Physics 17 Part O
Electromagnetic Waves

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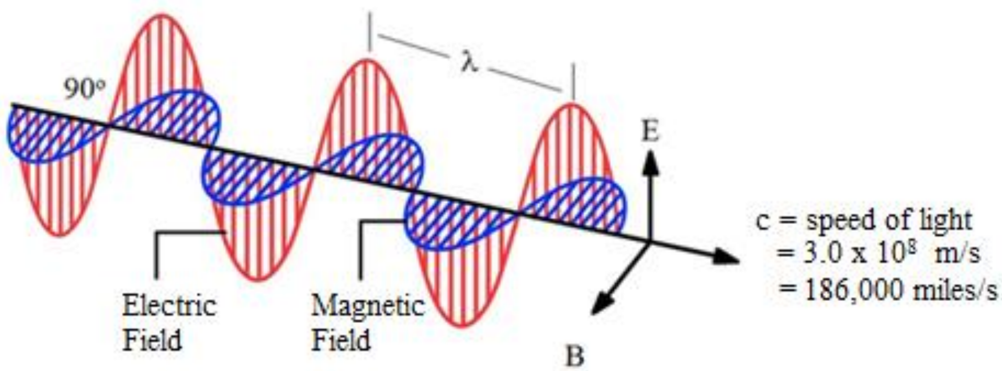
Video Lecture 1: Doppler Effect for Light
Video Lecture 2: Light Intensity
Video Lecture 3: Light Mixtures

Electromagnetic (EM) waves consist of traveling electric (E) and magnetic (B) disturbances caused by electric charges oscillating at a certain frequency, f. The EM waves thus created have a frequency f that is the same as the oscillation frequency of the electric charge.

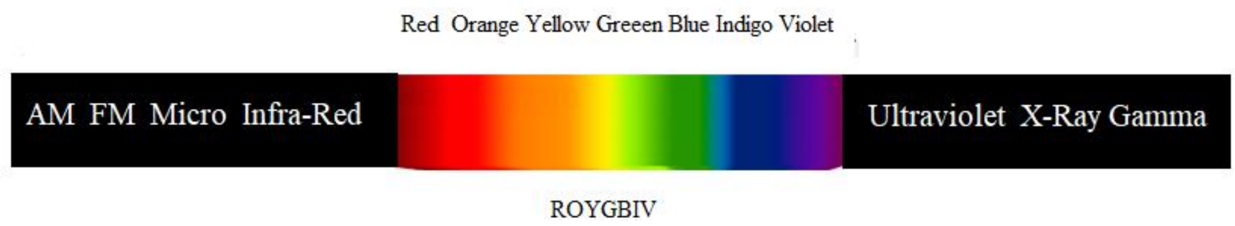
At any point, the electric component is perpendicular to the magnetic component. These waves travel through air and transparent materials with a speed that varies, depending on the substance. Through air or vacuum, the speed of electromagnetic waves is 3.0 x 10^8 m/s; this speed is called "the speed of light."



The equation for EM waves is the same as the one we've used in the past for string and sound waves, except in this case the speed of the waves is symbolized as c, and is called "the speed of light."

$$\lambda f = c$$

The Electromagnetic Spectrum

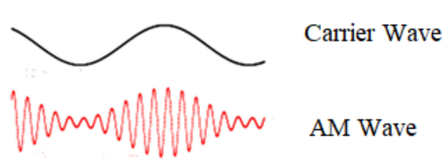


The smaller the wavelength, the more harmful EM radiation is to living things. X-rays and gamma rays have wavelengths short enough to break chemical bonds and unstabilize nuclei, which can lead to mutations of DNA and cancer; if the intensity of gamma radiation is great enough--such as can occur near the detonation of a nuclear weapon, such as an atomic bomb, or hydrogen bomb--death to living organisms can come virtually immediately.

AM and FM Waves

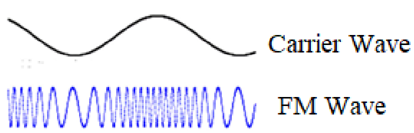
Varying pressure and frequency in sound information produced in the radio station is used to impress a kind of "code," or "pattern" on a so-called "carrier wave." The carrier wave is then said to have been changed, or "modulated." The modulated electromagnetic wave is broadcast by an antenna at a radio station. A radio receives this modulated wave and possesses the necessary de-coding apparatus to extract from the wave the exact pattern of varying sound pressure and frequency present in the spoken words and music that was input into the microphones in the radio station.

