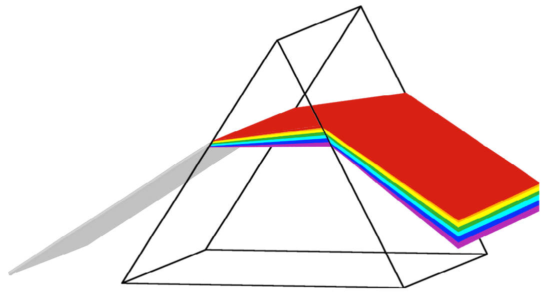
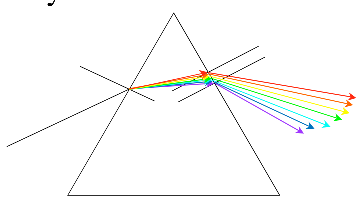
***You need to learn the concepts and formulae highlighted in red. The rest of the text is for your intellectual enjoyment, but is not a requirement for homework or exams.***

# Chapter 6
# COLOR AND COLOR VISION

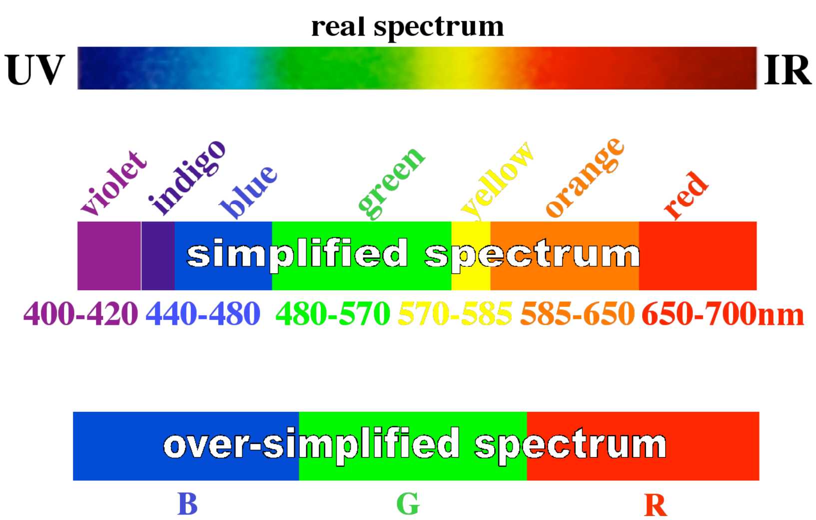


## COLOR

White light is a mixture of lights of different wavelengths. If you break white light from the sun into its components, by using a prism or a diffraction grating, you see a sequence of colors that continuously vary from red to violet.

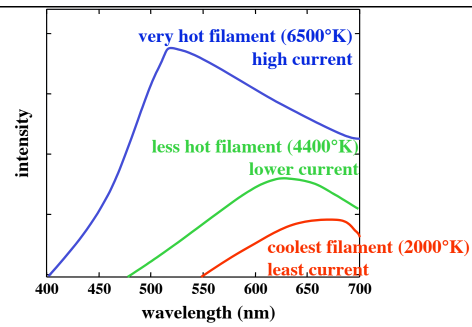


The prism separates the different colors, because ***the index of refraction n is slightly different for each wavelength***, that is, for each color. This phenomenon is called ***dispersion***. When white light illuminates a prism, the colors of the spectrum are separated and refracted at the first as well as the second prism surface encountered. They are deflected towards the normal on the first refraction and away from the normal on the second. If the prism is made of crown glass, the index of refraction for violet rays $n_{400nm}$= 1.59, while for red rays $n_{700nm}$=1.58. From Snell's law, the greater n, the more the rays are deflected, therefore violet rays are deflected more than red rays.



