Color and color management

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Courtesy: K. Ikeuchi, T. Darrell, T. Muenzer, L. Cerman for inspiration and some pictures.

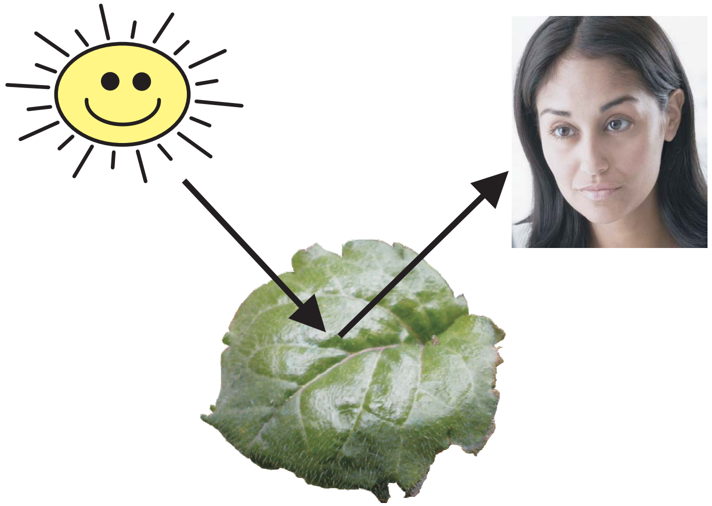
Outline of the talk:

- Color, the interplay of three phenomena.
- Color, physical basis.
- Color, subjective perception.
- Color triangle.
- Color spaces.
- Color management.

Color

Color expresses percepts emerging by an interplay of three components:

- Color relates to the properties of the observed object.
- Color relates to the properties of the illuminants of the scene and their properties.
- Color relates to perceptual mechanisms in humans.



Color characterizes the observer's perception caused by the visible light coming from some illumination sources (usually a mixture of visible light of different wavelengths), the spectrum of which is modified due to properties of the observed objects.

Use of color

Color in several disciplines:

- Physics.
- Human vision, physiology.
- Psychophysics, perception.
- Computer vision.
- Painting, photography, movies, computer graphics.

Color in image analysis

- Image formation, reflection physics.
- Segmentation.
- Image retrieval, e.g., in image databases.

Color, subjective perception

- Human color perception adds a subjective layer on top of underlying objective physical properties—the wavelength of electromagnetic radiation.
- Consequently, color may be considered a psychophysical phenomenon.

- The human visual system is not a very precise absolute color measurement device.
- If we wish to express our notion of color precisely we would describe it relatively to some standard (common object) as, e.g., the red of a British public telephone box.

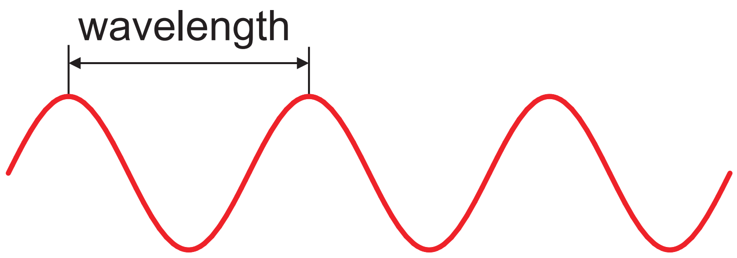
Color management, informally

- Color management procedures allows to secure that colors look naturally and very similar while being displayed on diverse displaying or printing devices.
- Color management is based on the principles describing how colors are perceived by humans.
- Perception of colors by human has to be quantified.

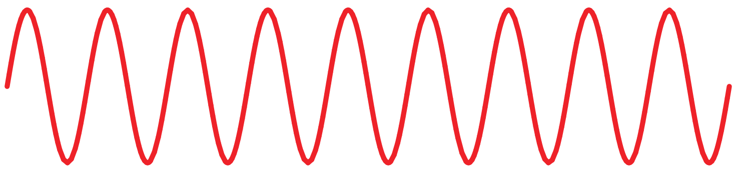
- This lecture explains: (a) what is color, (b) how is color perceived by a human, and (c) how is color quantified.
- After this explanation we will be able to explain, how to secure high fidelity transfer of colors among different display and print devices. Device color profiles serve for this purpose.

Photons and waves

- Light behaves in some experiments as a particle (Isaac Newton, ∼1670) and sometimes as a wave (Christian Huygens, ∼1670).
- This discrepancy was solved by quantum mechanics (Max Planck, Albert Einstein) by introducing the concept of a photon.
- The photon can be imagined as a pulsating quantum of energy spreading in space (by the speed of light in the vacuum).
- Each photon bears certain energy determining, how fast the photon pulsates. The frequency of pulsation corresponds to the photon wavelength.

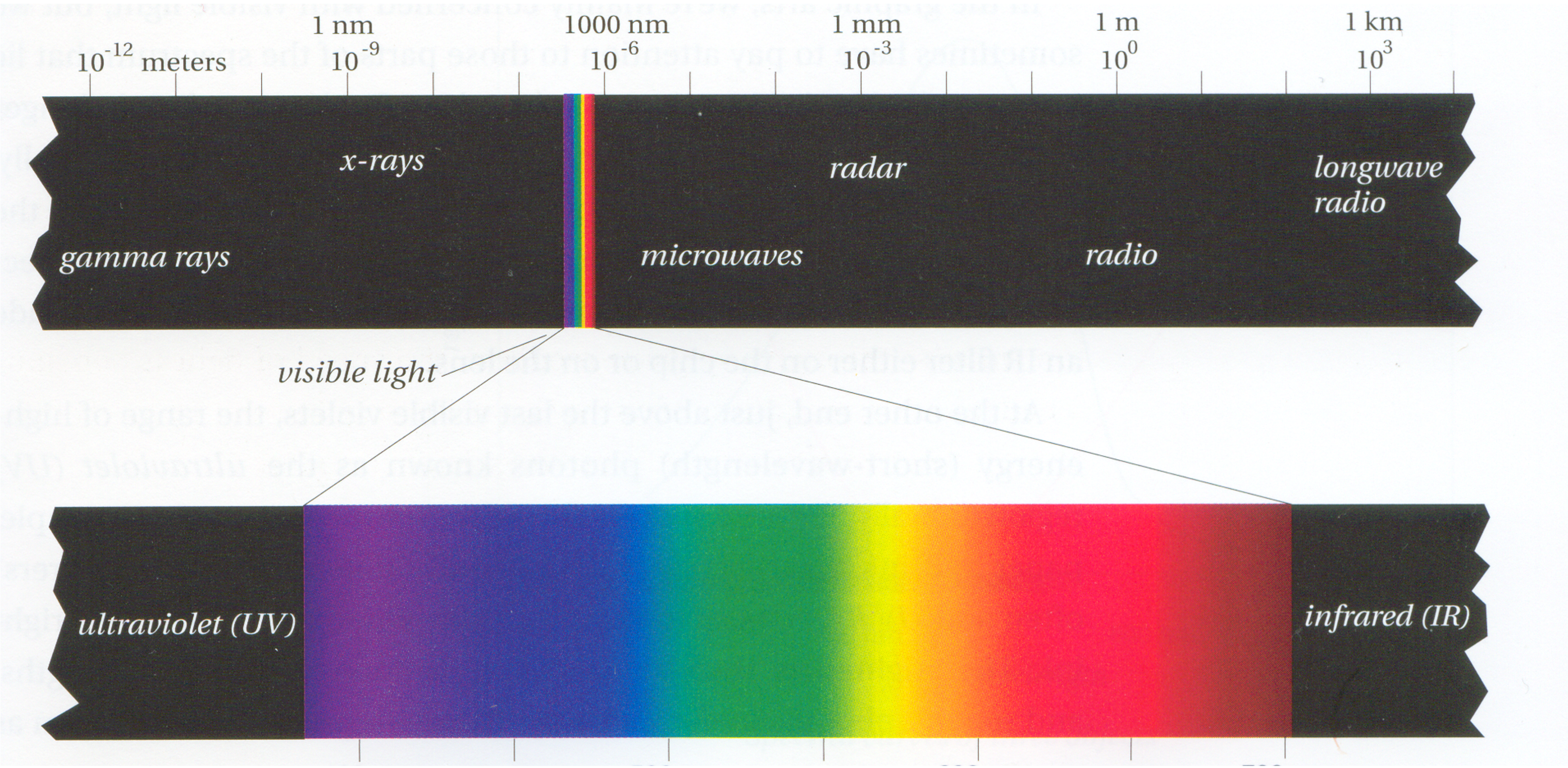


low energy, long wavelength

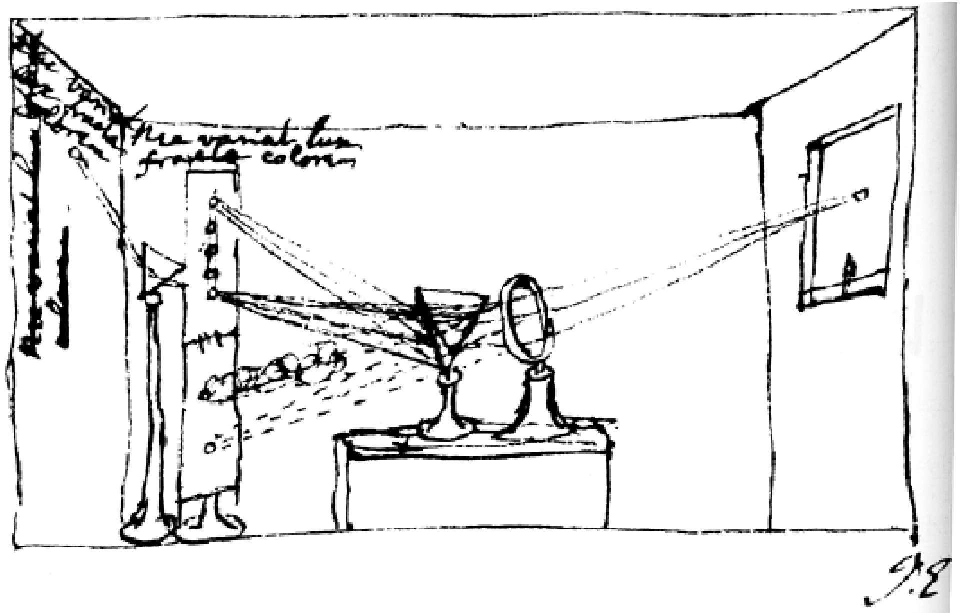


high energy, short wavelength

Radiation spectrum



Isaac Newton’s studies in 1666



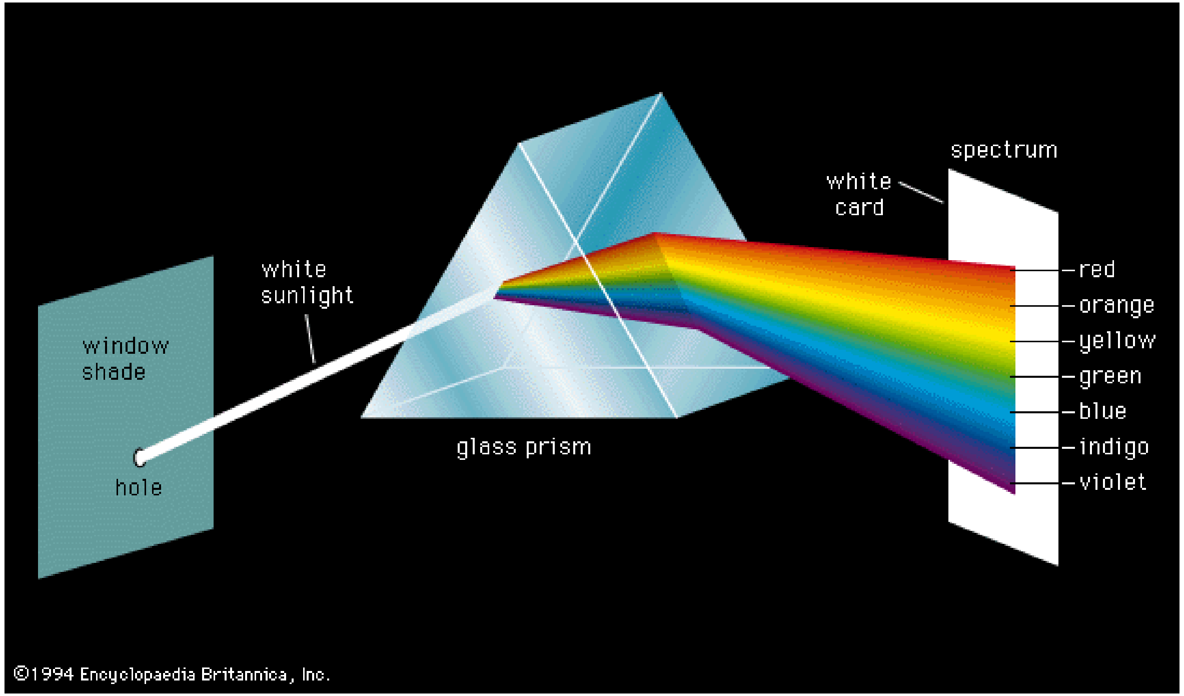
4.1 NEWTON’S SUMMARY DRAWING of his experiments with light. Using a point source of light and a prism, Newton separated sunlight into its fundamental components. By reconverging the rays, he also showed that the decomposition is reversible.

From Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

This was a radical idea to propose at time; over 100 years later influential scientists and philosophers refused to believe it.

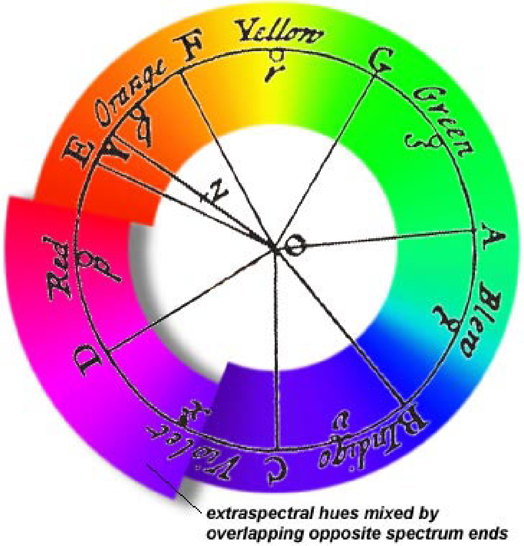
Color spectrum

- Color is a human interpretation of a mixture of light with different wavelength λ (a continuum of spectral colors).
- The perception of color is an entirely subjective experience.