AM ("amplitude-modulated") radio stations modulate the carrier wave by changing the wave "amplitude."



The Federal Communications Commission licenses AM radio stations and assigns to them the right to broadcast at frequencies within the range 535 kHz to 1605 kHz, in increments of 10 kHz.

FM ("frequency-modulated") radio stations modulate the frequency.



Example A:	Example B:
DNA-destroying gamma radiation has wavelength comparable to the diameter of atomic nuclei: 1.0×10^{-15} m, and is thereby capable of transforming strands of DNA (mutating it) and thereby cause cancer. What is the frequency of gamma radiation that has this wavelength? $f = c/\lambda$ $f = 3.0 \times 10^8/1.0 \times 10^{-15}$ $= 3.0 \times 10^{23}$ Hz	What is the wavelength of an AM radio station's carrier wave whose broadcast frequency is 600 kilohertz? $\lambda = c/f$ $= 3.0 \times 10^8$ m/s / 600×10^3 s^{-1} $= 500$ m Compare this to the wavelength of gamma waves, which have wavelengths about as wide as a nucleus.

Visible Light

The table below shows the average wavelengths of the various bands of visible light, ROYGBIV. For example, light with a wavelength anywhere within the range 620 -750 nm is "red."

The "blue" end of the visible spectrum is the short-wavelength end, while the "red" end is the long-wavelength end.

$$1.0 \text{ nm} = 1.0 \times 10^{-9} \text{ m}$$

Color	λ (nm)
Red	685
Orange	590
Yellow	570
Green	510
Blue	475
Indigo	445
Violet	400

In what follows, we will mainly concern ourselves with the colors red, green, blue, cyan, yellow, and magenta. There will be little or no discussion of orange, indigo, or violet.

The Doppler Effect for Light

If the distance between a source of light and an observer is increasing, the light frequency seen by the observer is lower than the frequency of light emitted, and the corresponding observed wavelength is longer than the wavelength emitted. This wavelength increase is labeled a “red shift,” because the observed light wavelength is shifted toward the longer wavelength end (the redder end) of the visible spectrum. If the distance is decreasing, a “blue shift” occurs.

<u>Introducing the Doppler Effect Equation for Light</u>

v = Relative speed between source and observer
f_o = Observed frequency
f_s = Source frequency

$$f_o = f_s (1 \pm v/c)$$

Sign Choice Rules:
Choose (+) if the distance between source and observer is decreasing.
Choose (-) if the distance is increasing.

Example:

650 nm light from a galaxy is observed on Earth as 590 nm light.

(a) What are the two frequencies?

f_s = (3 x 10^8 m/s) / 650 x 10^{-9} m
= 4.62 x 10^{14} Hz

f_o = (3 x 10^8 m/s) / 590 x 10^{-9} m
= 5.08 x 10^{14} Hz

(b) Is the galaxy moving toward, or away, from Earth?

The observed frequency is higher, so the galaxy is moving toward Earth.

(c) Is the light blue-shifted, or red-shifted?

Higher frequencies are bluer, so the light was blue-shifted.

(d) What is v/c?

By the Doppler rules stated earlier, we use the (+) sign in the Doppler equation because the distance between galaxy and Earth is decreasing.

$$5.08 = 4.62\ (1 + v/c)$$

$$v/c = 0.10$$

Light Intensity

"Light intensity" at some location is a measure of the light energy per second, per square meter incident on an area. Its units are watts/m^2.

The light sources we will consider are so-called "spherically symmetric" sources. The light intensity from such sources varies with the distance r from the source according to the equation below:

$$I = P/4\pi r^2$$

For example, at a distance r = 0.10 m away from a 60-watt source, the intensity is

$$I = 60\ W/(4\pi \times 0.10^2\ m^2)$$
$$= 477.46\ W/m^2$$

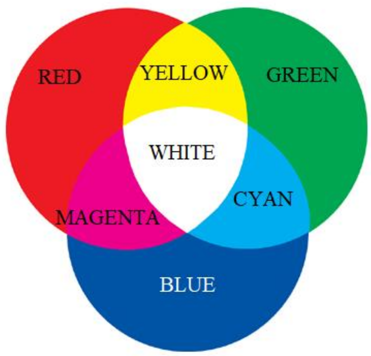
Mixing Colors of Light

Humans have "trichromatic" color vision, meaning that the color sensors (cones) in the retina respond more efficiently to the three "primary" colors red, green, and blue (RGB) light, than to other colors. Other colors of light that will be relevant in our current study are the three so-called "secondary" colors of light, colors which are mixtures of two of the primary colors of light.