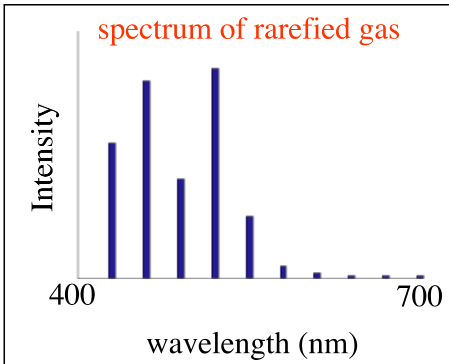

The infinity of colors you see in the real spectrum (top panel above) are called ***spectral colors***. The second panel is a simplified version of the spectrum, with abrupt and completely artificial separations between colors. As a figure of speech, however, we do identify quite a broad range of wavelengths as red, another as orange and so on. The accurate wavelength ranges for each color are reported in the second panel, each producing a specific sensation detected by our eyes. An even more extreme simplification is shown in the third panel, with 3 colors only, RGB, commonly used by computer monitors and TV sets. You may notice that, even in the most complete sequence of spectral colors of the top panel, many colors you know from everyday life are not present. Purple, magenta, and mauve are one class of colors missing from the spectrum. Others are browns, olive and hunter greens, as well as all the pale colors as pink, cyclamen, eggshell, aqua, sky-blue, etc. These are mixed, low intensity, and low purity colors, respectively, as will be described later.

It is interesting to look at the light produced by different kinds of light sources through a diffraction grating or spectroscope, to observe what wavelengths are present, and in what proportions. The light from a normal light bulb shows all the spectral colors, but the blue and violet are less intense than in sunlight. If one decreases the current flowing through the light bulb, the filament gets colder, the light it emits is dimmer and appears more yellow. When this light is analyzed with the spectroscope, it is evident that violet and blue have disappeared from the spectrum, which explains why it appears more yellow.




This observation can be represented by a graph of the intensity of lights of different wavelength for 3 different amounts of current flowing through the filament.

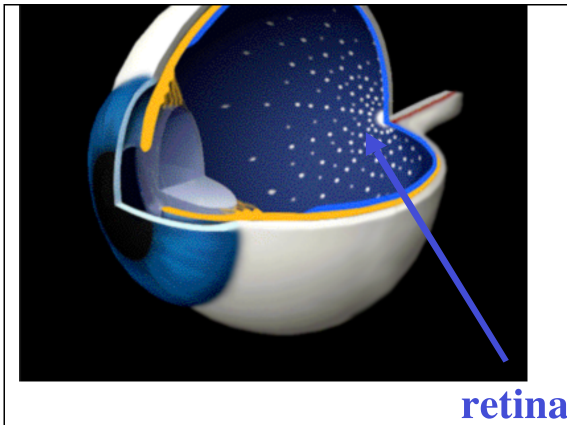
If, on the other hand, you analyze with a diffraction grating the light coming from a neon discharge tube you will find that only certain colors are present. You see many red lines, two or three orange ones, a yellow line, two faint green lines, and a few faint blue lines.



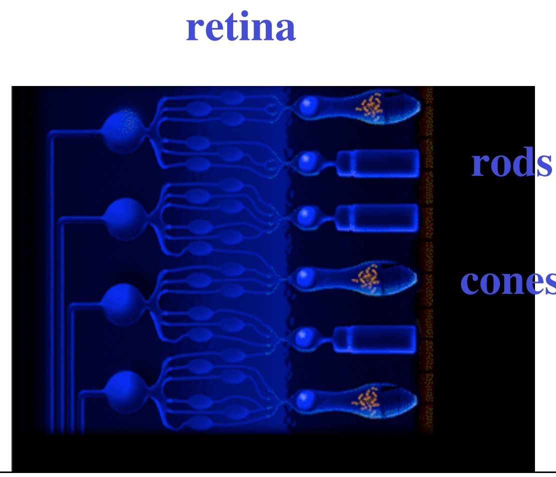

The spectrum of hot solids, as the light bulb filament, is always a *continuous spectrum*, and the amount of blue increases with increasing temperature. The spectrum of rarefied gases, as the neon, hydrogen or mercury lamps, is always a *line spectrum*, with only a few lines at specific wavelengths (colors). These spectra are analogous to the Fourier spectra in sound: both spectra show the relative intensities of light (sound) at various wavelengths (or frequencies).

