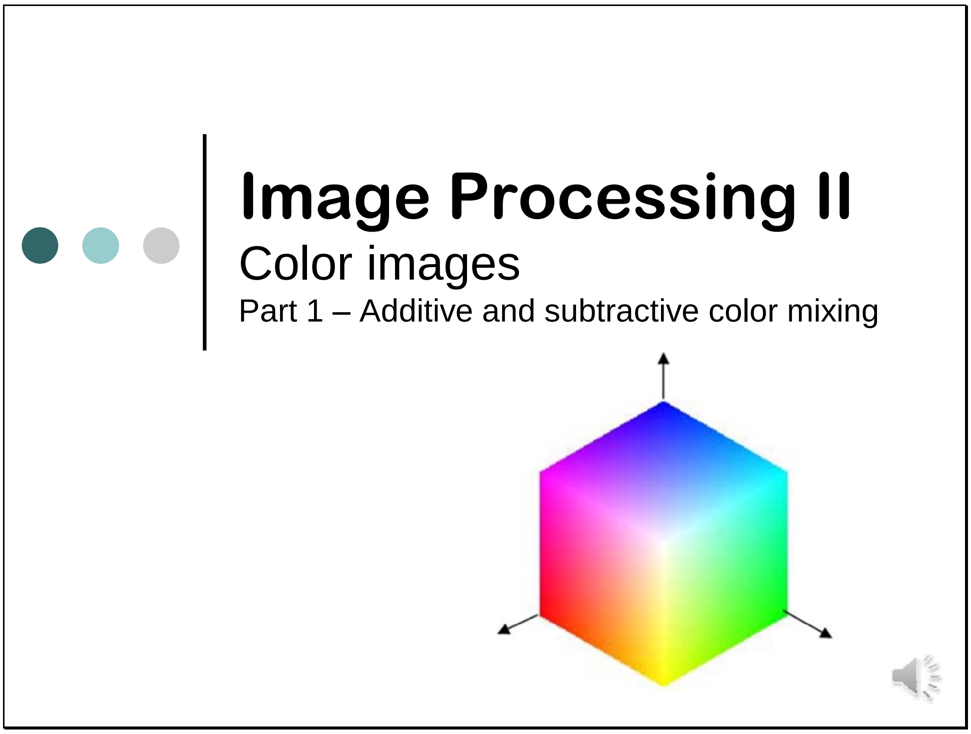
Christoph Biskup / Michael Habeck

Lecture notes



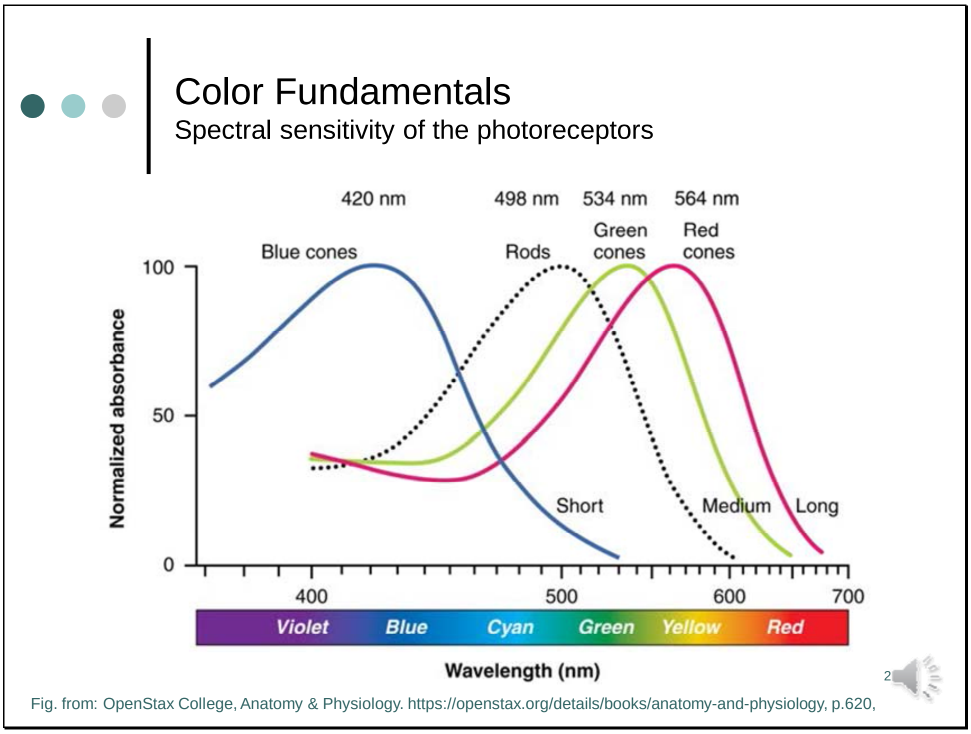
Welcome to another lecture video in image processing. This video will be about colors. Devoting a lecture to colors is motivated by two main arguments:

1.) In scientific imaging the color of the light we record is related to its wavelength. It can bear useful information we can use to evaluate the data we get in an experiment.
This applies also to our eye. Humans can discern only relatively few shades of gray, but thousands of color shades. Color helps us to distinguish and identify objects.

2.) Color is a powerful descriptor that often simplifies object identification and extraction from a scene. By assigning a color to a grayscale intensity or a range of intensities we can better distinguish intensities. Such pseudo-color images will be discussed in one of the next lectures, when we talk about image histograms.

In this lecture, however, we will talk about processing “true” color images.

Slide #2



Let's briefly recapitulate, what we have discussed before. In our retina we have two types of photoreceptors, rods and cones. Rods have their absorption maximum around 498 nm. They are very light sensitive and are inactive at light intensities used for color vision.

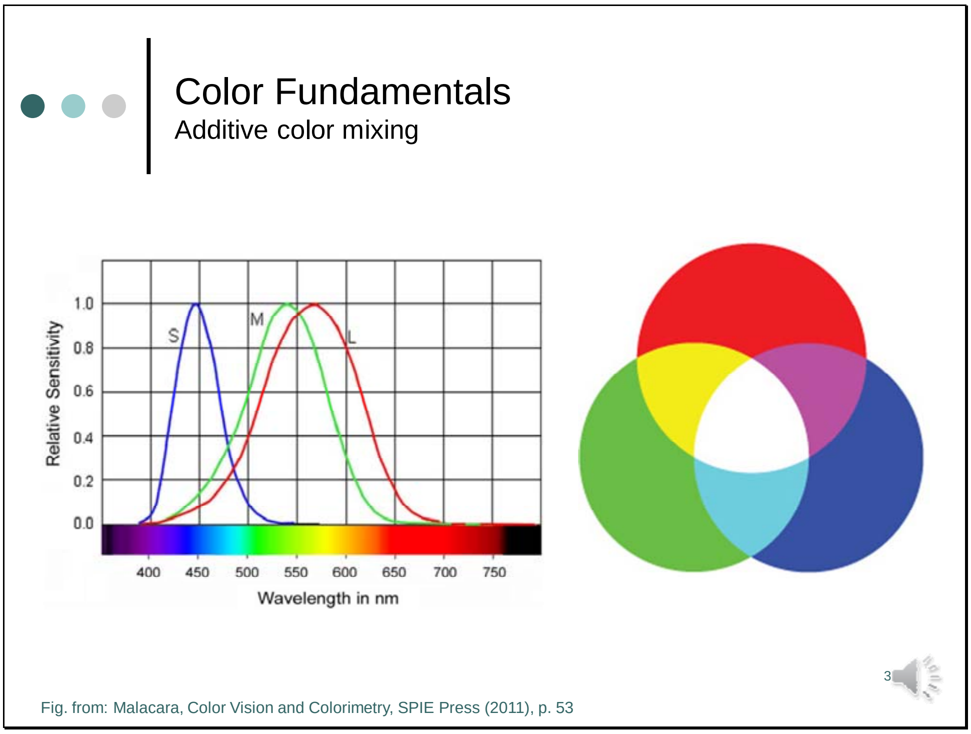
The sensation of color is produced by the physical stimulation of the cones. Blue cones absorb light around 420 nm, green cones absorb light best at 534 nm and red cones absorb light around 564 nm. In these curves only the relative absorbance is shown. Sensitivity, however, depends not only on the absorption coefficient, but on the number of respective cones, the concentration of the active photopigment, the quantum efficiency and the magnification by the signal transduction cascade.