Mixtures of the primary colors of light produce various color sensations when they are incident on the retina. Below are the colors produced when equal intensities of the primary colors of light are mixed together.

Don't confuse the primary colors of light with the primary colors of paint. We will discuss paint at the end of this part of the course, and devote our attention now to light colors, not paint colors.

Red	R	primary
Green	G	primary
Blue	B	primary
Yellow	Y = R + G	secondary
Cyan	C = G + B	secondary
Magenta	M = R + B	secondary
White	W = R + G + B	
Black	K	



Example:

What intensity of red light must be added to 70 watts/m^2 of cyan light to create white light?

70 C = 35 G + 35 B
Add 35 W/m^2 of red light.

35 G + 35 B + 35 R = 105 W

105 watts/m^2 of white light is created.

Example :

40 W/m^2 of green light is mixed with 60 W/m^2 of magenta light. What is the color of the mixture?

Solution:

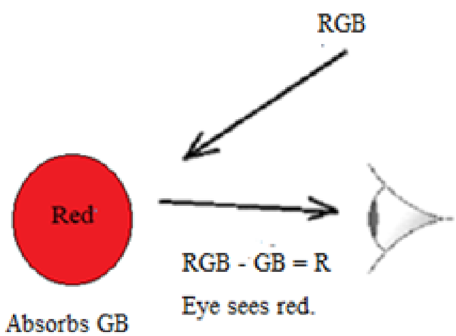
60 M = 30 R + 30 B
Add 40 G = (30 G + 10 G)

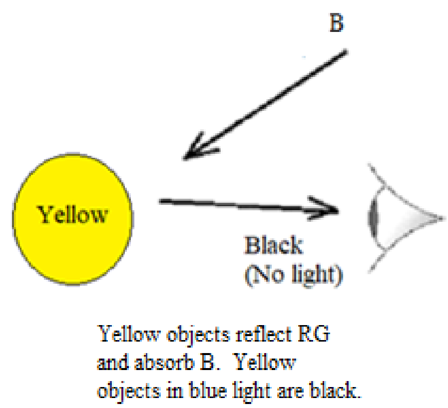
(30 R+ 30 B) + (30 G +10 G) = (30 R + 30 B + 30 G) + 10 G
= 90 W + 10 G
= 100 pale green

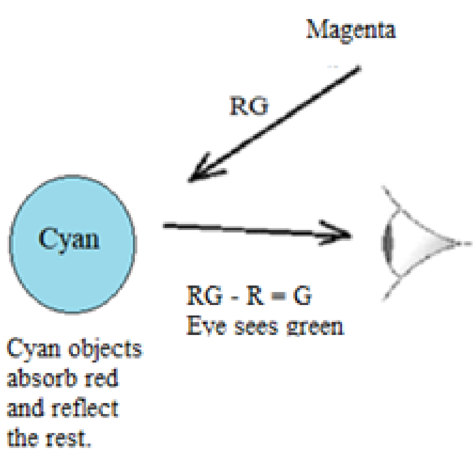
Colors of Objects

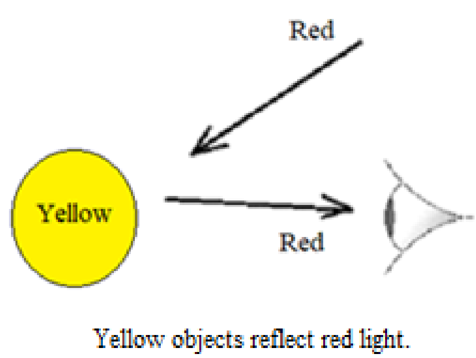
Unless otherwise stated, assume that objects are illuminated in sunlight (white light), which we may regard as being a mixture of equal intensities of the primary colors, red, green, and blue.

The color of an object in white light is whatever is the color of light is reflected.