## COLOR SENSITIVITY OF THE EYE

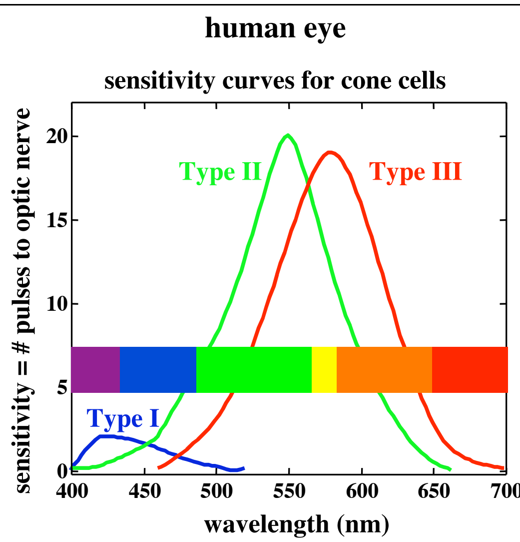
The retina, at the back of the eyeball, contains cone and rod cells. The ***rods*** provide low resolution, peripheral vision, and function well even in dim light, while the ***cones*** provide color, high resolution, central vision, and can only function in bright light.




From “Les secrets des couleurs”.

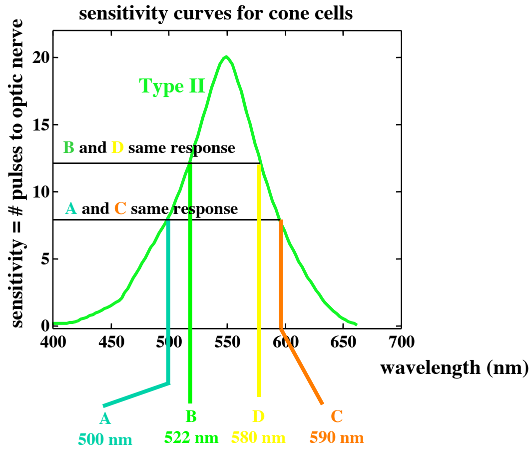



We will here focus on the ***color sensitive cones***, because their functioning explains the perception of colors and color mixing. Studies on color vision indicate that there are three types of cones: let us call them Type I, II, III. They are sometimes called blue, green and red sensitive cones, but this is not correct: blue green and red are not the only colors to which these cones are sensitive. The sensitivity curves of the three types of cones are shown below.

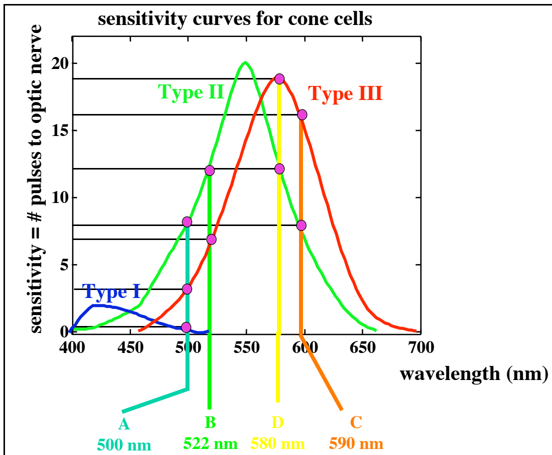



By ***sensitivity curve*** we mean how intense is the neural response to light changes when varying the wavelength of light, keeping the intensity constant. A different neural response is a different number of nerve pulses per second being transmitted by the cones in the retina to the optic nerve and the brain. The three types of cones are labeled with Roman numerals and not with color names as is usually done in order to stress an important point: *all three types of cones are sensitive to a broad band of wavelengths*, i.e. they are sensitive to many colors. Cones of type I are sensitive to violet, blue and to green light. Type II are sensitive to blue, green, yellow, orange and red light, type III to green, yellow, orange and red light.