Isaac Newton's findings

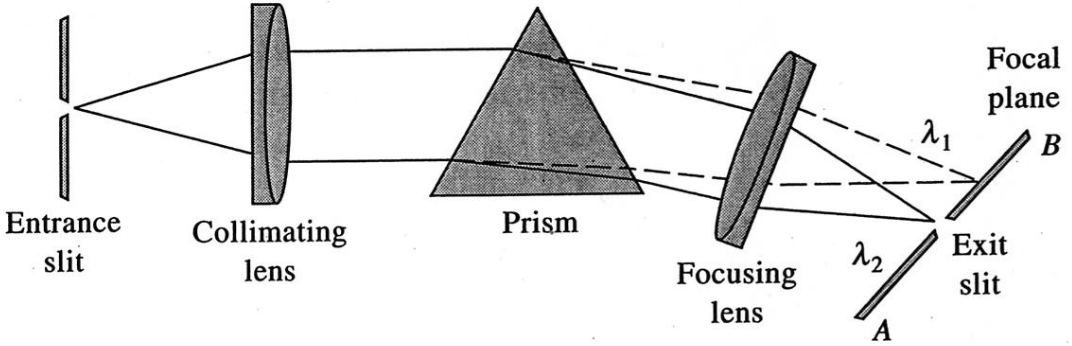
- Isaac Newton (1642-1727) studied nature of light using prism.
- He proposed in late 1660s that white light is a multispectral mixture. (He thought erroneously of 7 'primary' colors).
- This was quite a radical idea to propose at the time, and many philosophers, such as Johann Wolfgang Goethe (1749-1832), refused to believe it.
- Newton invented the color circle to predict how colors would look when mixed, i.e., using a linear combination rule.



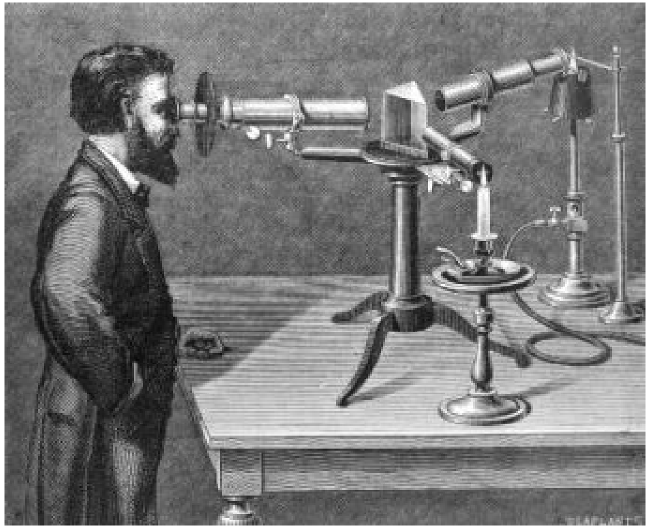
Newton circle (1709).

Capital letters refer to notes of the diatonic scale.

Spectrometer - color spectrum measurement



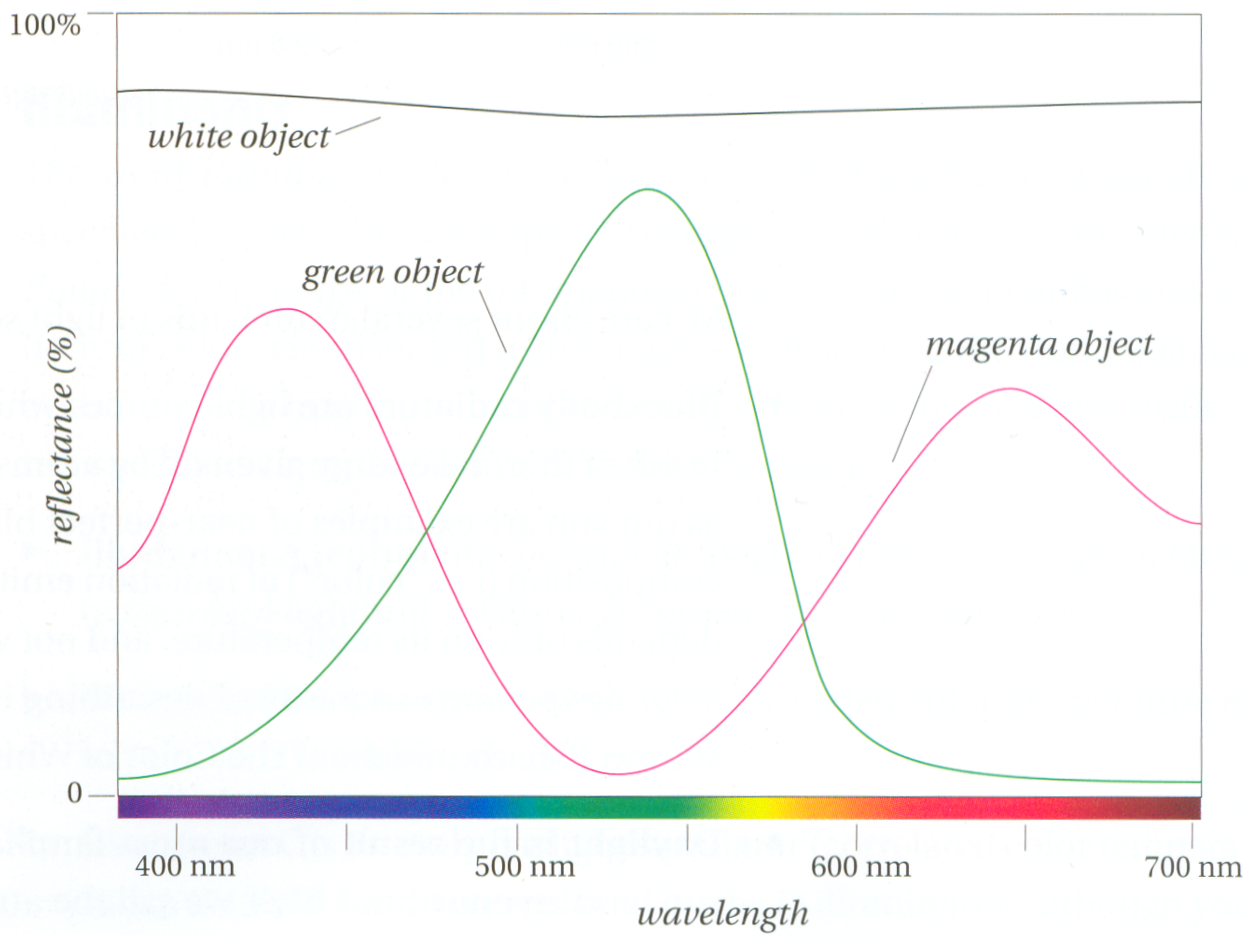
Principle of Bunsen's monochromator.



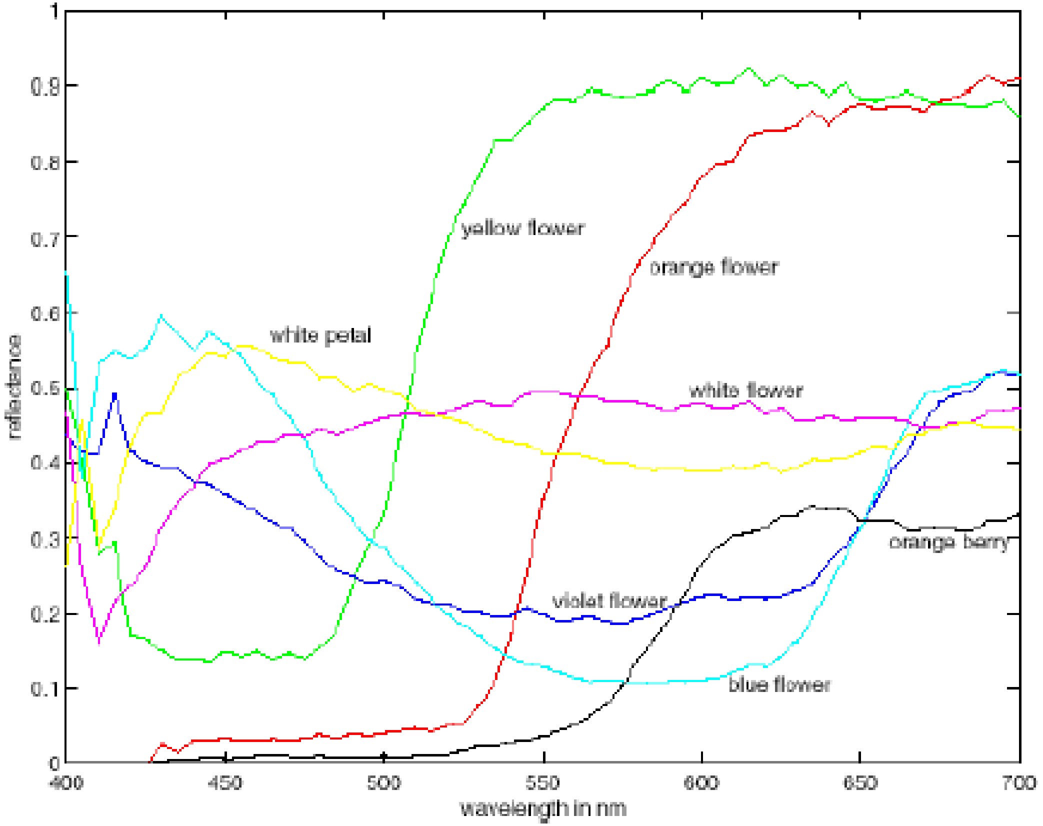
Bunsen-Kirchhoff spectrometer (1859).

- Used mainly in astronomy and chemistry to identify materials.
- Called also spectrofotometer, spectrograph or spectroscope.

Spectral curves of three different objects



Example: Spectral reflectance of flowers



Spectral albedoes for several different leaves, with color names attached. Notice that different colours typically have different spectral albedo, but that different spectral albedoes may result in the same perceived color (compare the two whites). Spectral albedoes are typically quite smooth functions. Measurements by E.Koivisto.

Forsyth, 2002

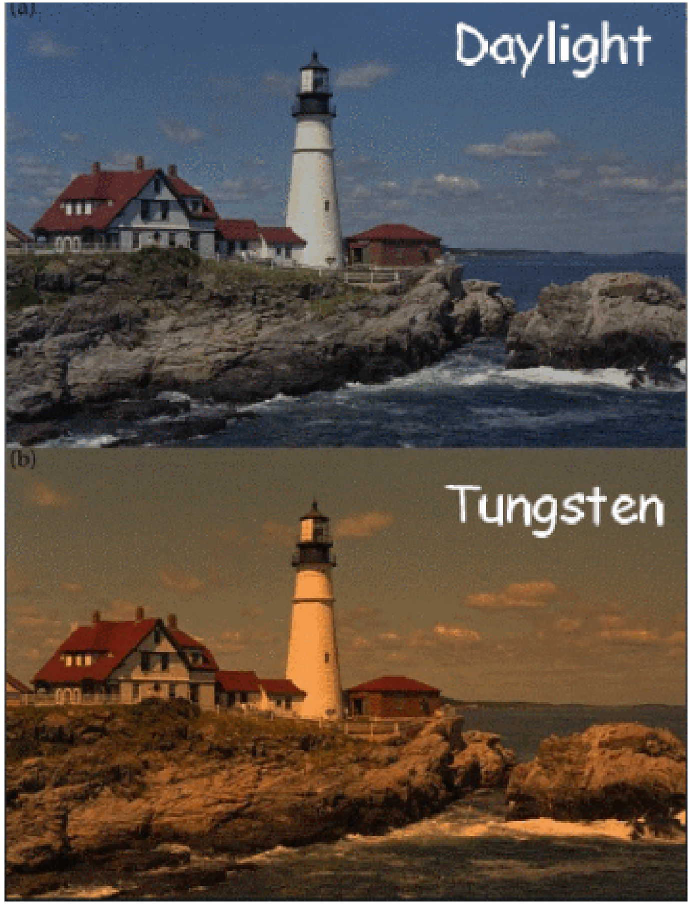
Color in physics

- Light $=$ electromagnetic radiation.
- Sensors do not have direct access to color, i.e., wavelength λ.
  Exception: spectrometer.
- Response of a sensor

$$s = \int_{\lambda_1}^{\lambda_2} s(\lambda)\, r(\lambda)\, \mathrm{d}\lambda\,, \quad \text{where}$$

$r(\lambda)$ is spectral sensitivity of a sensor,
$s(\lambda)$ is spectral density of light.