Although almost most humans enjoy color vision, we might perceive the world surrounding us differently. As we have discussed before, polymorphisms exist particularly for the red receptor. Due to these polymorphisms people have different sensitivities for colors. This is something important we need to keep in mind, when we talk about the standardization of colors.

But let's stick to the simple text book scheme first. According to this scheme, bright blue light with a wavelength of 450 nm would activate the "blue" cones predominantly, the "green" cones marginally, and the "red" cones minimally. The relative activation of the three different cones leads to the sensation of blue color. Likewise, light between 500 and 550 nm stimulates best the green receptors, and light beyond 600 nm stimulates best the red receptors. Accordingly, we get the sensation of green and red, respectively.

Light around 490 nm stimulates both, blue and green cones. This creates the sensation of a cyan color. Light around 570 nm stimulates both, green and red cones. This creates the sensation of a yellow or orange color. In this way we can perceive and distinguish light with wavelengths ranging from 380 nm to 780 nm.

Slide #3

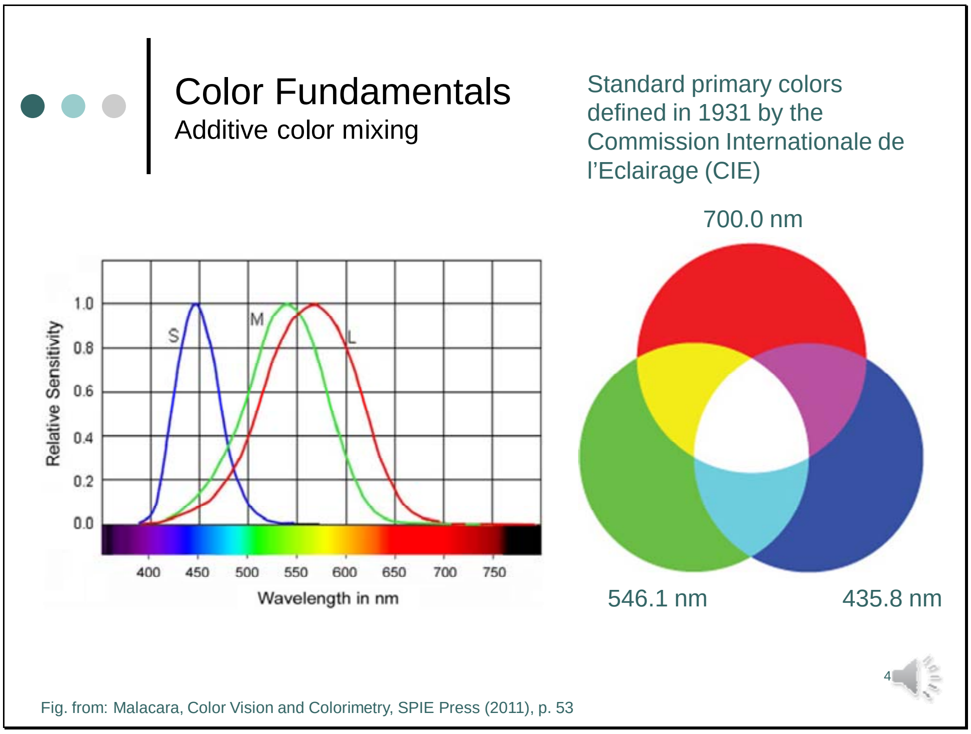


Instead of stimulating blue and green cones by using light around 490 nm, we can stimulate them by shining simultaneously blue and green light on them. This will also elicit the sensation of a cyan color. Our brain will not be able to distinguish if the simultaneous stimulation of the blue and green receptors was due to illumination at 490 nm or simultaneous illumination at 435 nm and 545 nm.

Cyan can be generated by mixing blue and green colors. Likewise, yellow can be generated by mixing green and red. Again, our brain will not be able to tell whether the simultaneous stimulation of green and red cones was due to illumination with 570 nm or simultaneous illumination at 545 nm and 700 nm. This process is called additive color mixing. By stimulating blue and red photoreceptors at the same time without stimulating green photoreceptors, we can generate a purple color. This color sensation cannot be elicited by monochromatic light, because light that would activate equally blue and red photoreceptors would also activate green photoreceptors.

The sensation of “white” is generated when all cones are stimulated. This can be achieved illuminating them with the entire visible part of the spectrum. Likewise mixing the three primaries in the right intensities produces white light. White light can also be generated by mixing a secondary color with its opposite primary color. Thus, mixing cyan and red, yellow and blue, purple and green generates the impression of “white”.