The information the cones send to the neuron axons in the optic nerve is just a succession of electric pulses. The ***rate*** at which pulses are sent ***depends both on the intensity of the light and its wavelength***.

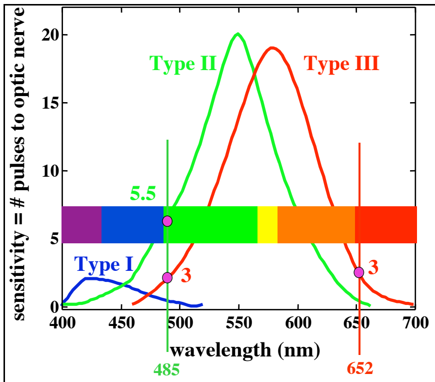



Consider four different colors: A (cyan with 500 nm wavelength), B (green, 522 nm), C (orange, 590 nm) and D (yellow, 580 nm). From the sensitivity curves above, you can read the responses on type II cones, which are identical for A and C, and for B and D respectively. *If you only had type II cones, you could not distinguish cyan from orange, or green from yellow*. By having the ***three types of cones***, the brain combines the responses from each type, and interprets ***many more colors***.

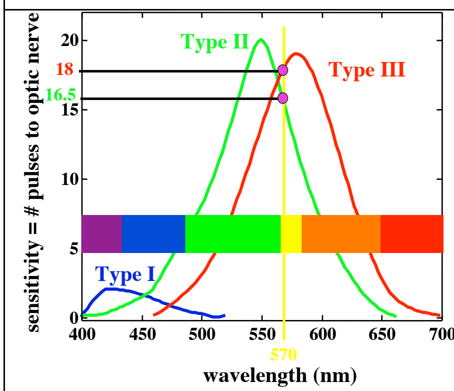



Look at the pink dots, indicating the response of all three types of cones: both A and C generate a response of 8 on type II cones, but simultaneously A gives 3 and C gives 17 on type III. Plus A also stimulates a small reaction on behalf of type I cones. All the brain receives is a set of three numbers: the responses of cones type I, II, and III. A and C can therefore be distinguished by the brain, with some careful data processing: this interpretation takes place instantaneously, and you can see and distinguish the colors as soon as you see them.

Most of the brain volume is used for the interpretation of visual input. This tells you how complicated it must be. Despite the complexity of the system, there are problems associate with having only three types of cones: some ambiguities take place.




A good example of the ambiguity generated by having *only* three types of cones is the following. Consider two lights of wavelengths 485 nm and 652 nm: these are green and red lights. If you project these two lights on a white screen (you *add* them) the brain will interpret them as the *sum* of the responses of all 3 types of cones. The response of type I is negligible. For type II is 5.5 and for type III is 3 + 3 = 6 (see pink dots on the graph).