Influence of illumination



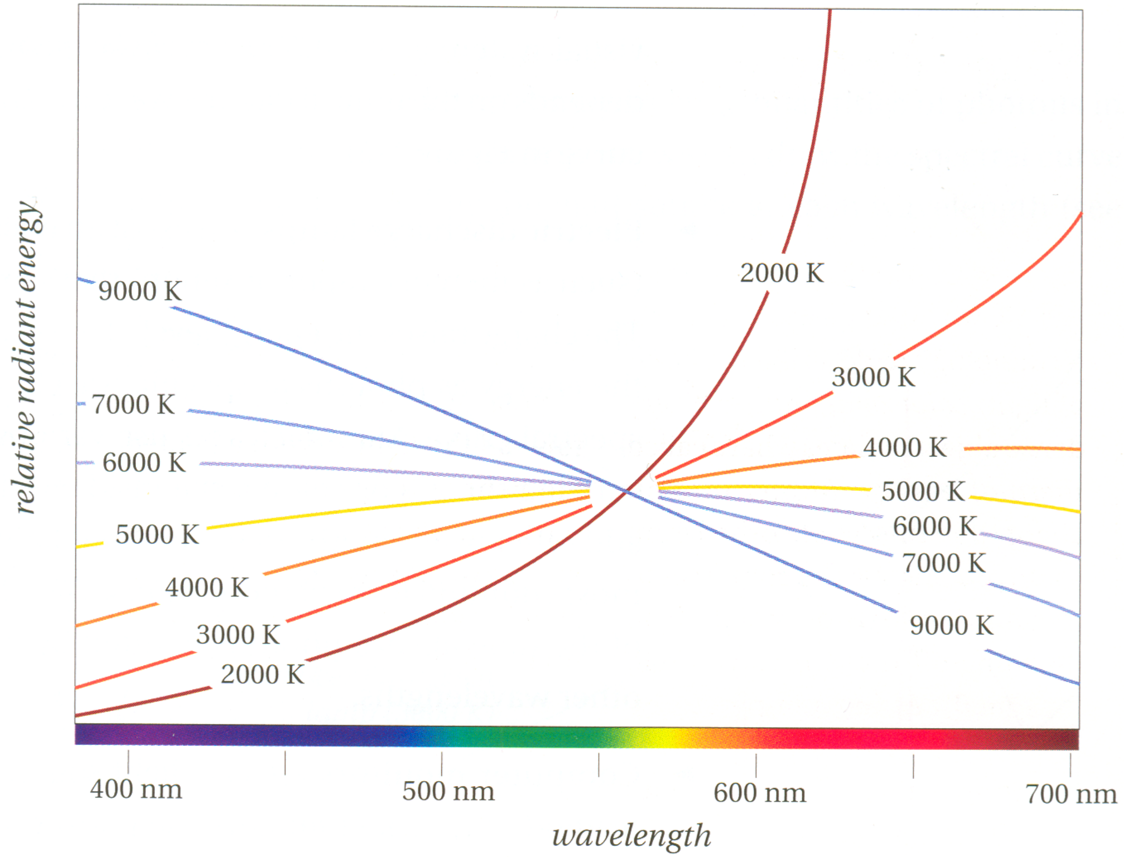
Influence of illumination (2)

Illuminants, physics point of view

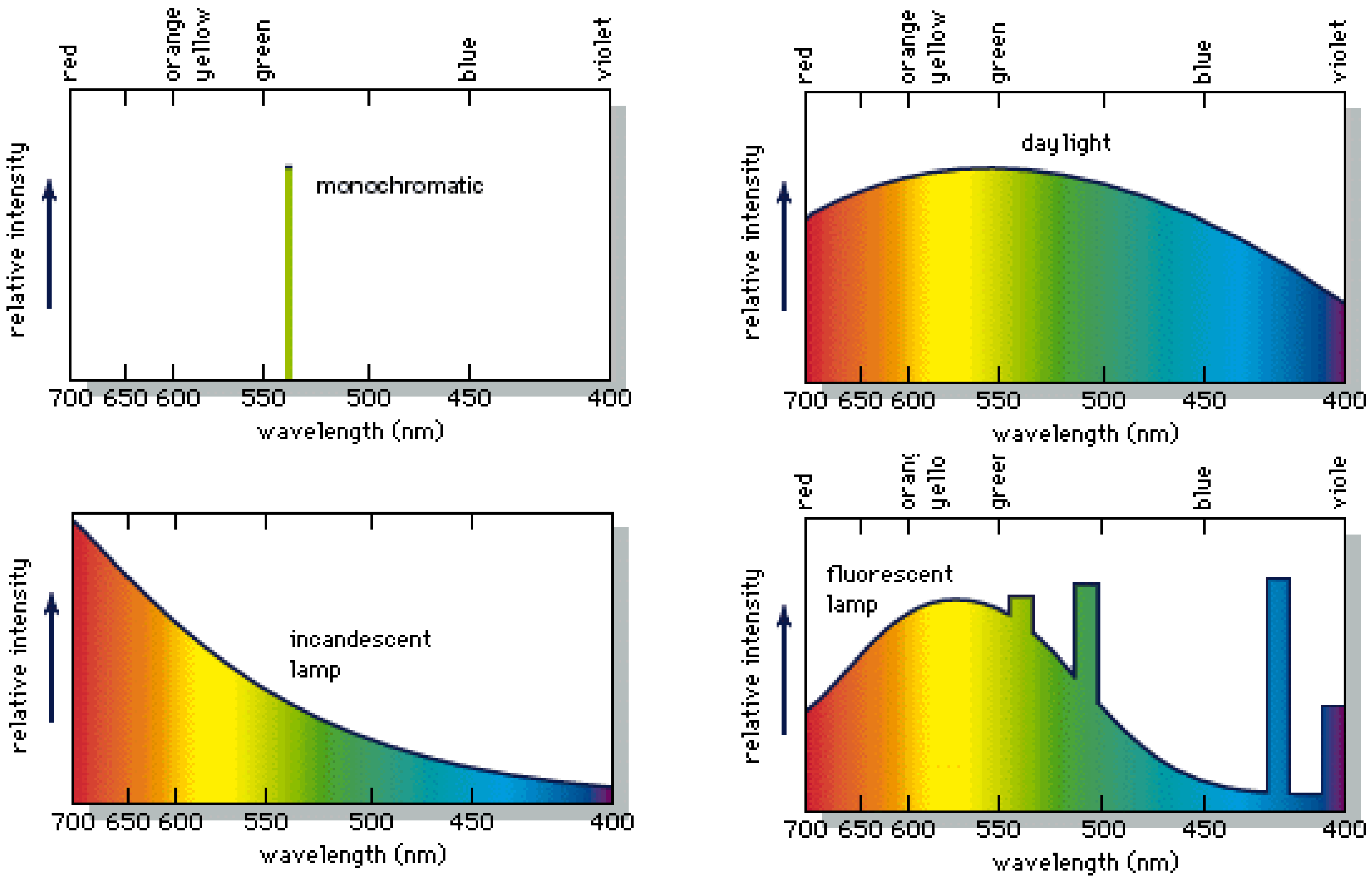
- Ideal radiator, black body – the light is radiated due to the heat energy of atoms. Approximately: incandescent bulb, stars, e.g., the Sun.

  The light spectrum depends only on the temperature $\Rightarrow$ concept: color temperature.
- Day light – radiation of the Sun (the black body) is strongly filtrated by the Earth atmosphere. The human vision evolved for this illumination and it it thus important while photographing.
- Electric discharge lamp (specially, fluorescent lamp) – the gas (e.g., mercury, xenon) excited by the electric charge emits light energy. The spectrum typically contains significant peaks.
- Computer monitors - cathode ray tube or CRT, liquid-crystal display or LCD (back-illuminated by fluorescent lamps or LEDs), plasma

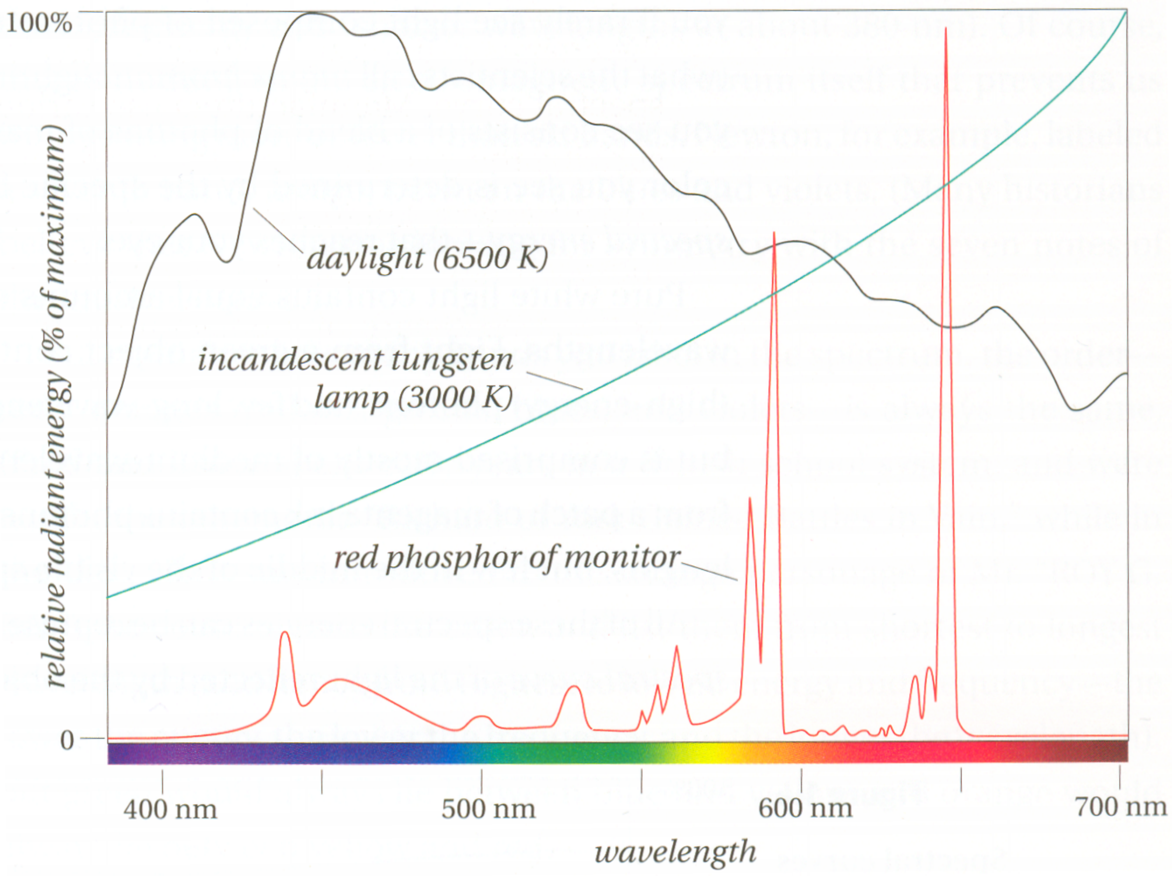
Spectra according to the temperature



Illuminant spectrum



Measured spectra of illuminants

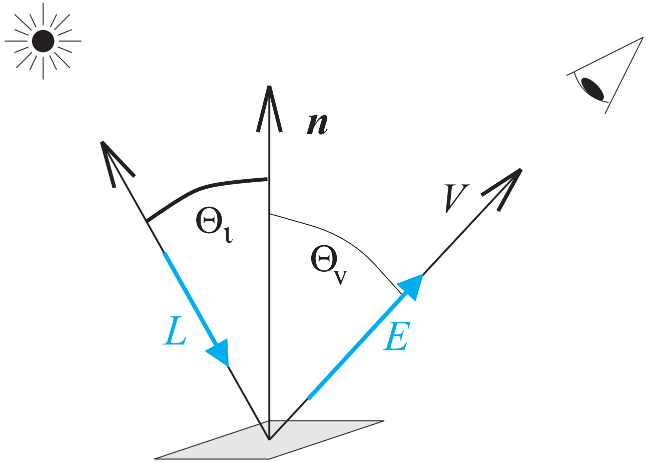


CIE illuminants

CIE = Commission Internationale de l'Eclairage.

- Illuminant A – typical spectrum of the ordinary incandescent bulb with the tungsten filament (the green curve on the previous slide).
- Illuminant B – Sun light at the temprerature 4874 K. It is used rarely.
- Illuminant C – older model of the day light at the temperature 6874 K. It is often replaced by the illuminant D today.
- Illuminant D – represents series of illuminants modeling different kinds of day light. The most common is D50 (for the temperature 5000 K) and D65 (for the temperature 6504 K). The examples are on the next slide.
- Illuminant E – "total energy", the significance of which is in theoretical calculations.
- Illuminant F – models illuminants with fluorescence. The most commonly used are F2, F3, . . . , F12.

Radiometry, a small review



- L – radiance.
- E – irradiance.
- $\mathbf{n}$ – surface normal.
- V – direction to observer.

Bidirectional Reflectance Distribution Function

$$\mathrm{BRDF} = f(\Theta_i, \Phi_i, \Theta_e, \Phi_e) = \frac{\mathrm{d}L(\Theta_i, \Phi_i)}{\mathrm{d}E(\Theta_e, \Phi_e)}$$

Radiometry in the color case

- All definitions are changed in such a manner that they are expressed “per unit wavelength”.
- All terms have the adjective “spectral”.
- Radiance becomes spectral radiance [watts per square meter per steradian per unit wavelength].
- Irradiance becomes spectral irradiance [watts per square meter per unit wavelength].

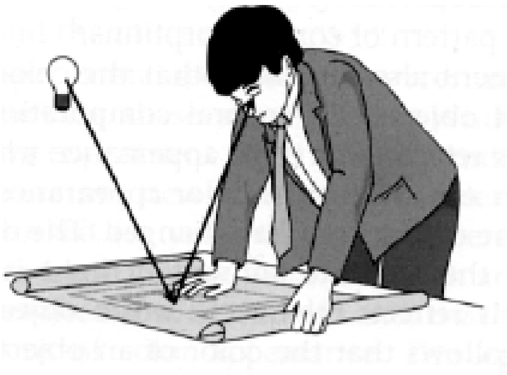
Radiometry in color (2)

- Dependence on wavelength λ is introduced into BRDF (Bidirectional Reflectance Distribution Function).
- L becomes spectral radiance.
- E becomes spectral irradiance.

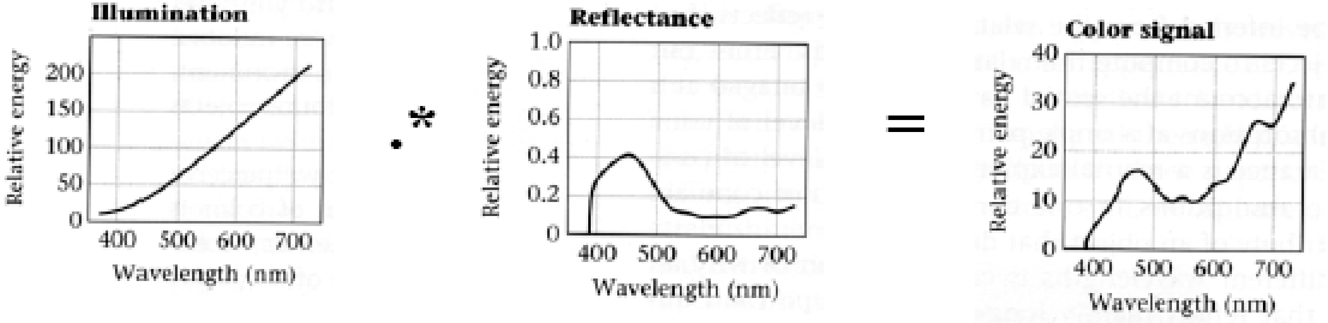
$$\mathrm{BRDF} = f(\Theta_i, \Phi_i, \Theta_e, \Phi_e, \lambda) = \frac{\mathrm{d}L(\Theta_i, \Phi_i, \lambda)}{\mathrm{d}E(\Theta_e, \Phi_e, \lambda)}$$

In computer vision, simplified models are often used which use relative measures instead of absolute measures.