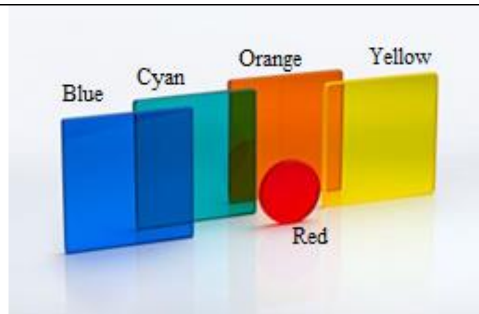




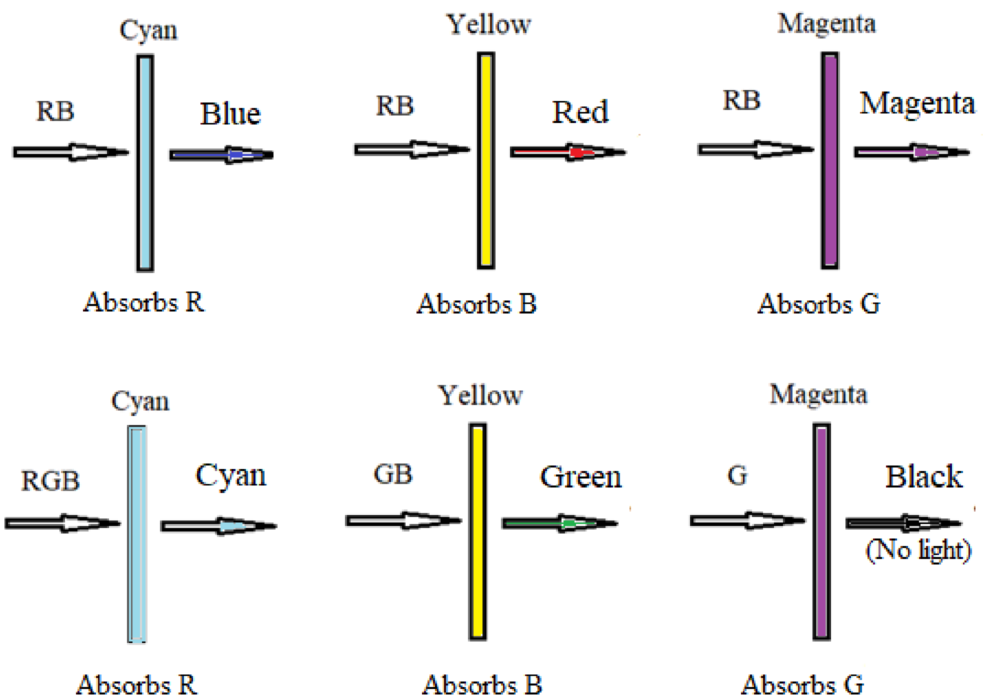




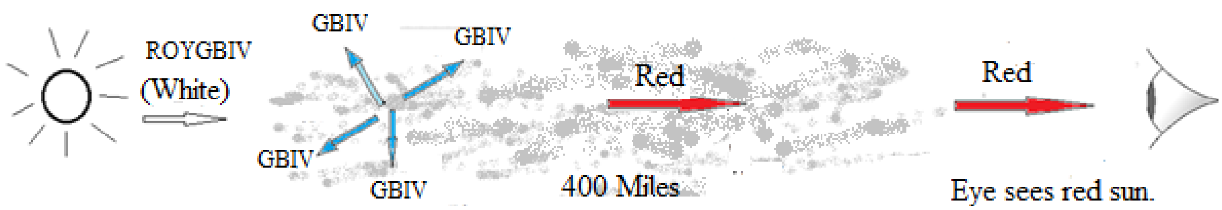
Filters

Filters are transparent media that allow only certain colors to pass through (be "transmitted"), while absorbing other colors. They're basically just "colored glass."	

Filter Color	Color Absorbed	Colors Transmitted
Red	Green, Blue	Red
Yellow	Blue	Red, Green, Yellow
Cyan	Red	Green, Blue, Cyan
Magenta	Green	Red, Blue, Magenta



Why are Sunsets and Sunrises Red?