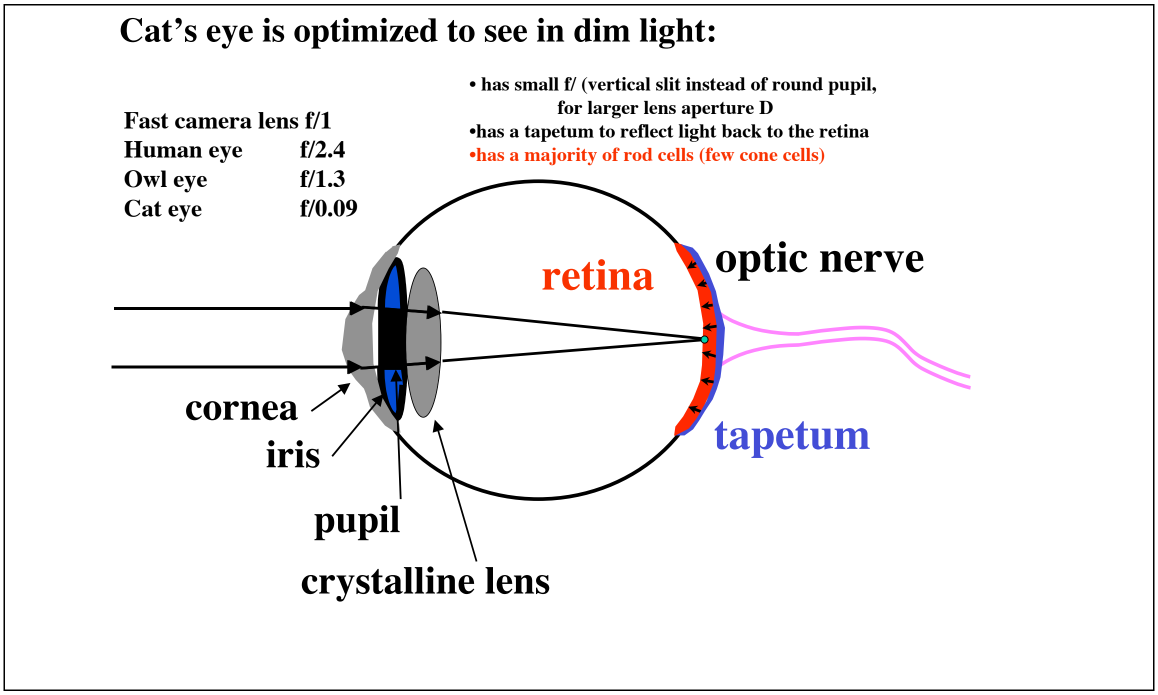


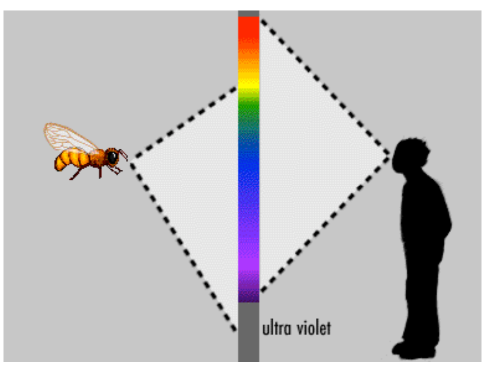

Let us now look at a third light, of wavelength 570 nm, which is yellow. This generates a response of 16.5 and 18 on type II and III, respectively. These responses are identical to the ones obtained above from the sum of green and red, only 3 times more intense: 5.5 x 3 = 16.5 on type II and 6 x 3 = 18 on type III. That is why when you add red and green lights the eye perceives the resulting light as yellow.

The *mixed yellow* appears dimmer than the spectral yellow (3 times dimmer). Analyzed with a spectrograph, the mixed yellow will have 2 wavelengths (485 and 652 nm) while the spectral yellow has only one wavelength (570 nm). Despite this spectroscopic difference, ***the eye cannot tell the difference between one light of 570 nm and the sum of two lights of 485 and 652 nm***! May be with 4 or more types of cones we would not have these ambiguities in our vision. On the other hand, with more types of cones even more volume of the brain would be taken up by vision, and may be we would not have other skills. Even worse, if we did not have these ambiguities, we could not as easily mix colors! We could not have such a simple coding system for RGB color TV, computers, projectors, and we would have much more difficulty mixing pigment colors.

***Cats*** have very poor color vision because they have very few cone cells. Their eyes are optimized in several ways for night vision. Cone cells only function in bright light, so cats evolved to have a majority of rod cells, which work well in dim conditions of light. Other differences between our eye and the cat's eye are summarized in the graph in the next page.