Relative reflectance

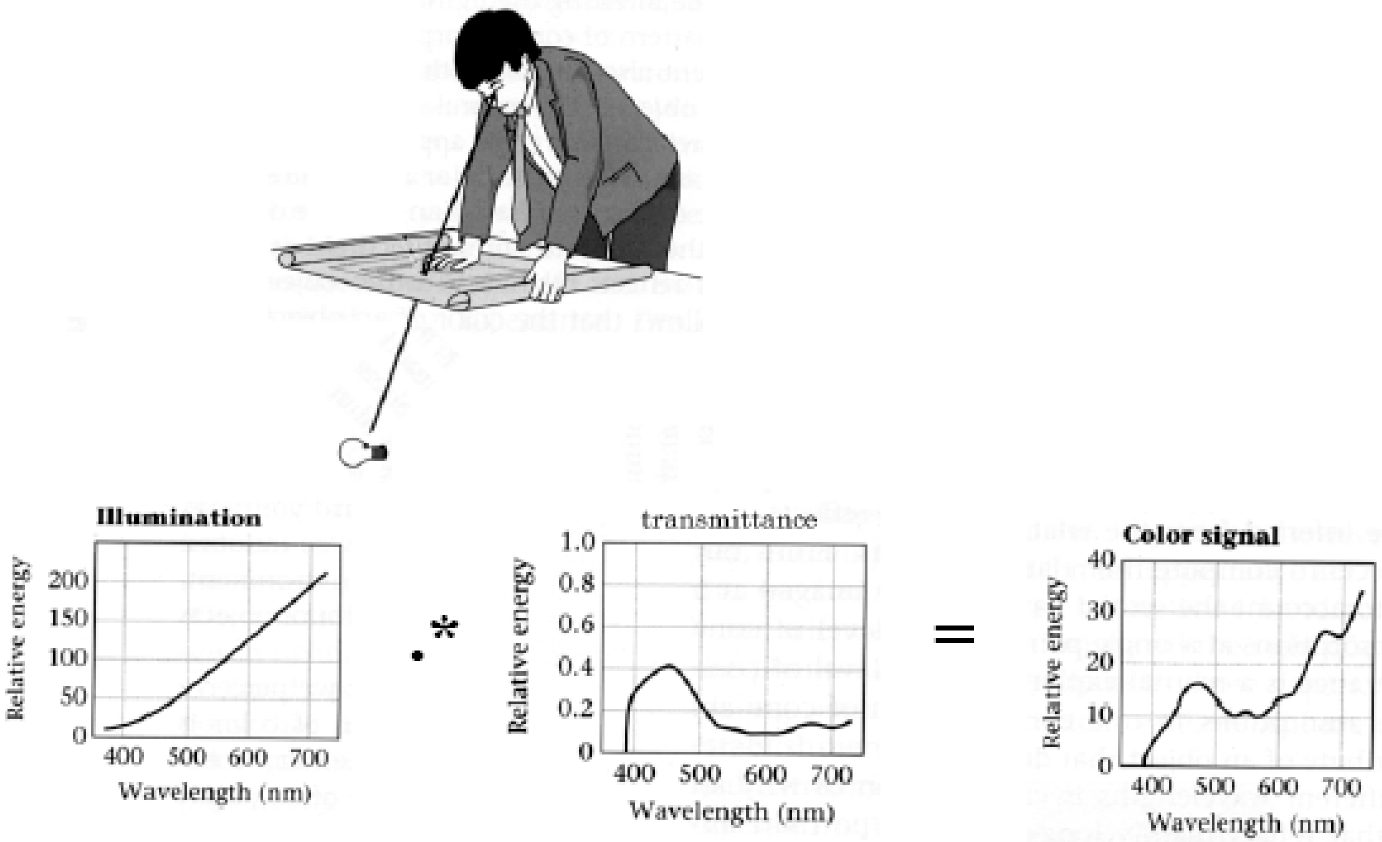


Often are more interested in relative spectral composition than in overall intensity, so the spectral BRDF computation simplifies a wavelength-by-wavelength multiplication of relative energies.



Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Relative transmittance

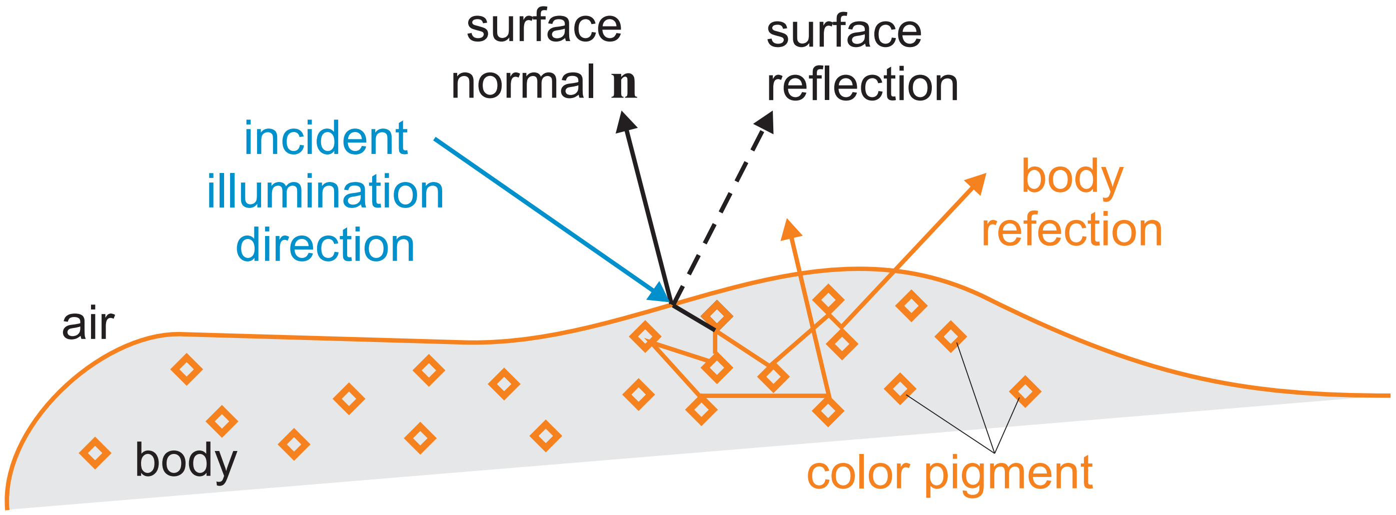


Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Why do we see object colors?

Irradiated surface:

- **Surface reflection** rebounds incoming as a mirror. Almost no influence to the spectrum.
- **Body reflection** and is predominant in dielectrics as plastic or paints.
  Colors are caused by the properties of pigment particles which absorb certain wavelengths from the incoming illuminant wavelength spectrum.

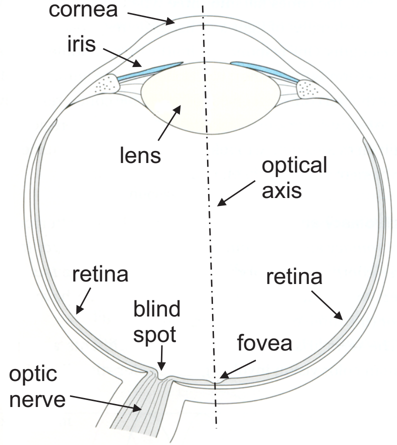


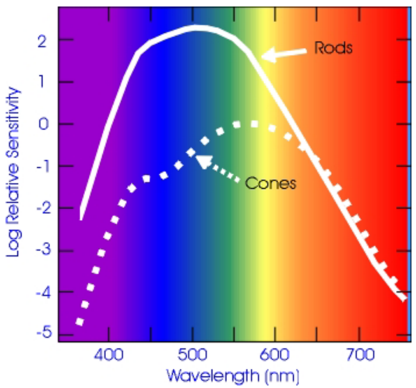
Fluorescence

- The scourge for the color management.
- Fluorescence describes a phenomenon, when some atoms absorb a photon of certain energy ($\approx$ wavelength) and emit photons with lower energy (higher wavelength).
- Fluorescence is used deliberately, e.g., for lightening up. A part of near ultraviolet radiance is transferred into the visible radiance, often violet or blue.
- This is the principle of lightening up in washing powders, tooth pastes and printing papers, printer inks, printer waxes, toners for the printers.

Spectrum visible to humans

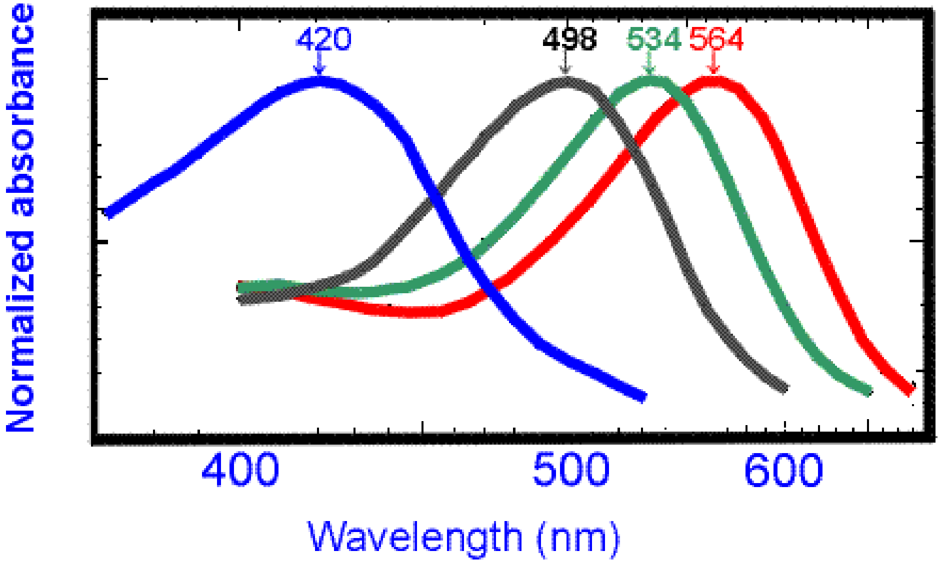
- Retina contains four types of light receptors.
- R, G, B cones for seeing color.
- Rods for monochromatic vision with the higher sensitivity.
- The response of receptors to the light intensity has logarithmic dependence. Why?
- Receptors of color were discovered by Hermann von Helmholtz. The situation on the retina was described in his book from 1867.
- There is an alternative theory of three pairs of complementary colors (red-green, yellow-blue, white-black) by Ewald Hering from 1872. The theory was confirmed by Edwin Land in $\approx$ 1970 who suggested Retinex theory as a model of color perception in the brain.





Trichromatic color perception in humans

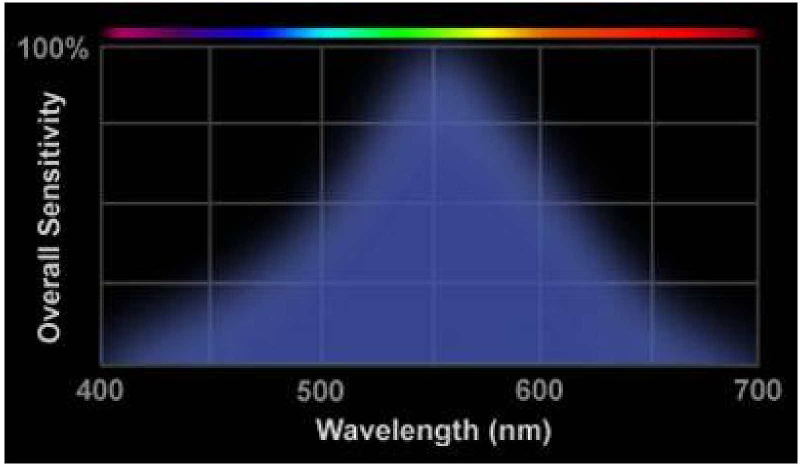
The eye “measures in a pixel” the wavelength by cones (components S-short, M-medium, L-long) and provides the response by combining these percepts.