Slide #4

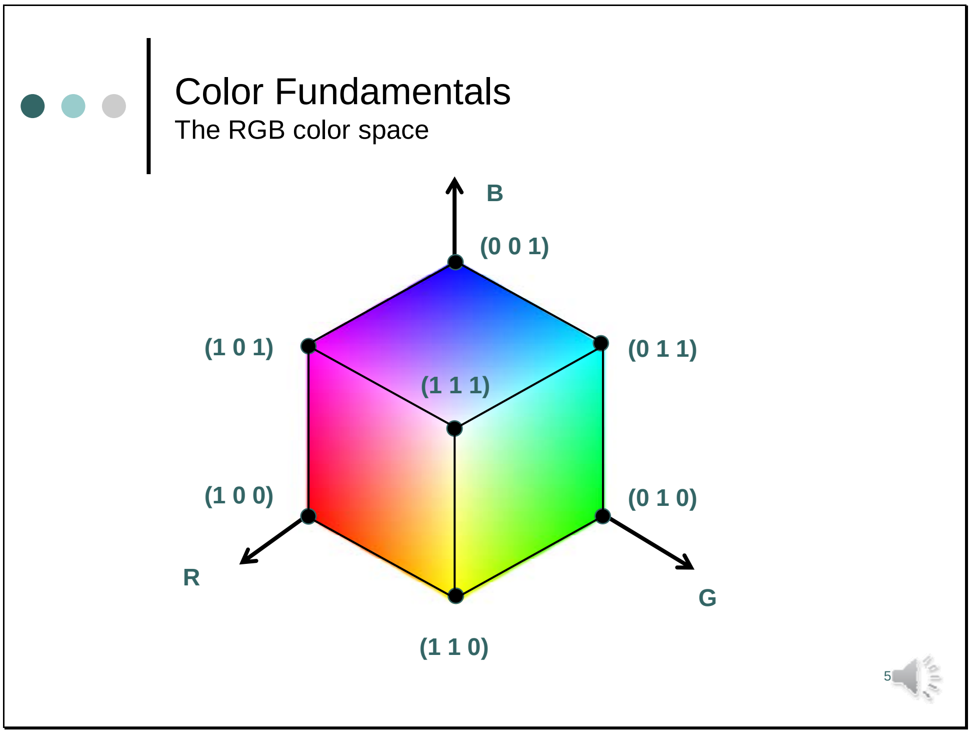


For the purpose of standardization of colors an International Commission on Illumination was founded. This commission is often referred to by its French name *Commission Internationale de l'Eclairage* which is abbreviated as "CIE". The CIE designated in 1931 the following specific wavelength values to the three primary colors:

Blue 435.8 nm, green 546.1 nm, red 700.0 nm. The first two lines correspond to the emission lines of the mercury lamp. This standard was chosen because it was easy to reproduce, and it was set before results about the spectroscopic properties of the photoreceptors became available. Thus, the CIE standards correspond only approximately with the absorption peaks of the photoreceptors.

It is important to keep in mind that defining three specific primary color wavelengths for purpose of standardization does **not** mean that these three fixed components can generate all colors of the visible spectrum. In some textbooks word *primary* has been misinterpreted to mean that the three standard primaries, when mixed in various intensity proportions, can produce **all** visible colors. This is wrong! Later you will see some examples.

Slide #5



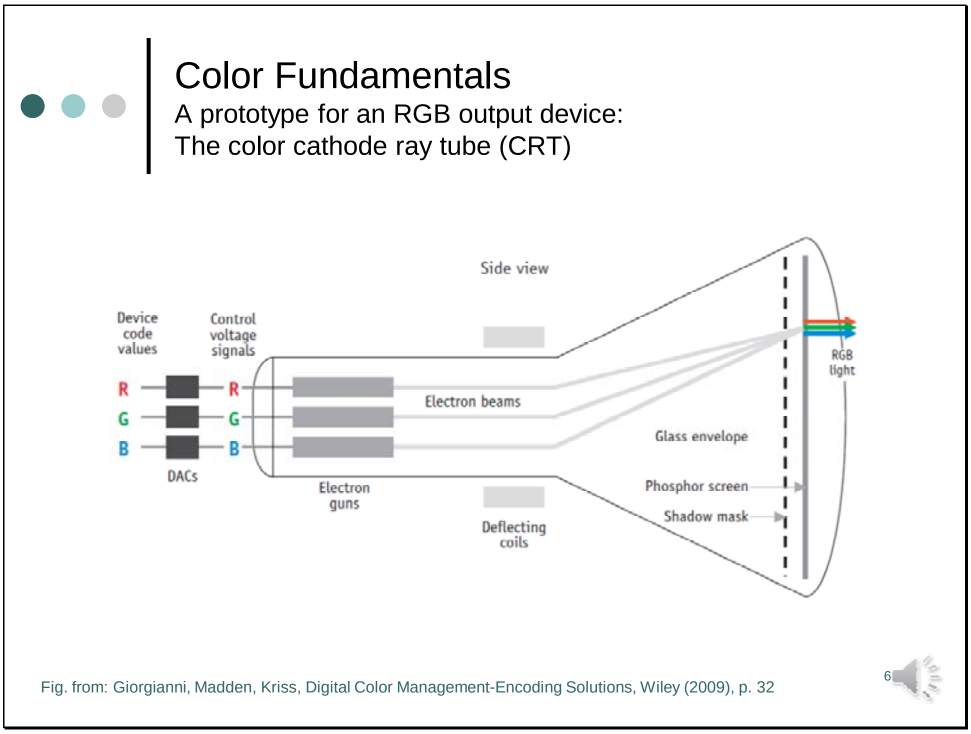
The color space which can be created by additive mixing of the primaries red, green and blue can nicely be shown in a 3D-Cartesian coordinate system. When the red, blue and green primaries are interpreted as unit vectors emanating from the origin, a cube with an edge length of 1 is formed. Here the vector for the red color follows the x-axis, the vector for green color is superimposed with the y-axis, and the unit vector for blue points into the direction of the z-axis.

The primary values are at three corners of the cube, the secondary colors cyan, yellow, and purple are at three other corners; black is at the origin; and white is at the corner farthest from the origin.

Since all primary color values have been normalized, the cube is a unit cube. As consequence, all values of red, green, and blue in this representation are in the range [0, 1]. Accordingly, the different colors in this model are points on the surface or inside the cube and are defined by vectors extending from the origin.

Since grayscale values are obtained by mixing equal amounts of red, green and blue, all grayscale values are located on a diagonal line extending from the origin, which corresponds to black, to the white point at position (1 1 1).

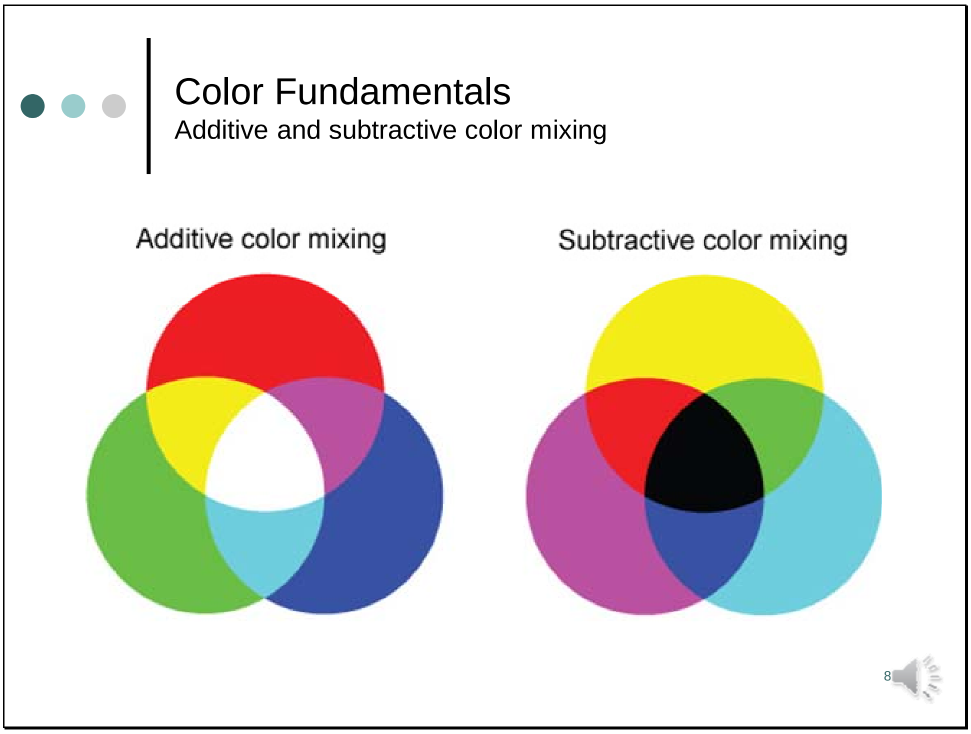
Slide #6



A prototype of an RGB output device is the cathode ray tube. Cathode-ray-tube monitors display images using three different phosphors which emit red, green, and blue light respectively. The phosphors are packed together in stripes or clusters. Most color CRTs have three cathodes at the back of the monitor, one for each primary color. Electrons are emitted from the cathode and are accelerated toward the front panel. On their way the electron beams are focused by focusing coils (not shown). Deflecting coils are used to deflect the electron beam to the desired position on the screen, making the red, green and blue phosphor dots at this position glow. As the electron beam is moved across the phosphor dots on the screen, an image is formed.