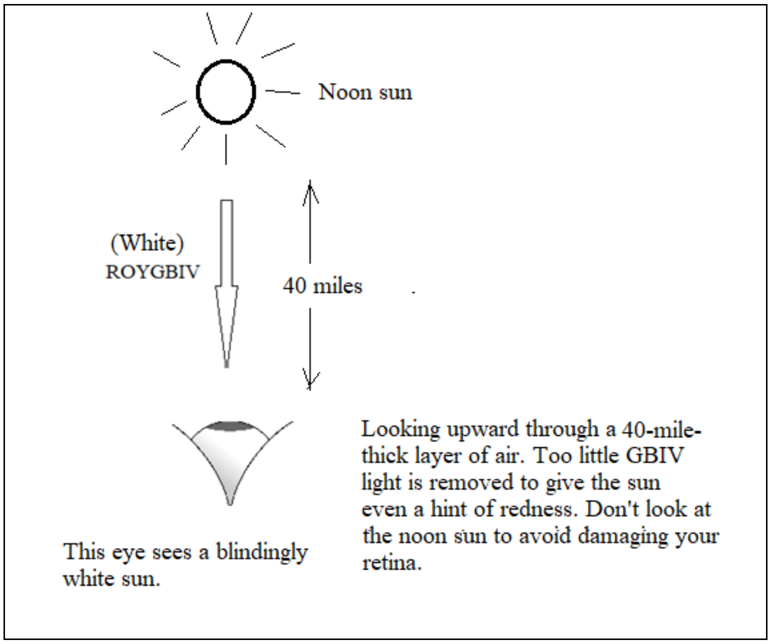


Blue Light Scattering

Oxygen and nitrogen molecules in the atmosphere absorb the green, blue, indigo, and violet (GBIV) light from of the incident white light from the sun, then radiate that light in every direction—right, left, forward, backward, upward, and downward. This "filtering out" of the GBIV light is called "scattering." The red, orange, yellow (ROY) light portion of the white light is also scattered, but in negligibly small amounts compared to blue light. The vast majority of the ROY portion of the incident white light makes it through the atmospheric "filter" unmolested.

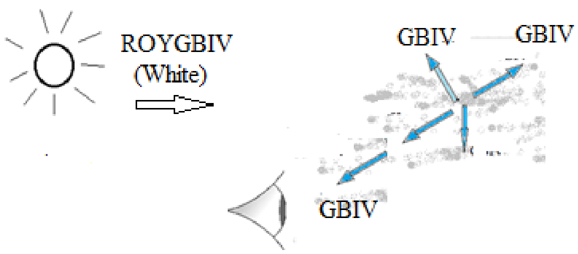
At dawn, and again at sunset, light from the sun, peeking over the horizon, will travel through about 400-miles of atmosphere. At the end of its journey, having had most of its GBIV wavelengths removed by the 400-mile-thick scattering filter, the light arriving at the observer will be almost entirely a mixture of red, orange, and yellow (ROY)

The Noon Sun


Noon sun
(White)
ROYGBIV
40 miles
Looking upward through a 40-mile-thick layer of air. Too little GBIV light is removed to give the sun even a hint of redness. Don't look at the noon sun to avoid damaging your retina.
This eye sees a blindingly white sun.

Why is the Sky Blue?

With her back to the sun, sunlight passes over the shoulder of the observer in the diagram below. Red-orange-yellow (ROY) light (not shown) goes straight through, while a significant amount of the blue end of the visible spectrum is scattered in all directions, including back toward the eye of the observer, who thereby sees blue light, i.e., blue sky.



With her back to the sun, this observer sees blue scattered light, i.e., she sees blue sky.

The red portion of the light is not relevant, and not shown.

Mixing Paints

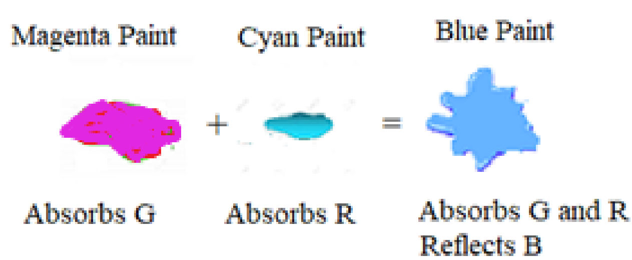
In art class, some persons learned that the three primary colors of paint are blue, red and yellow (BRY). In the world of physics, however, the three primary colors are cyan, magenta, and yellow (CMY). Anyone who has ever installed color cartridges in their printer knows that the three cartridges are C, M, and Y. Mix any two of them and you will create one of the other three important paint colors: red, green, or blue. The example below shows how the printer makes blue ink.

Mixing Primary Paints Example

Example:

What color of paint is created when magenta paint is mixed with cyan paint?

Any object that is magenta absorbs G, while an object that is cyan absorbs R. Mix the two paints, shine white (RGB) light on the mixture, and the mixed paint will remove G and R, while reflecting B.



Convince yourselves that mixing magenta and yellow paints makes red paint, while cyan and yellow make green.