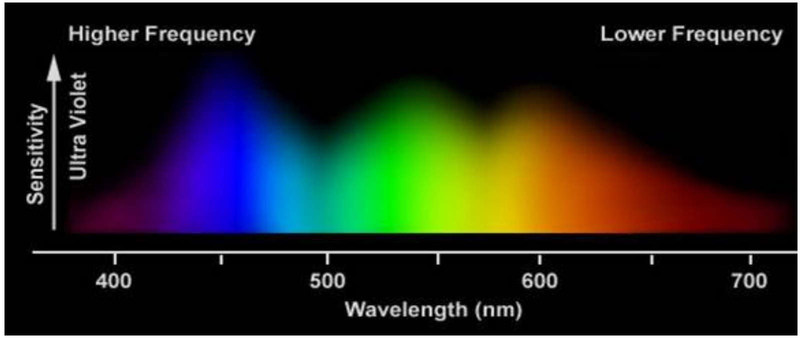


After Bowmaker & Dartnall, 1980

RGB components of a color image

Human eye sensitivity to λ



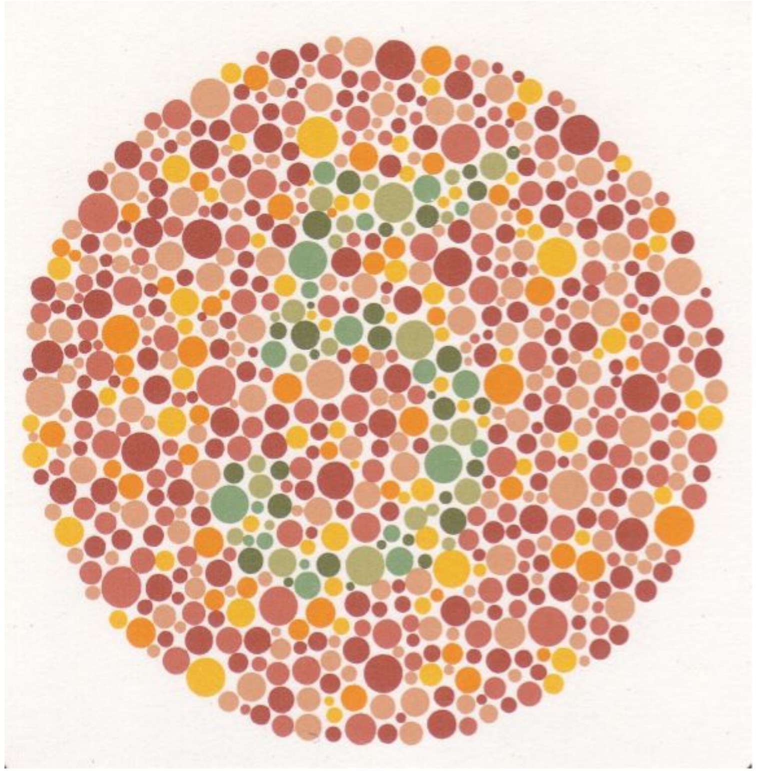


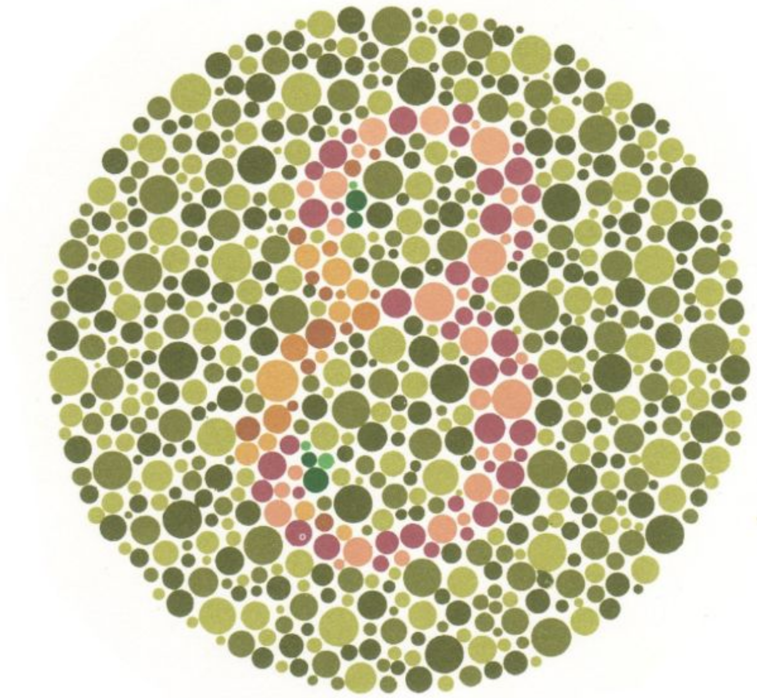
- CIE - Commission Internationale de l'Eclairage (Int. Commission on Illumination).
- Performed measurements with many humans.
- Measurements from 1931 and improvements in later years.

Color metamer

- A metamer, in general, describes the situation when two physically different phenomenon are perceived the same.
- Red and green adding to produce yellow is a color metamer, because yellow could have also been produced by a spectral color (single light with wavelengths between green and red).
- Human visual system is fooled into thinking that red+green is the same as yellow, when in fact red+green has a completely different spectral composition than yellow.
- This outcome provided by species evolution is ingenious because it allows by a simple mechanism of three receptors to see very many nonspectral colors.

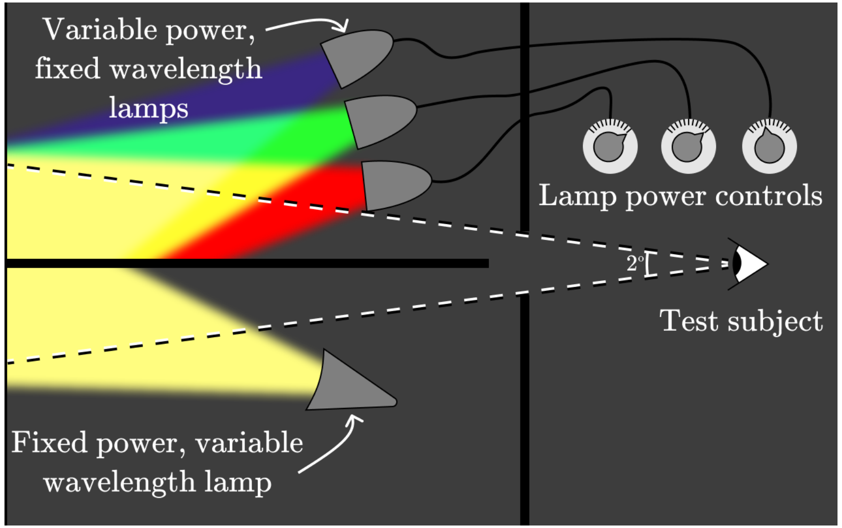
Color blindness, Ishihara plates





How to define the color space?

- Three type of cones suggest that color can be defined in a three-dimensional (vector) space.
- How to define a color space?

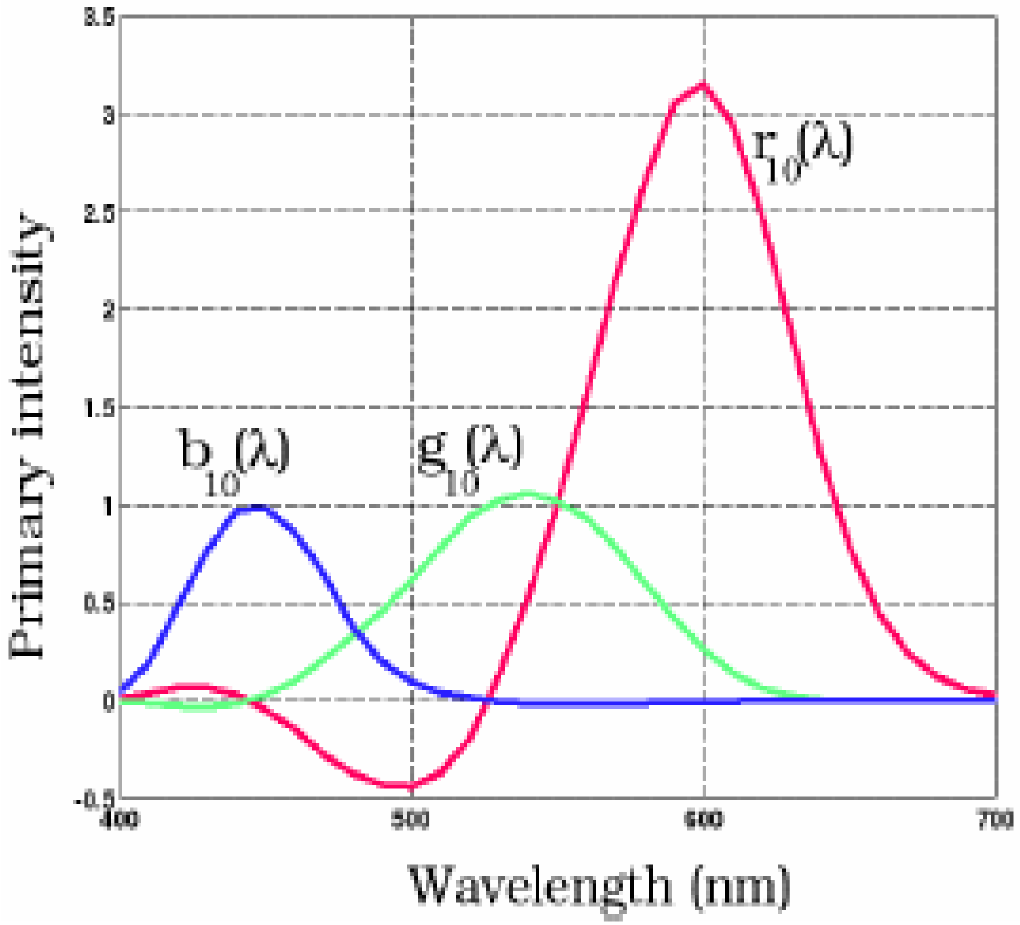


Idea of the experimental procedure.

- Shine a spot of the given wavelength λ on a screen.
- The second light spot is created by combining three pure R, G, B lights. The human is asked to control intensity of components (so called color matching functions) until the colors of the two spots look identical.
- This is possible because of color metamers.

RGB color matching functions

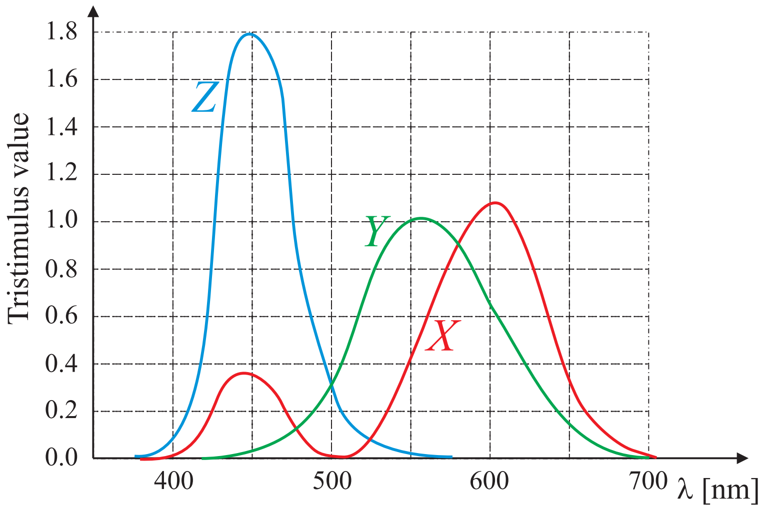
- Issued by CIE.
- Negative lobe in red!
- All wavelengths cannot be generated with RGB components.
- Solution: convert to a new synthetic coordinate system X, Y, Z to make the job easy.



Color space CIE XYZ

CIE created the XYZ color model as the mathematical abstraction.

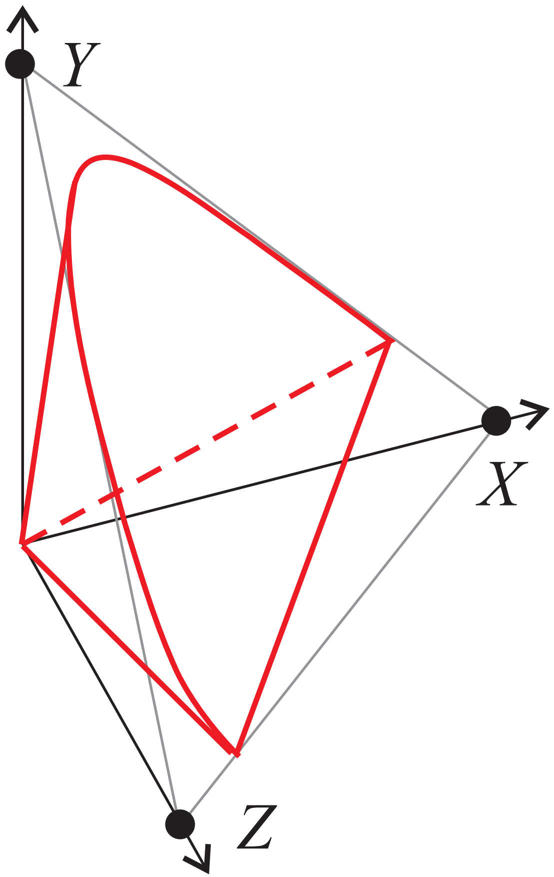
- XYZ coordinates correspond to the (imaginary) colors, the combination of which according to the matching functions created the same percept as the spectral color.
- Absolute standard because it is related to perception of the standard observer.
- There are newer standards CIE LAB 1976 (ISO 13665) and often used commercial standard HunterLab.



- Nonnegative values.
- $Y(\lambda)$ corresponds to the brightness.
- Normalization to make the area under curves equal.

Gamut of perceivable colors

- The gamut of all perceivable colors is a subspace of 3D space in X, Y, Z.
- Color $= c_X\, X + c_Y\, Y + c_Z\, Z$, where c_X, c_Y and c_Z are weights in the mixture.
- Gamut is often projected into a plane $X' + Y' + Z' = 1$ after normalization.



Gamut in 2D, CIE chromaticity diagram

Coordinates x, y.