The cat's eye has ***vertical slits*** as pupils, which can open up much more (at night) than the radial and circular iris muscles of the human round pupil. A larger aperture gives higher luminosity, because more light can go through the lens, but has the disadvantage of a small depth of field. The lowest f/ (fastest lens, highest luminosity) for camera lenses is 1, for the human eye f/2.4, another night predator, the owl has f/1.3, while the cat has an ***f number f/0.09***. The cat also has a ***tapetum*** (latin for carpet) of reflecting cells at the back of the retina. The retina is semitransparent, and it does not absorb all the light that illuminates it. Part of the light is transmitted through it, and is simply lost. Night animals have the tapetum to reflect that portion of the light back into the retina, as indicated by the arrows in the figure. The tapetum is immediately after the retina, therefore the reflected rays do not go out of focus much, and the rods in the retina have a second chance to detect them.




Many snakes are thought to see infrared, but this is not true: snakes sense the heat irradiated (infrared) by their prey at night through their tongue, they do not see it. One exception is the rattlesnake, which has an infrared pin-hole system, and actually sees infrared. Dogs see colors just like humans, so do flies, while bees do not see red, but see ultraviolet, which humans cannot see. Some flowers, to attract bees, have structures on the petals which are only visible in the ultraviolet, and we can only see them in photographs.

**Visible light** **UV light + quartz lens and UV filter**

The images above show the photograph taken illuminating a flower with visible light, and a photograph of the same flower taken using a UV lamp as illuminating light and a filter in front of the camera lens (a special one, made of quartz) that transmits UV light (~300 nm) as well as visible light wavelengths. The camera lens must also be made of quartz to transmit UV. Bees would see the flower as displayed on the right, we see is as on the left. Notice the much higher contrast in the bee-eye-catching version.

A more direct way of studying how our eyes perceive color is to analyze the addition of lights, or ***additive color mixing***, which is described below, and in Chapter 7.

Before starting to add light, let's introduce a few criteria and definitions, which will be useful to understand how colors are mixed.

**PHYSICAL AND PSYCHOLOGICAL COLOR**

The physical color and the perceived, psychological color are different. An example of ***physical color*** is spectral yellow in sunlight or from a sodium lamp. This is a color to which only one wavelength is associated, or a ***spectral color***. The single wavelength of a spectral color is called ***dominant wavelength***.

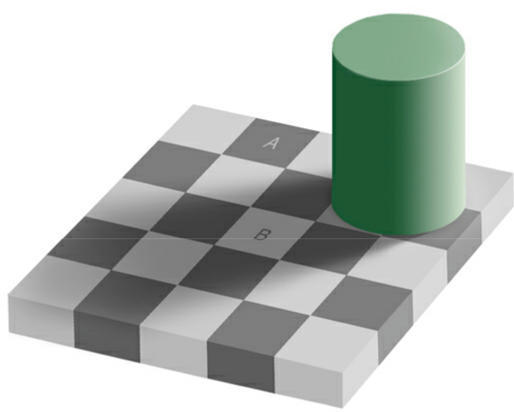
The ***psychological color*** or ***hue***, can be ***a single wavelength or a superposition of different wavelengths***. For the example of yellow, the color we see can be a spectral yellow, with a dominant single wavelength of 570 nm, or the superposition of red and green lights with two different wavelengths: 485 nm and 652 nm.

The ***purity*** is the amount of the spectral component (dominant wavelength) present in the ***physical color***, compared to the amount of white added to the same color. Any physical color is the sum of spectral color and white. If the color contains 0% white, it has high purity. The more white is added, the less pure the color becomes. Spectral yellow has the highest purity, while pale, pastel yellows have low purity.

In the ***psychological color***, the parameter describing the amount of white is the ***saturation***. Purity and saturation describe the same quantity, that is, the percentage of spectral color, physically and psychologically, respectively. Psychologically, pure yellow (0% white) appears to have *"low saturation"* (that is, it seems to be lighter), while red and green have *"high saturation"* (they seem darker and fuller colors compared to yellow). There is no physical correspondence to this impression.