If the electron beam is swept fast enough across the screen and if the decay rate of the phosphors is long enough the scanning process cannot be perceived with the human eye. From normal viewing distances the dots merge to form a continuous image.

Slide #7



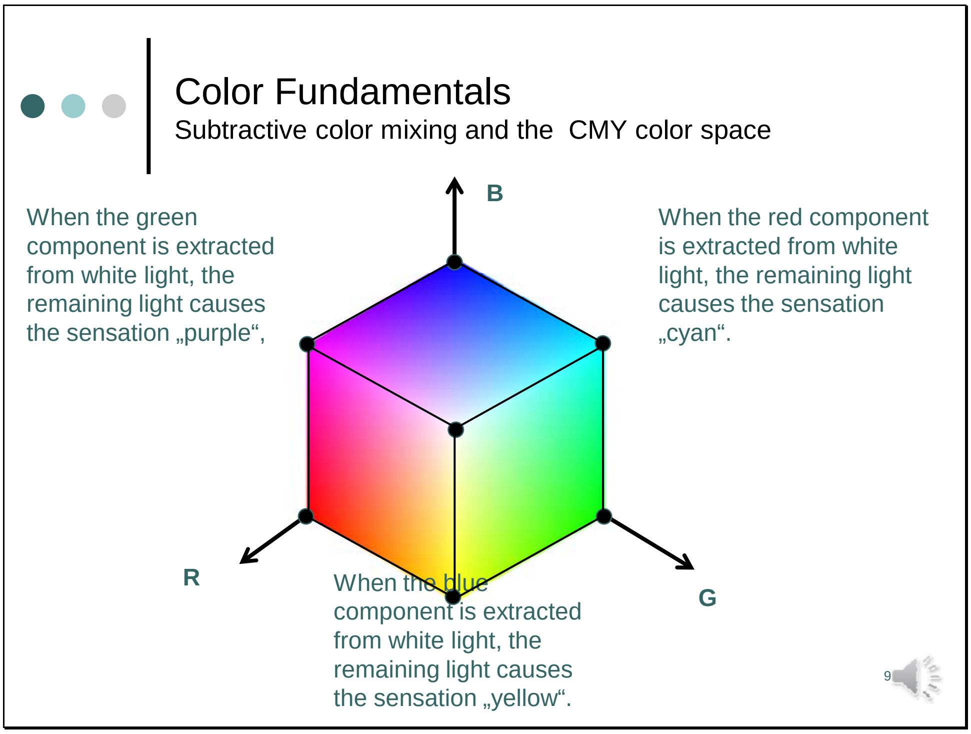
Models of **additive color mixing** predict the appearance of color created by coincident components of light.

In contrast to this, models of **subtractive color mixing** predict the color of light after it passes through successive layers of partially absorbing media. This is the principle of how dyes and inks are used in color printing and photography. When white light hits a print or photograph, a part of the light is absorbed by the dyes at the respective pixel. The remaining light is reflected and reaches the eye of the observer.

The right panel shows the subtractive combination of yellow, purple and cyan pigments:

- Yellow is the complement of blue, meaning that yellow serves as filter that absorbs blue. Ideally the yellow filter is completely transparent to green and red light, so that these colors create the sensation of a yellow color on our retina.
- Cyan is the complement of red, meaning that the cyan serves as a filter that absorbs red and lets pass blue and green light. These colors will be perceived as cyan light.
- Purple is the complement of green. Green is absorbed, red and blue light pass the filter and are perceived as purple.
- Mixing of two pigments extracts further colors from the remaining light. For example, cyan and yellow, extract red and blue; the remaining component is green. Cyan and purple extract red and green; the resulting color after applying the two filters is blue. Yellow and purple filter extract blue and green; the resulting color is red.
- Cyan, yellow and purple together extract all colors. The result is black.

Slide #8



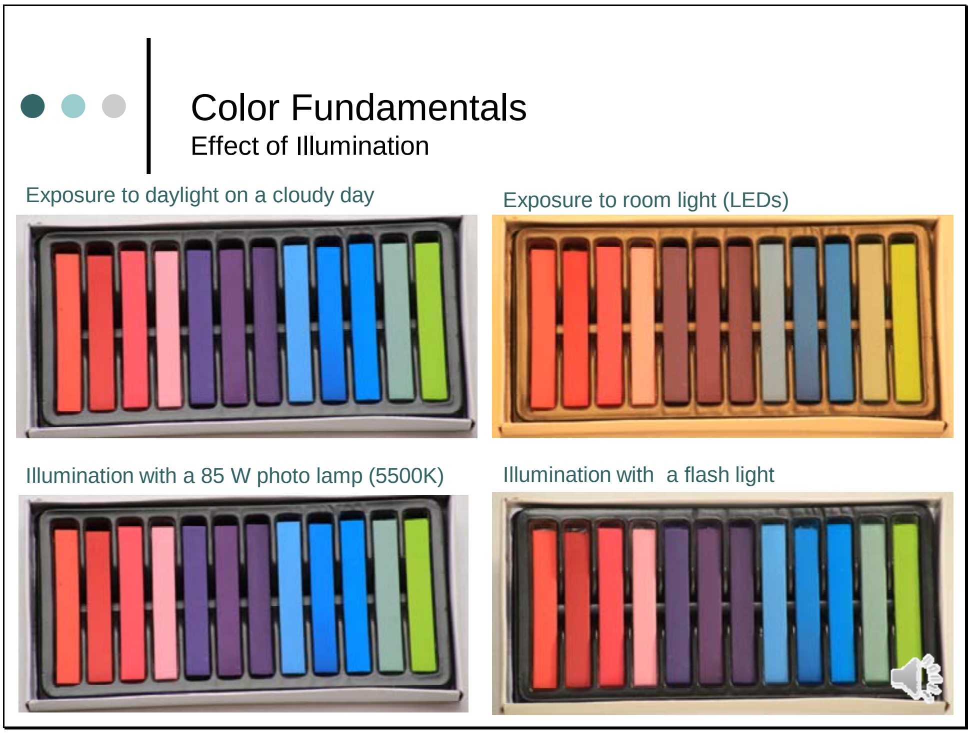
The color cube, which we have used to explain additive color mixing can also be used to explain subtractive color mixing.