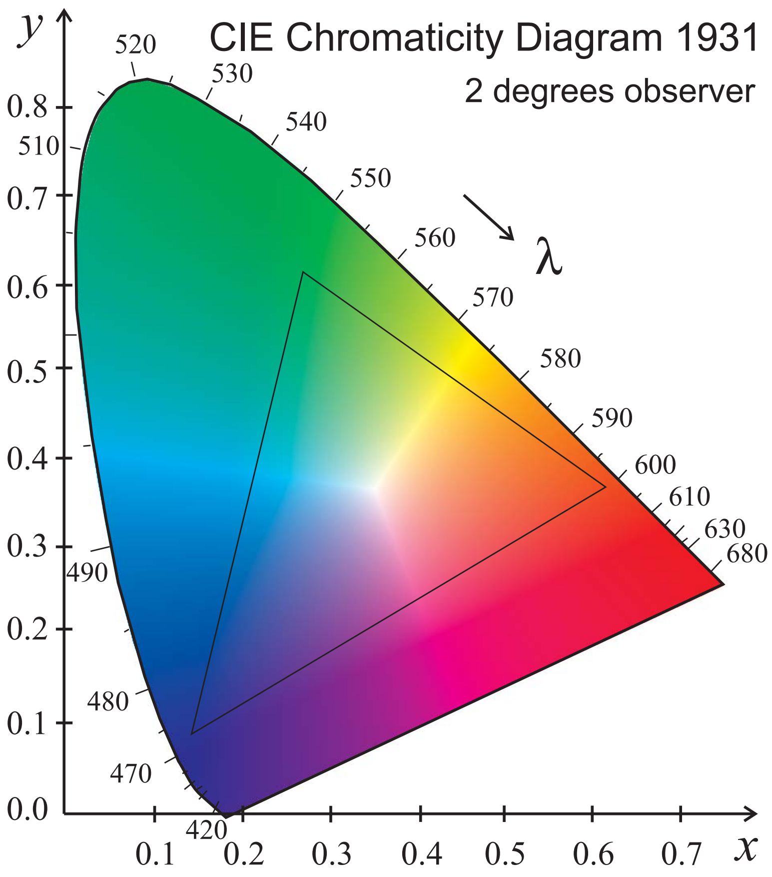
$$x = \frac{X}{X+Y+Z}$$

$$y = \frac{Y}{X+Y+Z}$$

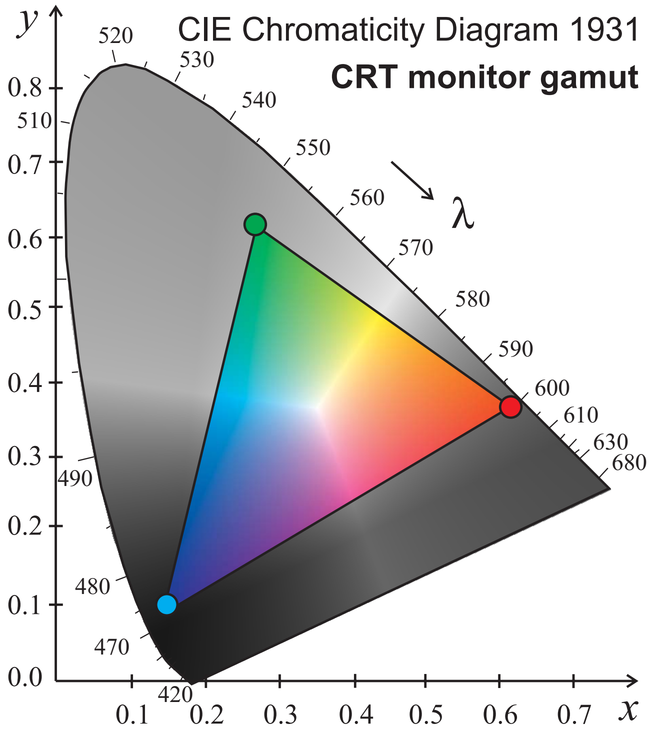
$$z = 1 - x - y$$

All visible spectral colors appear on the outline of the 'horseshoe'.

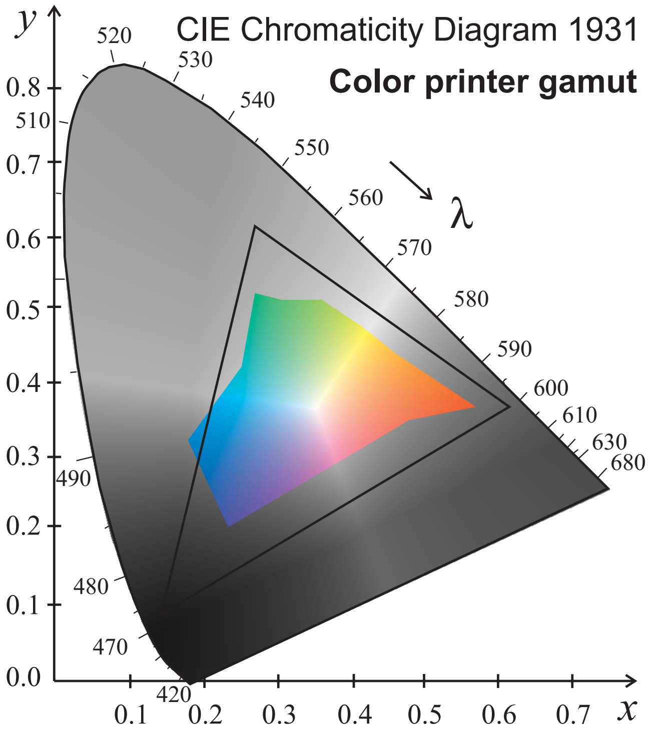
All visible mixtures appear inside the horseshoe.



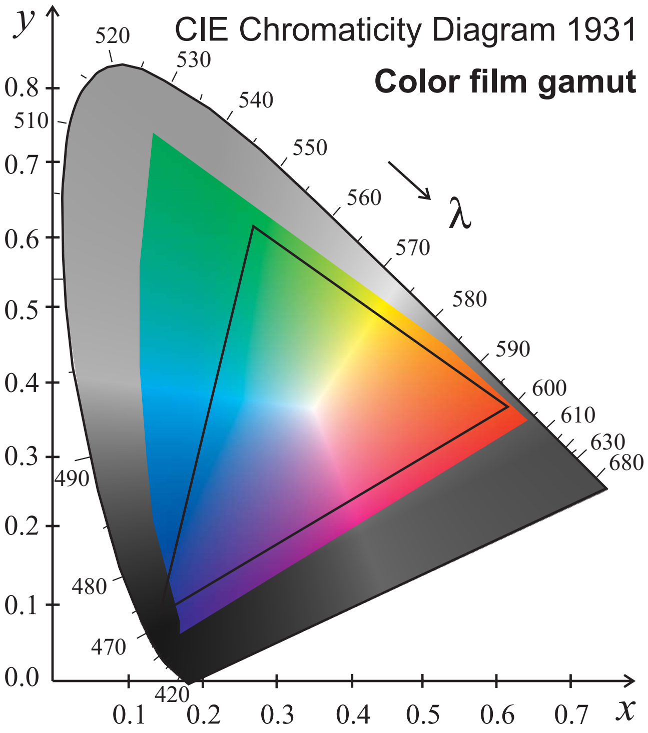
Color gamuts of devices



CRT monitor

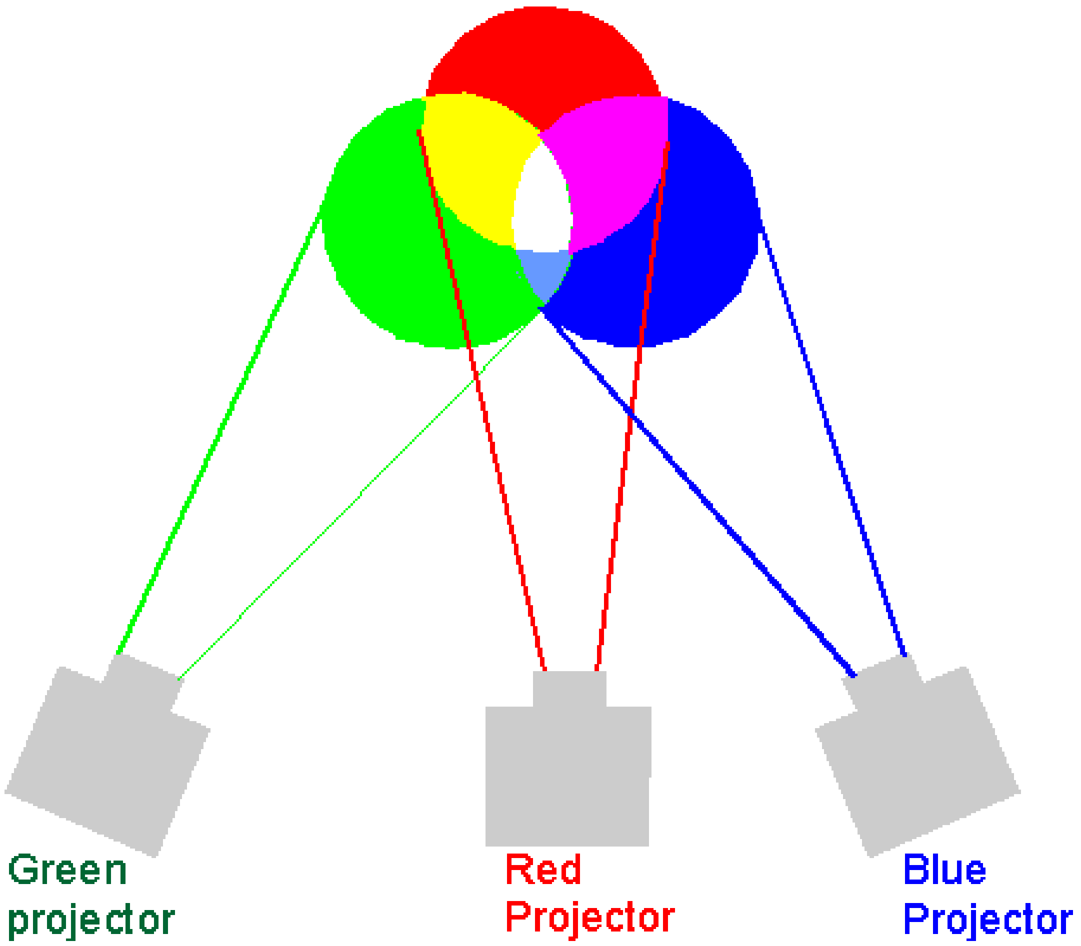


printer

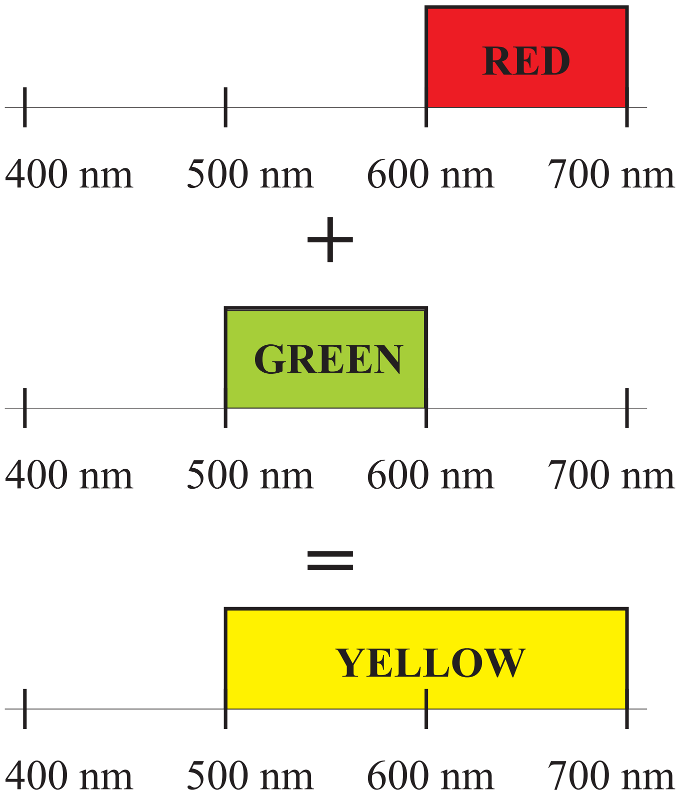


film

Mixture of colors

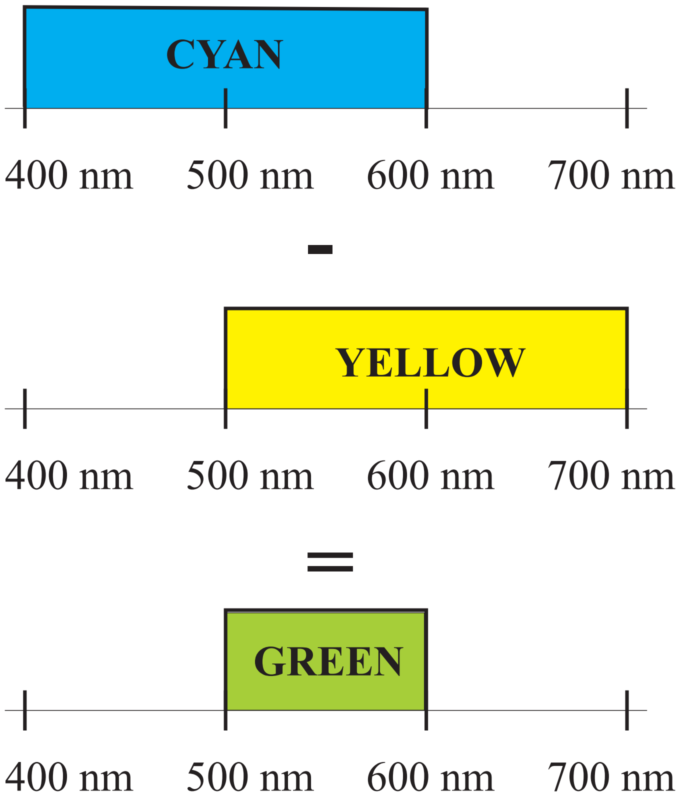


Additive color mixing



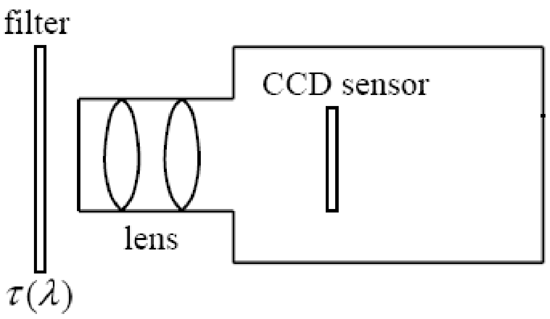
- Red plus green makes yellow.
- Additive mixing model holds for CRT phosphors, multiple projectors aimed at a screen, human eye cones.

Subtractive color mixing

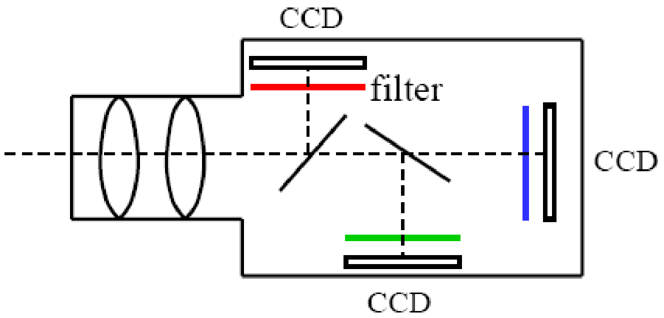


- Applies when colors mix by multiplying the color spectra.
- Cyan (called blue in crayons) minus (actually multiply) yellow makes green.
- Subtractive mixing model holds for most photographic films, paint, crayons, printing, cascaded optical filters.