To the ***intensity*** of the ***physical color*** corresponds the ***brightness*** of the ***psychological color***. The perceived, psychological brightness cannot be measured. It is proportional to the logarithm of the intensity, but it varies dramatically from person to person, and even for the same person, depending on the surrounding illumination and to the ***adaptation*** of the eye to both color and light intensity. If the eyes are dark-adapted, that is, if they've been in darkness for a few minutes or longer, when the light is turned on a dim color may appear brighter than it does when the same eyes of the same person have been in bright light. The physical intensity of that color, which is a measurable quantity, remained unchanged in both conditions.

The perceived brightness of a color also depends on the surrounding illumination: a snowball inside is perceived as white, but it diffusely reflects much less light than a piece of coal outside, under the sunshine, which is perceived as black. This depends on the rest of the environment surrounding the object observed. In bright sunshine a black object can still reflect a large amount of light, but since everything else around it reflects even more, it is perceived as black. This effect does not only take place in the extreme brightness of sunshine: observe the checkerboard below.




**The checker shadow illusion**
The squares marked A and B are the same shade of gray. Checker B appears much lighter than checker A because it is surrounded by darker shades of gray. You can find this and many other similar illusions on the Edward H. Adelson web site at MIT:

http://www-bcs.mit.edu/gaz/

**LIGHT INTERACTION WITH OBJECTS IN THE WORLD**

The light illuminating objects can be:

- absorbed
- specularly reflected
- diffusely-reflected or scattered
- transmitted and refracted
- combinations of the above

If light from a light bulb is illuminating an object and is completely ***absorbed***, no light is reflected, and the object appears black. If some light wavelengths are absorbed and others are ***scattered***, the object will appear ***colored***. If light is ***specularly reflected***, and the object is an aluminum or silver mirror, the light does not change color at all, and is reflected in one very specific direction, defined by the law of reflection (i = r, see Chapter 1). The virtual image of the object can only be seen from a very specific position. If light from the light bulb is ***diffusely reflected, or scattered***, by the object, it bounces back in all directions and the object can be seen from any angle. If the object is transparent, light will be also ***transmitted and refracted***. The most common situation is to have a ***combination*** of absorption and scattering at different wavelengths, which generates the color of all objects surrounding us. If the objects are shiny, they also specularly reflect part of the light. Let us look at the specific details.

**DIFFUSE REFLECTION or SCATTERING**

***Diffuse reflection*** or ***scattering*** takes place when light illuminates an object that does not have a perfectly smooth and flat surface. We have seen that in specular reflection, or reflection from a mirror, the angle of incidence is equal to the angle of reflection. In diffuse reflection this is not the case. In fact an object can have any kind of surface roughness, texture or finish and we can usually see it from all angles. Light illuminating any non-mirror object is ***diffusely reflected in all directions***, away from the object. The diffusely reflected light rays are then visible from all angles, all around the object.

At the microscopic level, in most cases the condition for specular reflection is still satisfied, but there are so many different microscopic surface orientations on a rough, non-mirror-like surface that the end result is light bouncing off in all directions.

For simplicity, we can subdivide all the colors in white light into three spectral ranges only: blue, green and red as shown at the beginning of this Chapter. We are therefore neglecting the spectral orange, violet, blue-green or cyan. This is an oversimplification in some cases, but it is useful and can be applied to most real situations. In the examples below and the remainder of this book, we will use this simplified spectrum.

A ***black*** object, e.g. a piece of lava-rock, when illuminated by white light ***absorbs most of the light intensity***. It does not reflect light of any color (wavelength). A very small amount of the illuminating light is diffusely reflected, and from that small amount we can tell the shape and size of the rock. Our eye can see the small amount of light, perceive its very low brightness, and interpret the color as black. All colors in white light (red, green and blue) are equally absorbed, and a small proportion of each one, in equal amounts, is diffusely reflected.