- Extracting blue from white light, leaves the red and green part of the spectrum, which causes the sensation “yellow”.
- Extracting red leaves blue and green, which are perceived as “cyan”.
- Extracting green leaves blue and red, which are perceived as “purple”.

Using one filter is equivalent of setting one component to zero. The 3D color space is reduced to two dimensions. Using two filters is equivalent to setting two components to zero. The color space is reduced to one dimension.

When subtractive color mixing comes into play, for color perception not only the absorption or reflective properties of the dyes and the sensitivity of the cones matter. It is also the light source which was used for illumination. Since dyes subtract only a part of the spectrum used for illumination, the spectral composition of the original spectrum matters as well.

Slide #9



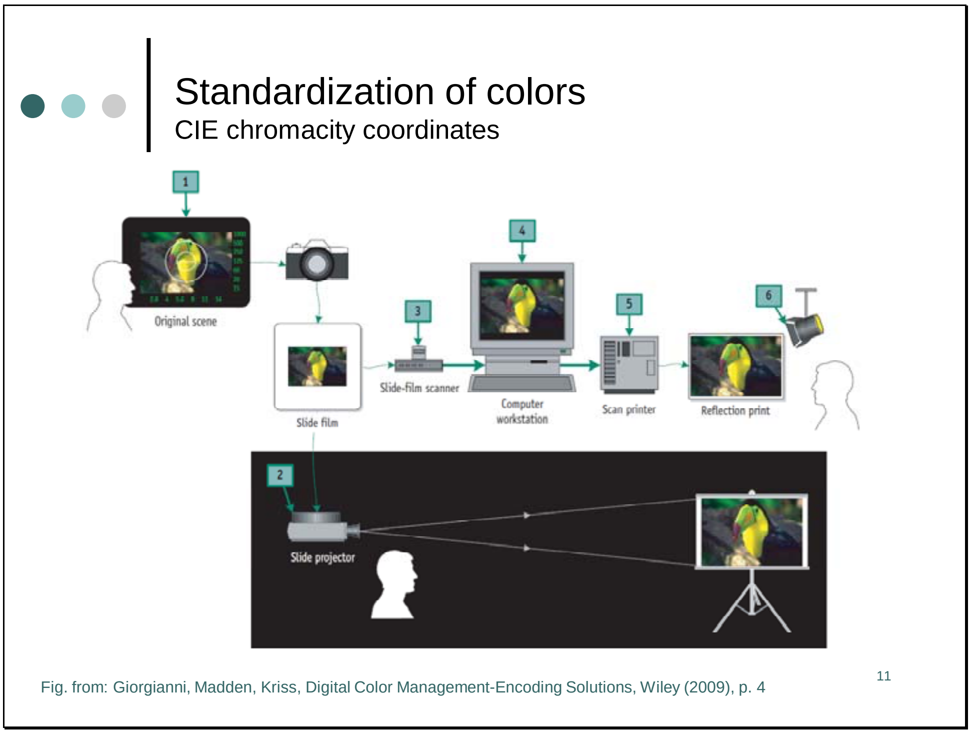
The example I showed in the introductory lecture, demonstrated nicely that the color we see is also determined by the illumination source we use. Just compare the blue and green pieces of chalk recorded at daylight and at room light. The color appears to be different. The same applies for the wrapping.

The settings used for the images are as follows:

- Camera: Canon EOS 6D Mark II, Lens Tamron 70-300mm, 1:4-5.6, set to Macro 180 mm, AV=8.0, ISO200
- Upper row, left: daylight on a cloudy day, t= 1/80 s
- Upper row, right: exposure to LED room light, t = 1 s
- Lower row, left: Illumination with ESSDI photo lamp (energy saving lamp), t = 1/80 s
- Lower row, right: Illumination with Canon Speedlite 430EXIII-RT, t = 2.5 s

This brings us to the question about how the spectrum of light sources is composed. Let's start with the sunlight. If we assume that the sun is a black body, we can answer the question with the knowledge of Physical Chemistry you have acquired in the first semester.

Slide #10

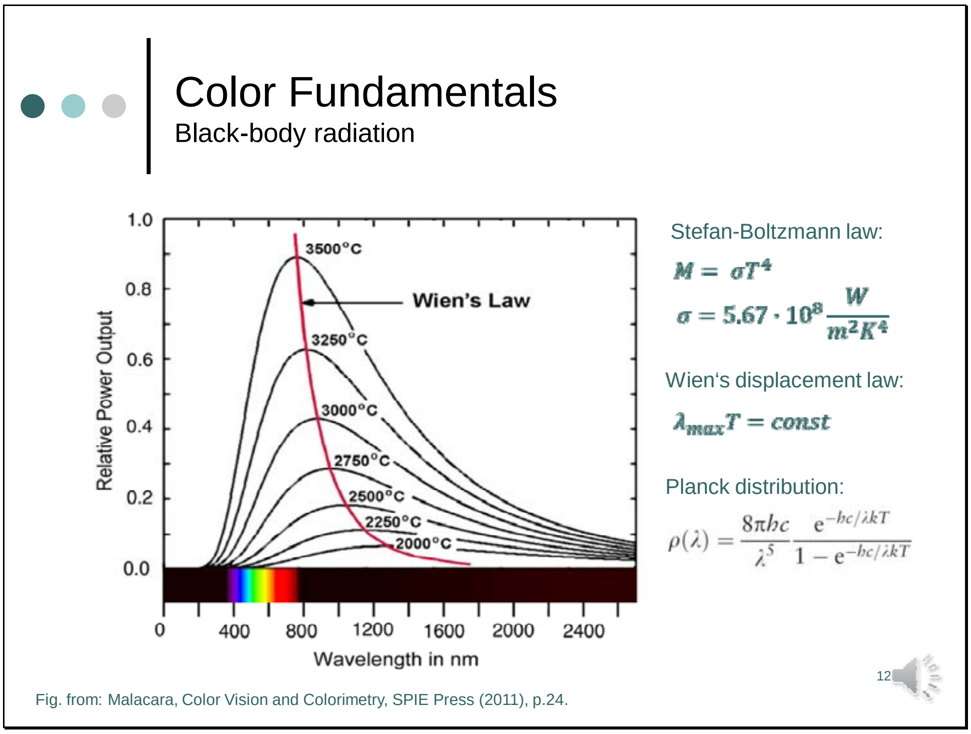


There can be a number of different light sources involved in a single digital imaging system, and each will affect the colors that ultimately are produced.

For example, consider the system shown in this slide. An original scene is photographed on a color slide film, and the slide is projected and also scanned. The scanned image is temporarily displayed on the monitor of a computer workstation, and a scan printer is used to expose a photographic paper to produce a reflection print that is then viewed.

There are six different light sources to consider in this system. First, there is the source illuminating the original scene. Another light source is used to project the slide for direct viewing. There is a light source in the slide-film scanner, which is used to illuminate the slide during scanning. The computer monitor also is a light source (the phosphors of its display emit light). The scan printer uses a light source to expose the photographic paper. Finally, a light source is used to illuminate the reflection print for viewing.