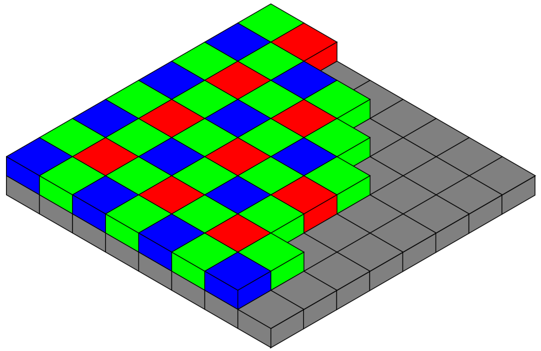
Color cameras



1 chip camera + filter

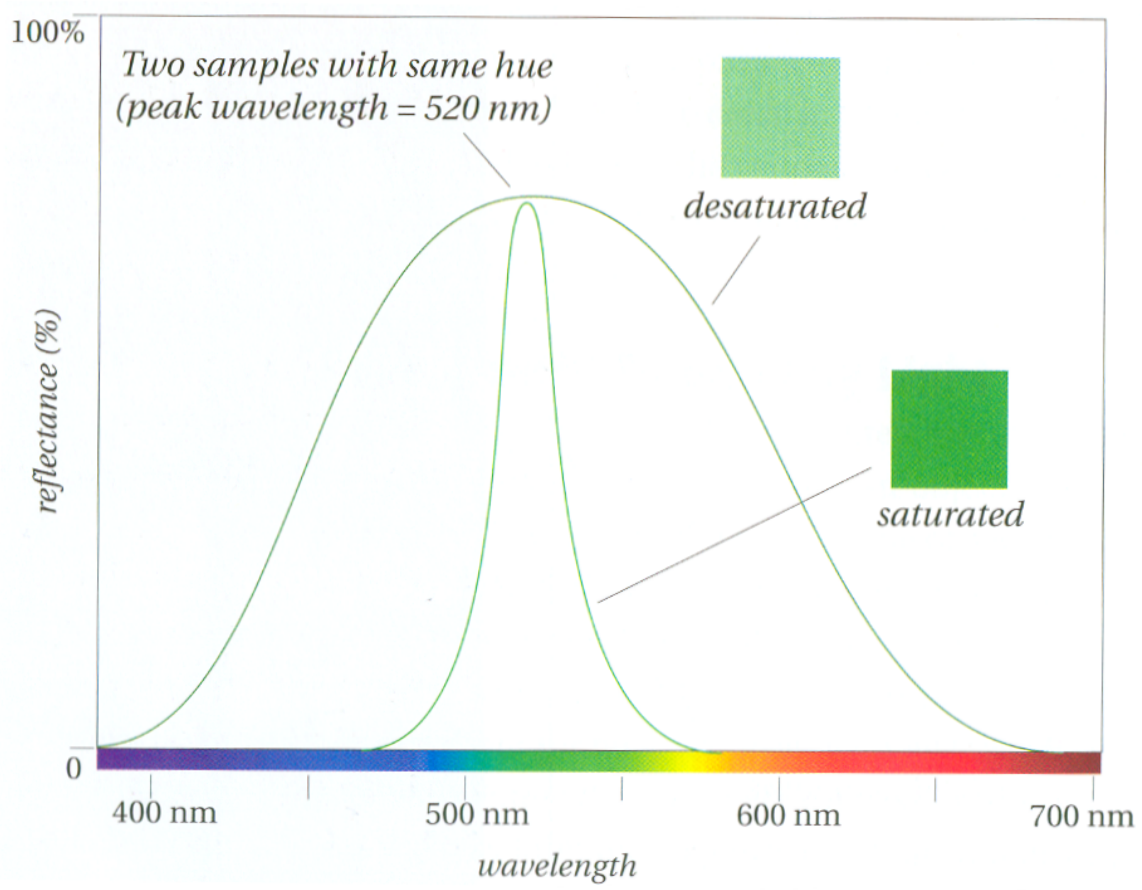


3 chip camera



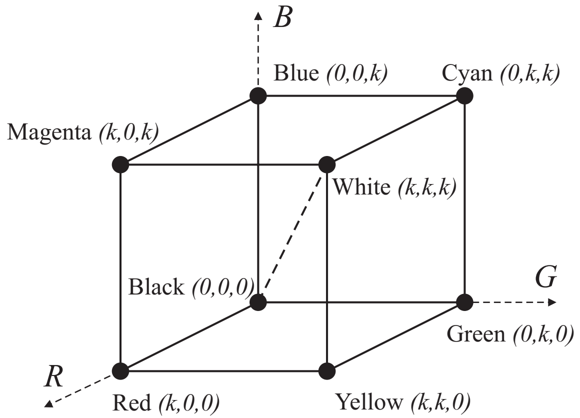
Camera with a Bayer filter on the chip

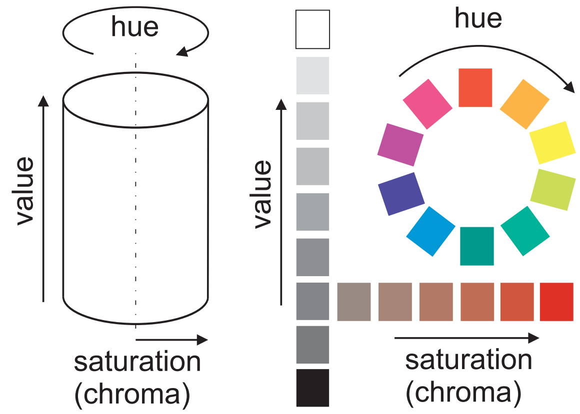
Saturation in the color spectrum



Additional color spaces

- **RGB** – related to the color television originally.
- **YIQ** – used by the NTSC television norm (USA, Japan). The Y component corresponds to luminance, the remaining components describe the color, chrominance.
- **CMYK** – Cyan, Magenta, Yellow, blacK.
  Useful in devices with subtractive color mixing model,
- **HSV** – Hue, Saturation, Value.
  Useful in digital image processing.

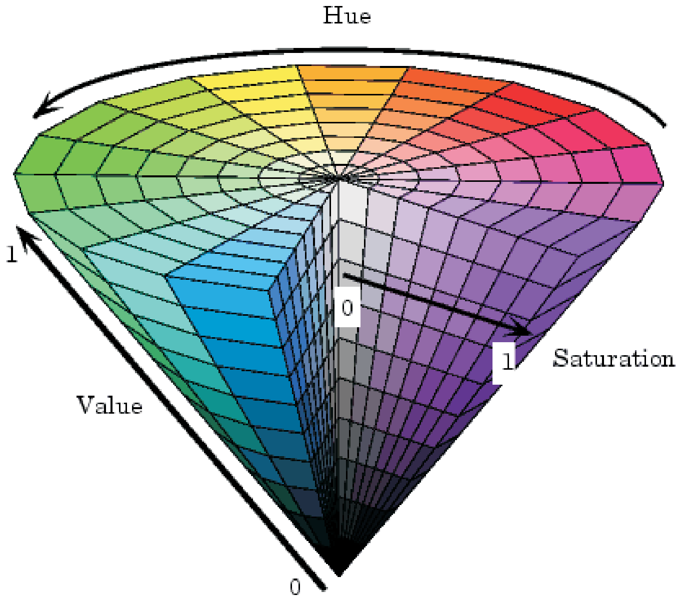




Illustration, chromatic components: Hue, saturation, value – color space

Motivation: painter's palette color mixing.

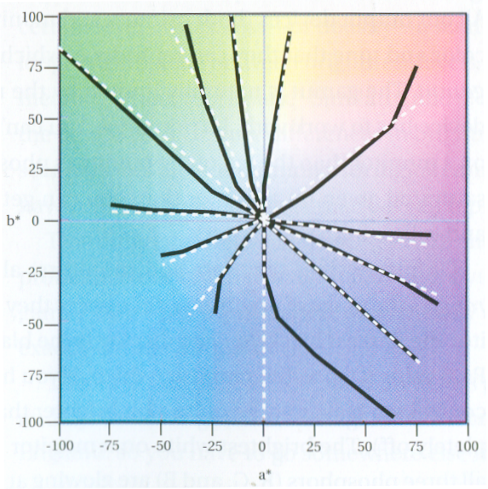
- **Hue** corresponds to the dominant wavelength which is the projection of the color to the limits of color triangle. Spectral colors are there.
- Names of the colors corresponds to different hues. However, binding between names and hues varies in different cultures.
- **Saturation** of the color expresses, how far is the color from neutral gray color. It also tells how much is the dominant wavelength (hue) contaminated by other wavelengths.



Color space CIE LAB

The most often used absolute color space for the color management. It was created from the CIE XYZ space by a non-linear transformation.

- CIE LAB mimics the way how a human judges a color when the perception of it should be uniform.
- The base color are L* (light), a* describing the color pair red-green, b* describes the color pair blue-yellow, cf. Hering's color pairs.
- The change of the base color by an increment should cause similar change in the visual perception. For imperfections, see the figure.
- CIE LAB is used as a base space for transferring the color spaces of devices, which is the core of the color management.



- The hue is displayed as the polar angle.
- The saturation is shown as the distance from the center (neutral gray).
- White dashed lines should correspond to constant brightness. However, the perceived brightnesses are imprecise (black solid lines).

Basic parameters of display and input devices

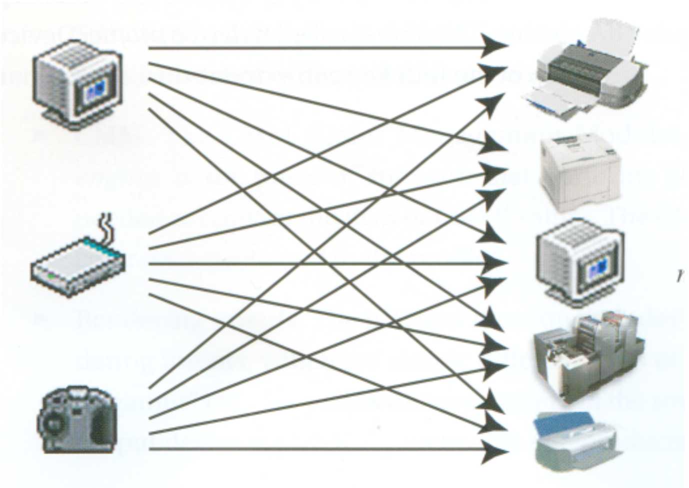
For color management, it is needed to know (measure) the basic parameters of monitors, cameras, scanners, printers, . . .

- **Three base color** (called colorants), their color and intensity of base colors.
- **White point**, its color and intensity. In human vision, all other colors are referred to the white color unconsciously. Thus, while calibrating the white point, the color is more important than the intensity.
- **Black point**, its color and intensity. Blackness (density) of the black tells about limits of the dynamic range which the device is able to display/capture. Dynamic range is important to perceive details in intensity. In printers, the black ink/toner is added, cf. CMYK. The black point cannot be adjusted on LCD monitors.
- **Tone reproduction curve** tells how the intensities are transformed in individual color components in the color spaces of two devices. These characteristics are often nonlinear. They are implemented as look-up tables, LUTs.

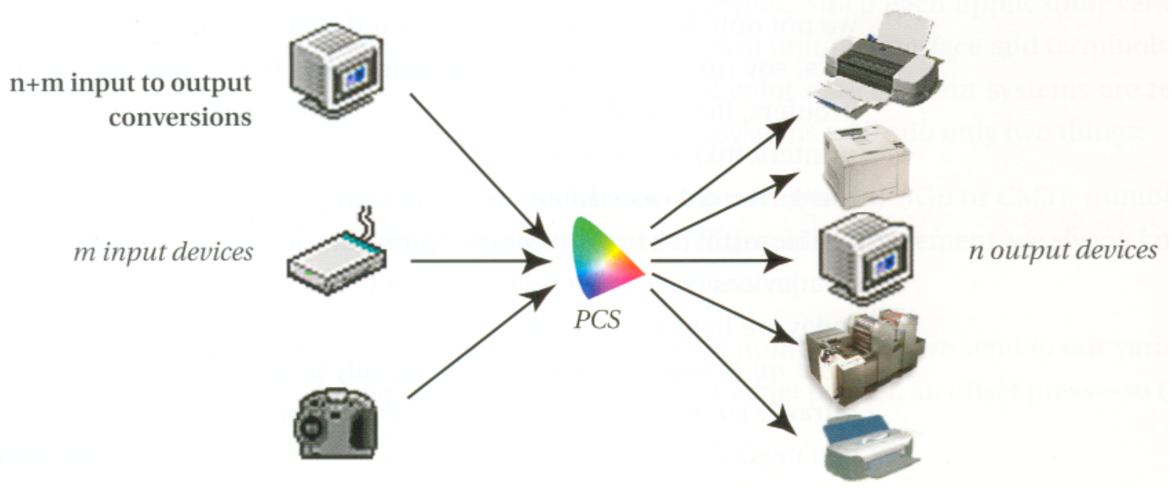
Transfer of colors among devices

- Color management serves to the accurate color transfer from the source, through 'our' image file to the target display or printing device.
- Due to physical laws constraints, it is not possible to display all colors in their all saturations, hues and intensities. This holds for the dynamic range too.
- The intersection of the input and target color space is often only a subset of the original color space (range of colors).
- The nonlinear transform in color components given by the transfer tables of base colors are usually not directly compatible.