A ***white*** piece of paper behaves in a very similar way: all colors are equally reflected, but in this case ***no light is absorbed***. ***All the illuminating light is diffusely reflected***, the blue, green and red components are reflected in equal amounts, our eyes see the high brightness, and the paper appears white.

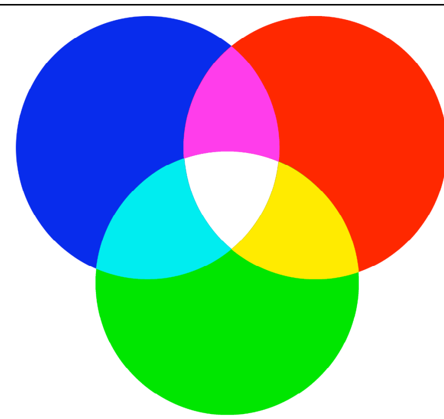
***All colored objects absorb certain wavelengths and diffusely reflect others.*** An apple appears red because, when illuminated by white light, it absorbs green and blue, and diffusely reflects red light only.

A lemon appears yellow because it absorbs blue light and diffusely reflects red and green. Our eyes perceive red and green wavelengths, add them up, and interpret the lemon as yellow. We may also think about the color perceived in a different way. ***An object appears as the color complementary to the color it absorbs***. In the lemon case, it appears yellow because it absorbs blue, which is the complementary color to yellow. Furthermore, the lemon appears shiny on the surface because a small portion of the light (white light!) is specularly reflected. So does the apple above.

The *Complementary colors* are:

**yellow ⇔ blue**
**magenta ⇔ green**
**cyan ⇔ red**

and they appear on opposite sides of the diagram on the right.



*Scattering* has the additional characteristic of depending on the size of the particles that light illuminates and from which it bounces off. If the particles are larger than the wavelength of light, the scattering is the same for all wavelengths (all light colors), if they are smaller, the scattering is wavelength dependent. Let us see a few cases in which scattering produces interesting effects.

Water is transparent. But then, why is ***water*** in a fountain or a ***waterfall white***? This phenomenon depends on scattering. The water particles, the droplets in the waterfall, are much larger than the wavelength of visible light (400-700 nm), therefore light scattering is ***wavelength independent***. If white light is illuminating the waterfall, white light is scattered back in all directions, so we see the waterfall as white from all directions. The same wavelength independent scattering is responsible for the ***whiteness of the clouds***. The ice crystals and water droplets forming the clouds are larger than the wavelength, therefore they appear white.

More about scattering: ***why is the sky blue***? Again, air, with very good approximation, is transparent, so why does a lot of air (the sky) appear blue? In this case the air particles (76% nitrogen molecules, and 21% oxygen molecules) are much smaller than the wavelength of light and this causes the scattering to be ***wavelength dependent***, this is also called ***Rayleigh scattering***. The amount of light undergoing Rayleigh scattering is proportional to $\frac{1}{\lambda^4}$, where $\lambda$ is the wavelength of light. Therefore blue light, which has the shortest wavelength (400-500 nm), is scattered more than green (500-600 nm) and red light (600-700 nm), and the sky appears blue.

Imagine the light from the sun coming towards you. Along the way it encounters air molecules in the atmosphere, and it bounces off of them at all angles, then the blue light, which was already scattered more than green and red at the first bounce, keeps bouncing off the air molecules again and again, and the whole sky becomes illuminated, and homogeneously blue. In the absence of an atmosphere to scatter light, the sky would not be illuminated at all, and appear black as it does from the Moon. On the Moon, areas that are directly illuminated by the sun, in line of sight of the sun, are extremely bright, while shadows are completely dark.

***Why is the ocean blue***? For two reasons: the first is that the ocean reflects light from the sky, which is mostly blue. The second is that the red part of the spectrum is absorbed by water, therefore blue and green are left (not absorbed) to be diffusely reflected. Not by chance “aqua” is a blue-green color (blue-green = cyan is complementary to red). Water absorbs red therefore appears cyan.