Slide #11



Let's recap what you have learned:

A black body at the temperature of absolute zero on the Kelvin scale (-273.15 °C) looks perfectly black. It absorbs all of the light that falls on its surface and emits no light. It has no color.

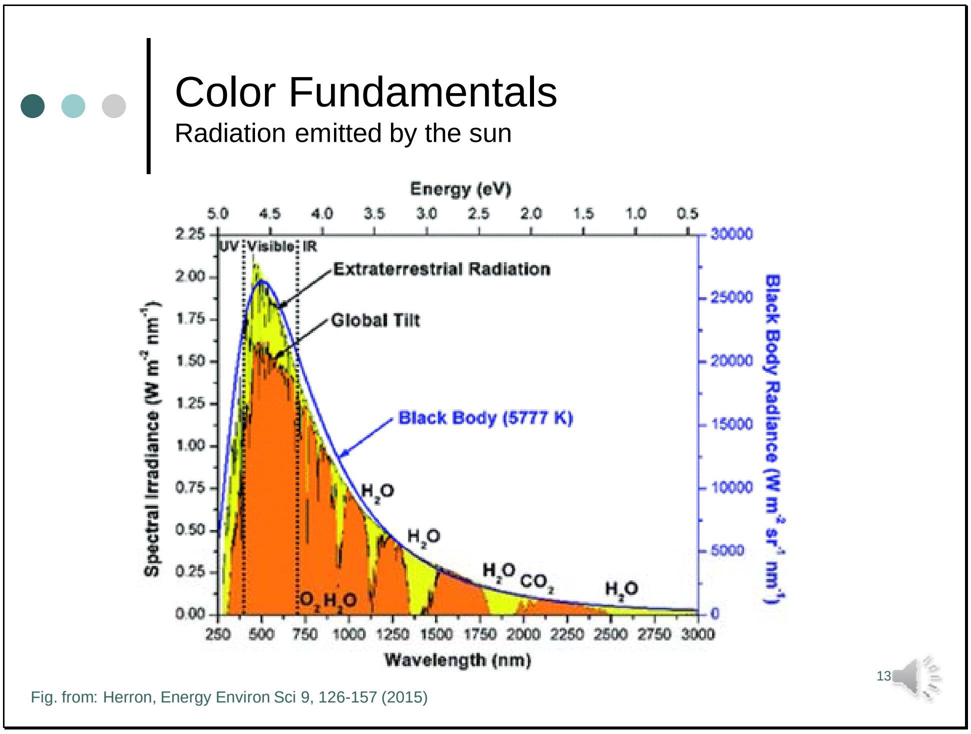
If a black body is heated, it will become luminous, with a radiance and color that depends on the temperature. According to the Stefan-Boltzmann law, the emitted power is directly proportional to the forth power of the black body's temperature.

A black body looks red at about 1000 K (727 °C), yellow at about 1500 K (1227 °C), white at 4500 K (4227 °C), and bluish-white at about 6500 K (6227 °C).

Not all wavelengths are equally represented in the radiation. The energy density of a black-body radiator is given by the Planck distribution. According to Wien's displacement law the observed peak moves to shorter wavelengths as the temperature is raised.

The temperature of a black body can also be used to characterize the color of a light source. In this case we speak of a color temperature. The color temperature of a light source is defined as the temperature an ideal black-body radiator has to have to emit the same spectral distribution of light.

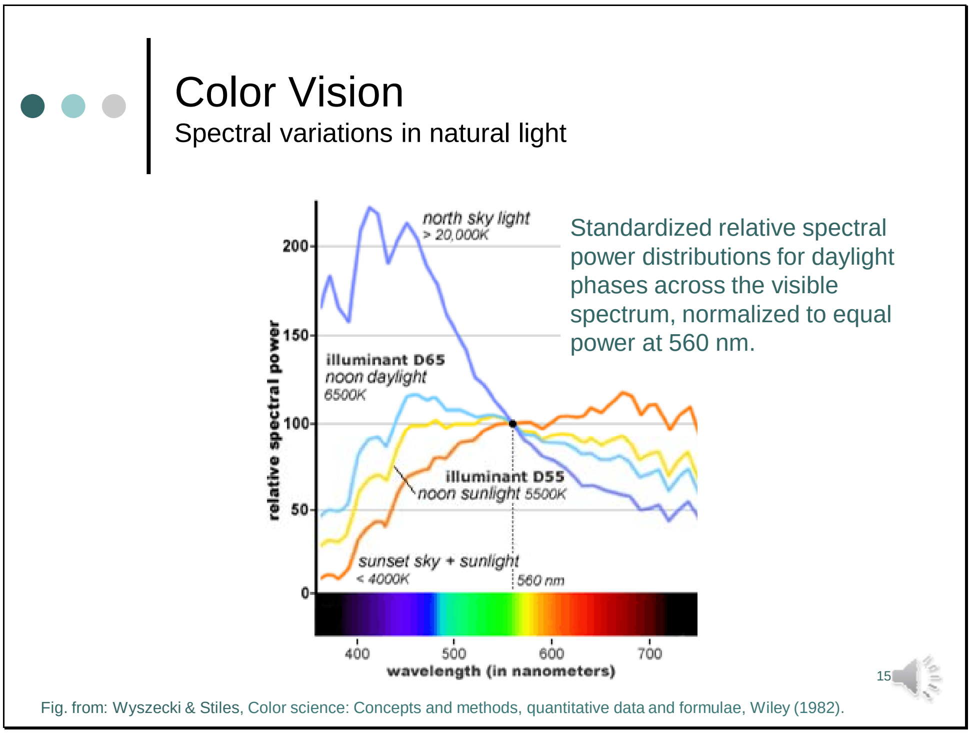
Slide #12



The radiation emitted by the sun (yellow curve) closely matches that of a black-body radiator at an effective temperature of ~5800 K.