Color management
Simplification via the intermediate representation



$m \times n$ possibilities

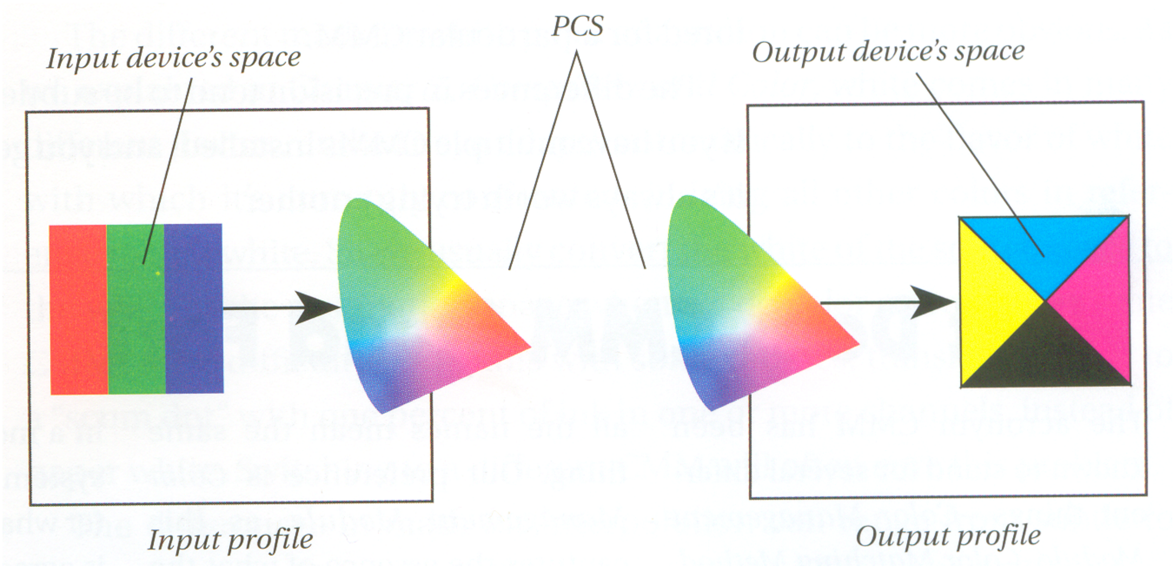


$m + n$ possibilities

The connector among devices is the Profile Connection Space, PCS, i.e., representation of the color independent on the specific, usually CIE LAB nebo CIE XYZ.

ICC, International Color Consortium

- Several companies around the year 1980, e.g., Adobe, Agfa, HP, Kodak, Tektronix, solved the color management between pairs of devices.
- Apple Computer introduced ColorSync for the Mackintosh operating system in 1993 and has initiated a consortium of companies later known as ICC, the International Color Consortium.
- The main document of ICC is the open document "Profile Connection Space".



Components of the color management system

- Profile Connection Space, which was already explained.
- Profiles. The profile describes mapping between coordinates in a particular color space (e.g., in RGB or CMYK) and the actual colors which the coordinates correspond to. The matching coordinate in the CIE LAB or CIE XYZ space is assigned to them.
- The Color management module CMM is a program which recalculates the RGB or CMYK coordinates to the required CIE LAB or CIE XYZ coordinates. CMM explores color information stored in profiles.
- The rendering intents provide a solution to the problem if the color appears out of the displayable range of a particular rendering device. The ICC specification contains four such rendering intents.

Rendering intents

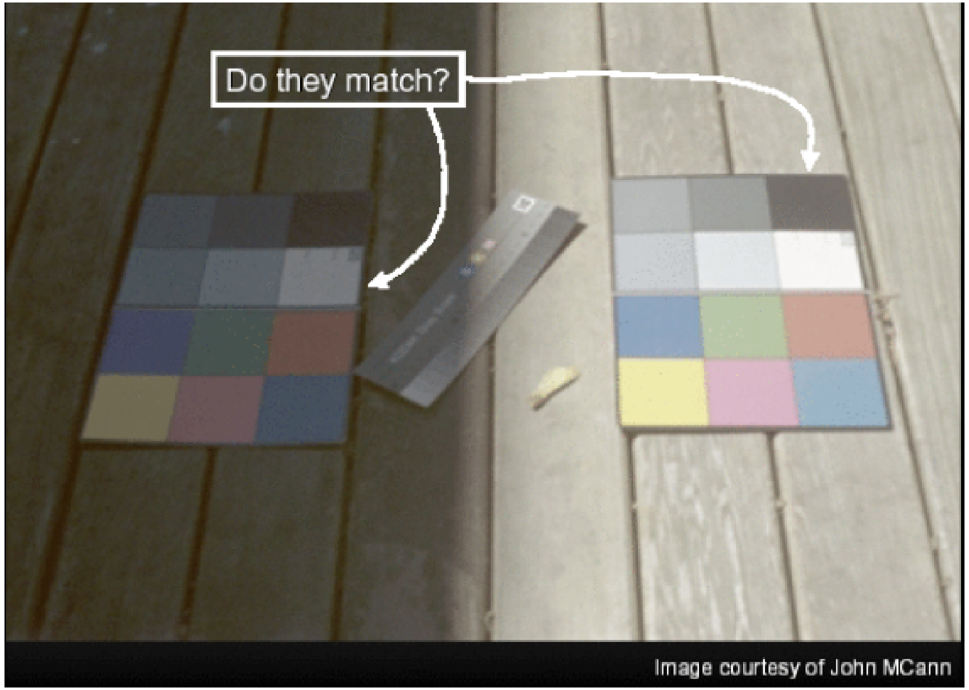
- Rendering intents are part of the Profile Connection Space specified by ICC (International Color Consortium).
- It describe how to solve the problem if the required color is outside of the displayable range, i.e., how to replace the color by some other available color at the output device.
- The Profile Connection Space norm contains four rendering intents methods. These methods are implemented in image editors, e.g., in PhotoShop:
  1. **Perceptual** – tries to keep the overall color perception. Suitable for images in which many colors lie outside of the color range.
  2. **Saturation** – gives preference to live colors and does not care about accuracy. Suitable for artificial images, cartoons, business graphics, etc.
  3. **Relative colorimetric** – explores the phenomenon that the human vision always adapts to the white color. The rendering intend converts the source white to the target white (e.g., color of the yellowish paper). The colors without the color range are displayed exactly and the colors outside the color range are displayed as the closest displayable color. For photographs, it is more suitable than the perceptual rendering intent.
  4. **Absolute colorimetric** – differs from the above that it tries to simulate the source white in the output color space. It is used for pre-verifying the future print on some other device, e.g., a computer monitor.

Color management, practically

- We learned everything needed to apply the color management practically, e.g., for printing the outcome of a small photographic project in some photographic minilab, the color profile of its output device is known.
- We need a special calibration sensor to calibrate the used computer display.
- Next, in the photoeditor (e.g., Photoshop) the changes in colors have to be made.
- The student will learn both steps in the laboratory exercises.

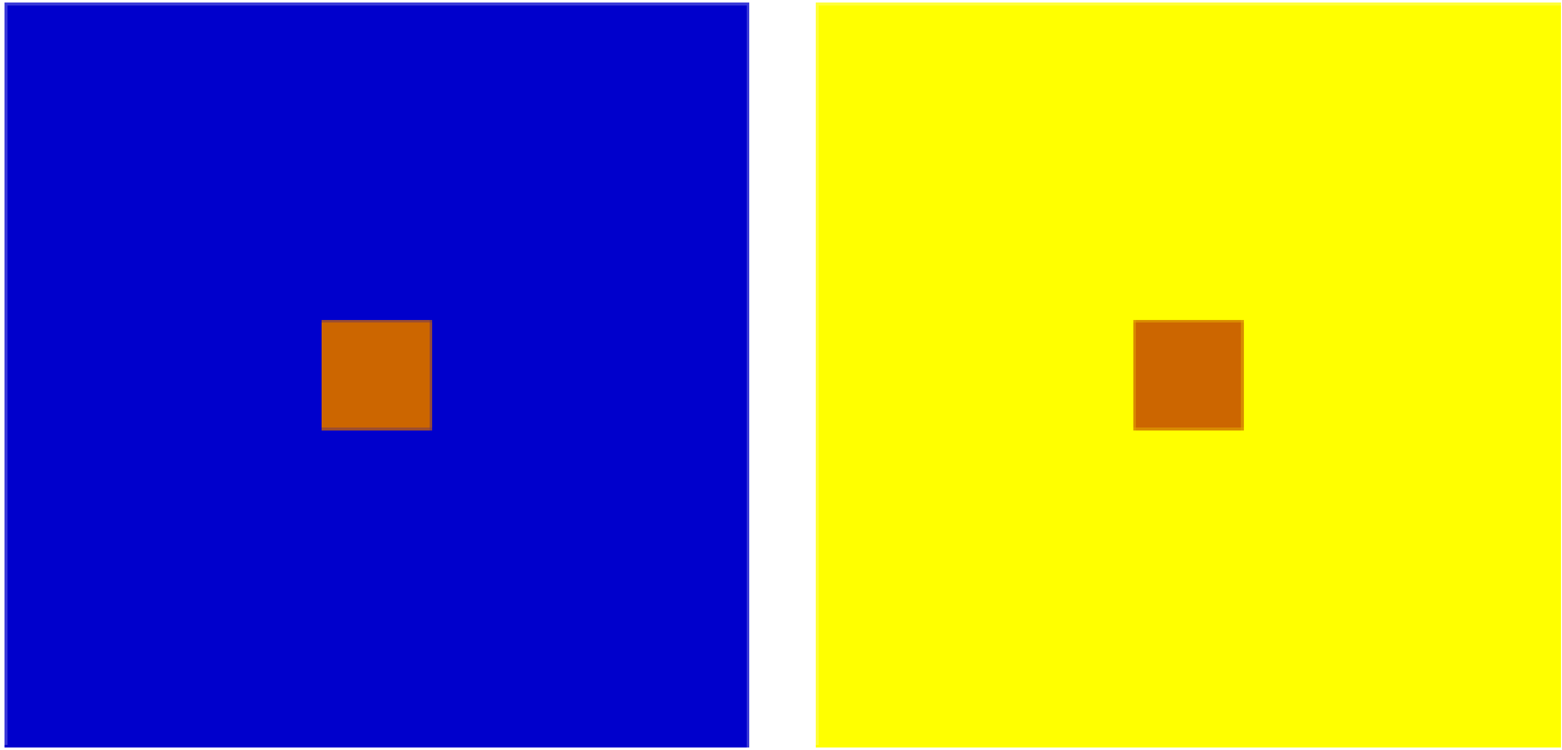
Color constancy, motivation

Color constancy refers to our ability to remove the effect of the illuminant in perceiving the color of objects.

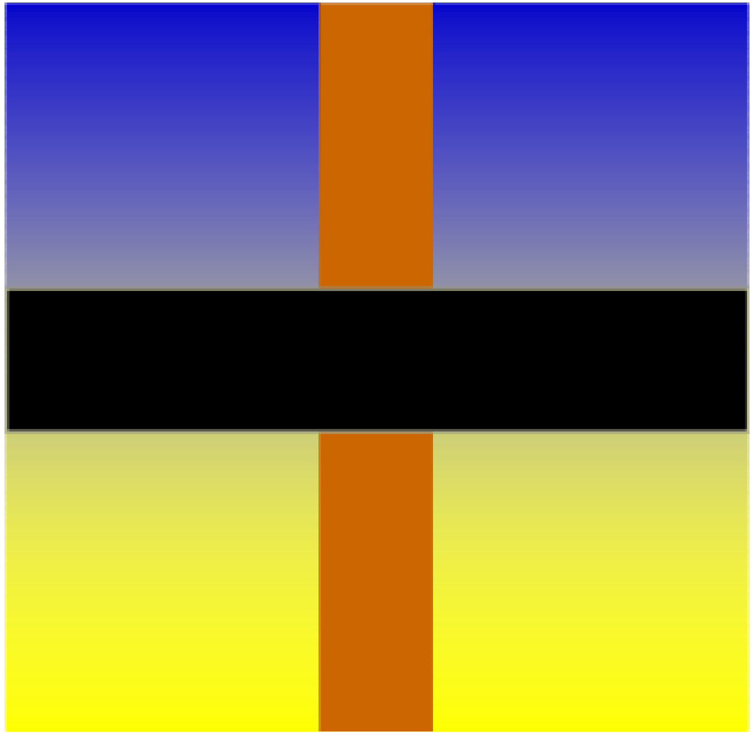


Colorimetry versus color perception.

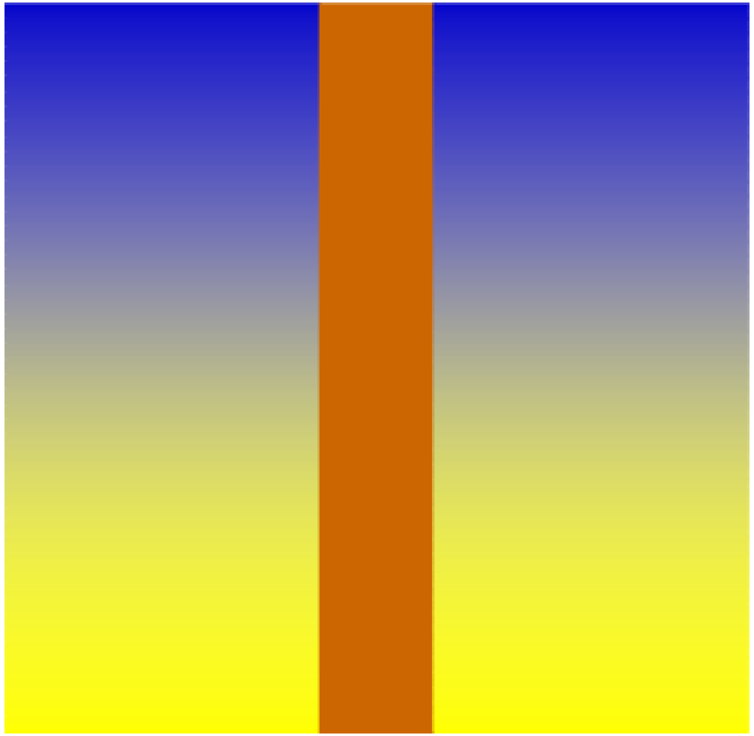
Failures in color constancy



Failures in color constancy (2)



Failures in color constancy (3)



Illusion caused by the outline

Bezold effect