greater than ½ wavelength.


SATELLITE DISH

So when you look at an antenna or satellite dish on the roof of your neighbor's house, you can get a pretty good idea of the wavelength that the antenna is designed to receive. Satellite TV broadcasts are assigned frequencies between 38.6 GHz and 275 GHz, which correspond to wavelengths between 1.0 mm and 1.0 cm. On a typical satellite dish, the dish surface is just a reflector which focuses the light waves from the satellite in geosynchronous orbit onto an antenna located in the "feedhorn" sitting near the focal point of the curved dish.

9:1k Introduction to Light – AM Radio

AM Radio waves are even longer in wavelength and lower in energy than TV and satellite broadcasts. AM radio waves begin with a frequency of 1710 kHz and extend up through 530 kHz. These wavelengths correspond to wavelengths of 175m and 566m. Obviously, a **dipole** antenna of this length would be impractical and so in this case we make use of a slightly inferior, but more useful **monopole** antenna. While the dipole antenna should ideally be slightly greater than ½ wavelength, no such limit is placed on monopole antennas.

In a dipole antenna the length of the antenna is sized so that one end of the dipole antenna lies in the crest of the light wave while the opposite end sits in the trough of the light wave. Because of this requirement dipole antennas have to be oriented so that the ends of the dipoles can lie in the appropriate locations. In automotive applications this can be very limiting. As the car turns, the relative orientation of the antenna changes and the signal strength can vary dramatically. Monopole antennas, however, point straight up and down, and so when the car turns right or left, the relative orientation of a monopole is unchanged and the resulting signal strength remains constant.

As a result, although the monopole antenna isn't perfect, it is an excellent compromise for mobile applications.

MONOPOLE ANTENNA

9:1l Introduction to Light – Long Wave Radiation

Long Wave radiation refers to all other light waves longer than about 1000m. Waves in the **Extremely Low Frequency** [ELF] range [<3000Hz] are used to communicate with submarines all over the world. A frequency of 3000Hz translates into a wavelength of over 100,000 meters. With this long wavelength these waves can easily bend around corners [including around the Earth itself] and can be transmitted through seawater.

The disadvantage of these waves is that due to their very low frequency, the rate at which information can be transmitted is very low and typically these signals are used to contact the submarine and direct the submarine to surface so that more conventional modes of communication can be utilized.

[The use of this ELF signal was used as a plot element in the movie ***Crimson Tide*** where the slow communication rate of this mode became an issue.]

One other interesting application of light can be seen in the Very Large Array located near Socorro, New Mexico. These antennas are mounted on railroad like cars and can be moved over a system of tracks that covers more than 22 miles. Because of this extremely large base line, this antenna array can achieve a resolution of 0.04 seconds of arc at its highest operational frequency. [The VLA is designed to receive radio waves in the range 74 – 50,000 MHz, or 400-0.7cm.]