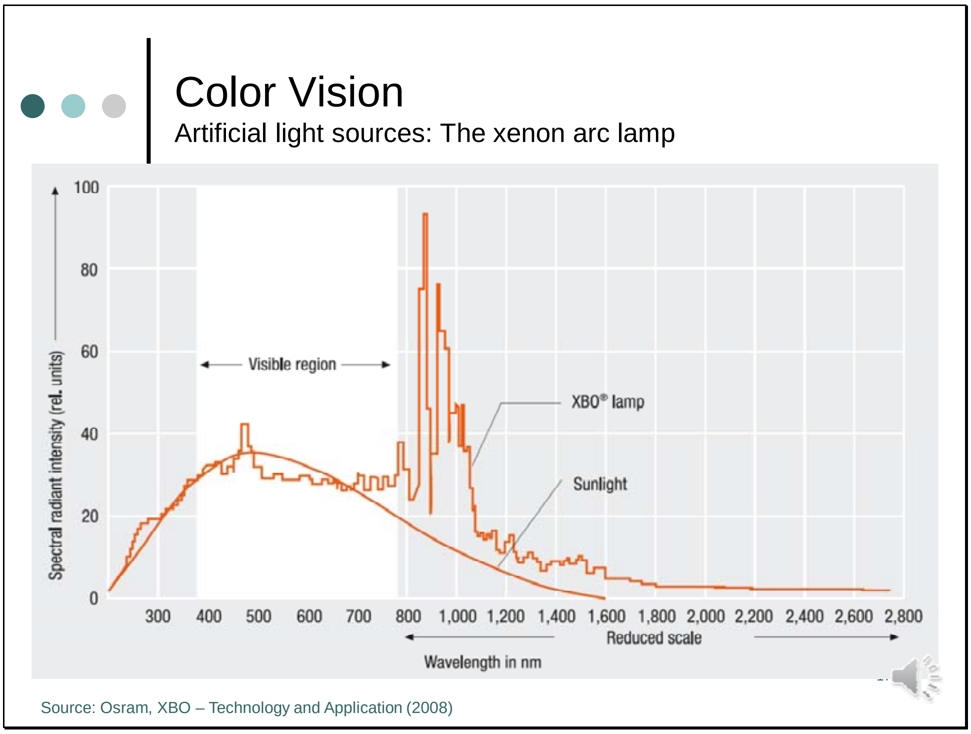
More than 25% of the extraterrestrial radiation is absorbed by gases such as O_3, CO_2 and H_2O in the atmosphere of the earth. Of the solar radiation reaching Earth's surface, about 52% of the energy is in the infrared region (>700 nm), 43% is visible-light radiation (400–700 nm) and about 5% is in the ultraviolet range (<400 nm).

Slide #13



The sun may appear white, yellow, orange or red depending on its position in the sky. The changing color of the sun over the course of the day is mainly a result of the scattering. Due to the strong wavelength dependence of Rayleigh scattering blue light is scattered more than red light. This results in the indirect blue light coming from all regions of the sky. At sunrise or sunset the light reaching the surface has to travel a greater distance in the atmosphere of the earth, so that the blue parts of the spectrum are scattered away. The light that reaches the earth tends to be red.

Slide #14

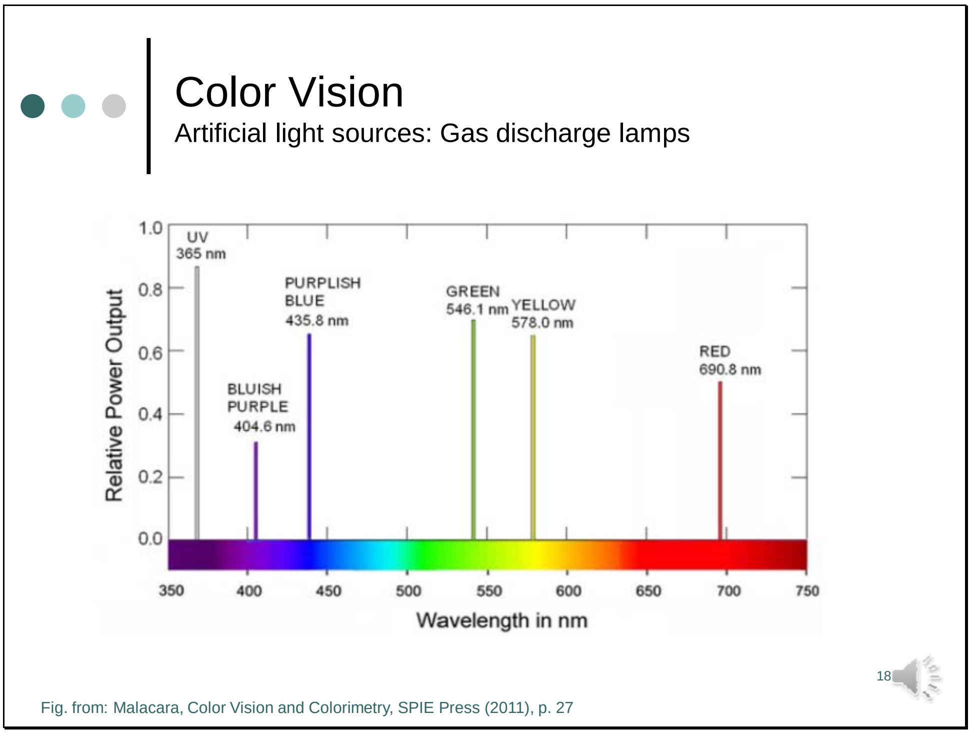


Now let's consider some artificial light sources:

In the visible region between 380 and 780 nm the xenon lamp spectrum follows the spectral curve of a black body radiator at 6200 K. It is pure white like the midday sun.

This is the reason why xenon arc lamps are used wherever a good color fidelity is necessary. The most prominent examples are movie projectors in theaters, but also many microscopes are equipped with xenon arc lamps.

Slide #15



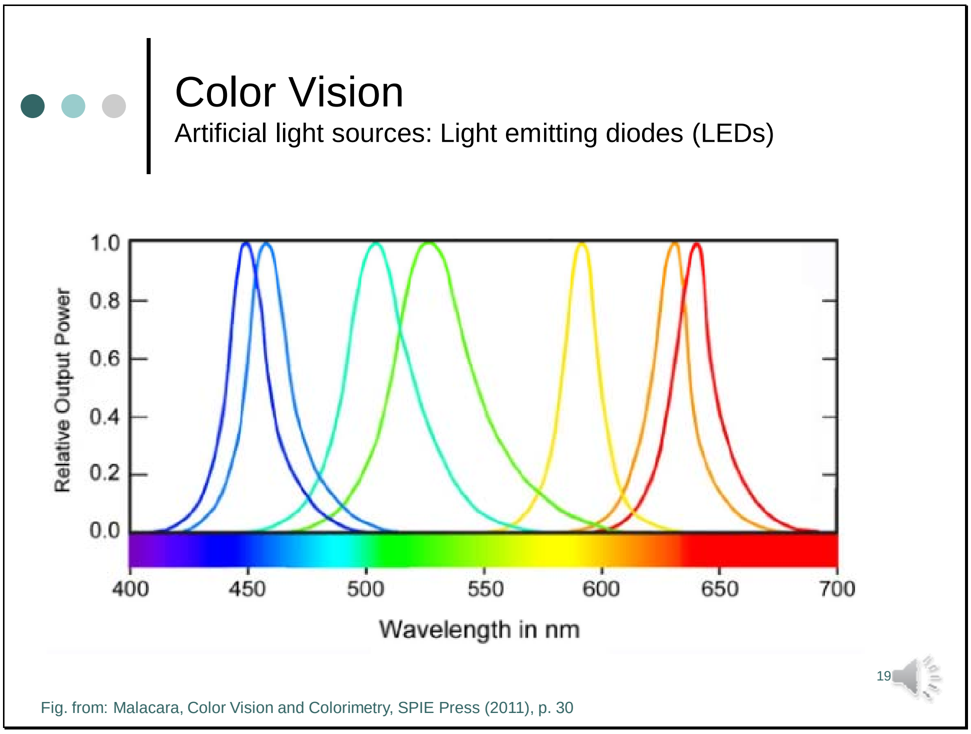
Other lamps are different.

The tubes of gas discharge lamps contain a low-pressure noble gas such as neon, argon or krypton or a vaporized metal. By impinging electrons or ions electrons are kicked out of the electron shell. When ions and electrons recombine light characteristic for the respective electron shells is emitted. The slide shows the characteristic spectrum emitted by a mercury lamp. In the spectrum you will also find the lines defined as CIE standard.

In fluorescent lamps a fluorescent coating on the inner surface of the tube can absorb a part of this light and emit longer fluorescent light.

In any way, these light sources are different from daylight. Nevertheless, light emitted by these light sources might appear white, since emitted wavelengths stimulate at the same time blue, green and red photoreceptors.

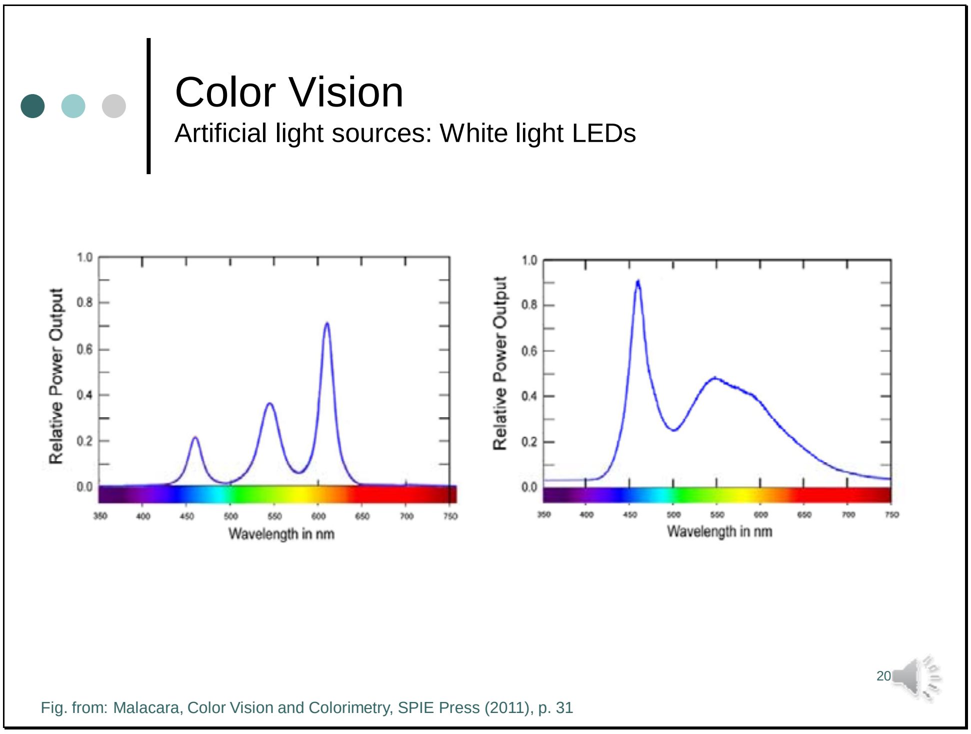
Slide #16



The same applies for light emitting diodes (LEDs). A light-emitting diode consists of several layers of semiconducting materials. Electrical voltage drives electrons from the n-layer and holes from the p-layer to the active layer, where they recombine and emit light. The light's wavelength depends entirely on the semiconducting material used.

Red and green light-emitting diodes have been with us since the sixties of the last century. But, despite considerable efforts of academic and industrial research, developing blue light LEDs remained a challenge for many decades. Their invention at the end of the last century made it finally possible to use LEDs for generating white light. Since LEDs have an unsurpassed energy efficiency this invention changed lighting technology completely. Since it was so important, the inventors of blue LEDs, Isamu Akasaki, Hiroshi Amano and Shuji Nakamura were awarded with the Nobel Prize in Physics in the year 2014.

Slide #17

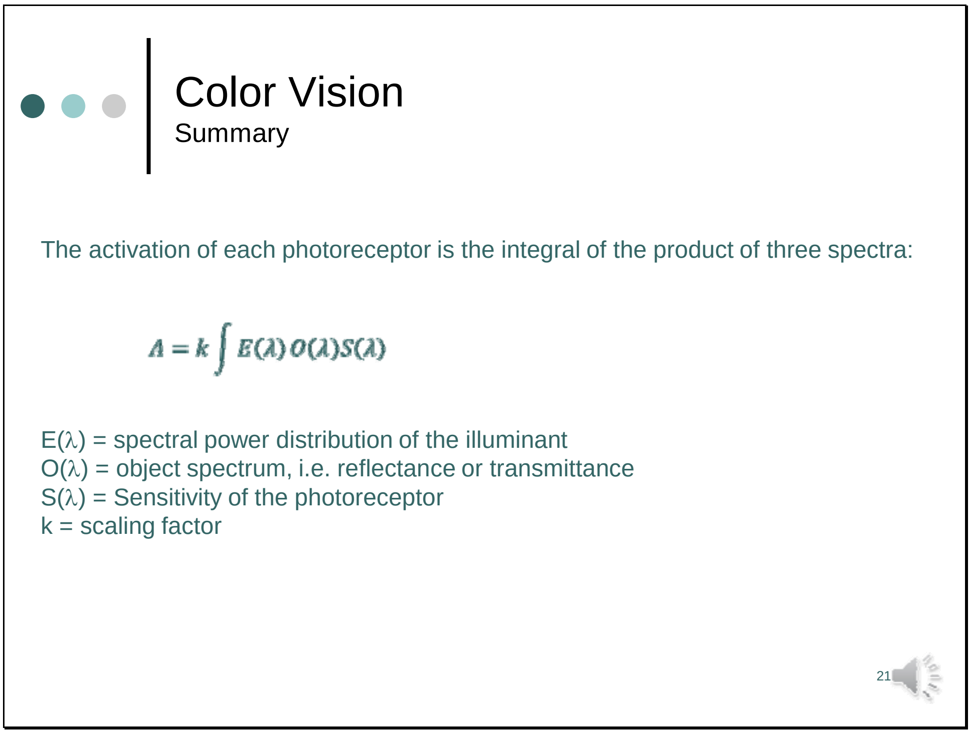


White-light emitting diodes can be produced in different ways. One is to combine red, green and blue LEDs. Due to the simultaneous stimulation of red, green and blue cones, this light appears white to our eyes. With this combination the resultant color can be tuned, by changing the relative intensities of the LEDs. However, the color of an object whose color falls in between the spikes will not be faithfully rendered.

Another way to produce white light is to use a blue LED and phosphor material, that converts blue light to a broad spectrum.

So much for the characteristics of some light sources. Of course, the list of light sources can be extended. Important is to keep in mind that many of them have a spectral power distribution that is different from that of sunlight. This matters a lot, since it is an important factor which determines the color of the object we are investigating.

Slide #18



This slide summarizes all important aspects we have discussed so far.

In brief, the activation of each photoreceptor is the integral of the product of three spectra

- the spectral power distribution of the illumination source
- the reflectance or transmittance of the object
- the sensitivity of the photoreceptor.

In this way the perception of color can be standardized. Of course, that would not include the processing of the information in our brain. Practice shows that this is not so simple. But, this is something we will discuss in the next part of this lecture.