G89.2223 Perception
Maloney

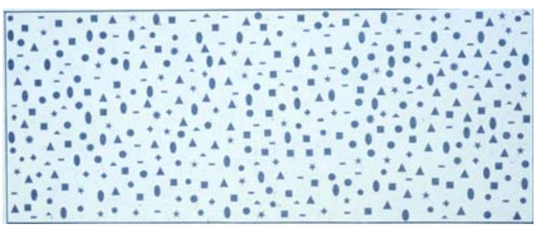
October 5, 2009

Color Perception

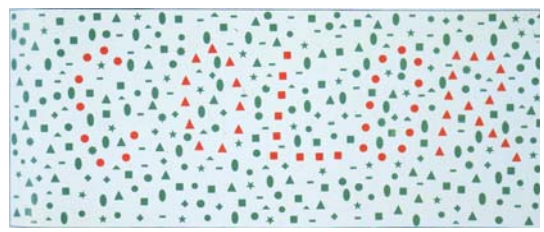
Acknowledgments (slides)
David Brainard
David Heeger

Color – What's it good for?

Color, What is It Good For?



Color, What is It Good For?



perceptual organization

Color, What is It Good For?

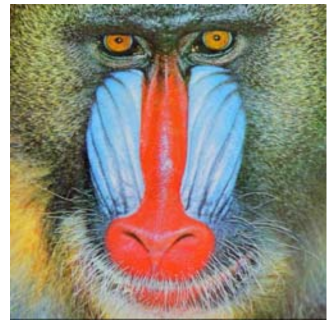
Color, What is It Good For?

perceptual organization

Color, What is It Good For?

signaling ripeness

Color, What is It Good For?



sexual signaling

Color, What is It Good For?

signaling wickedness?

Color – what is it good for?

- •improved discrimination, grouping
- •signaling
- •remote sensing of surface properties

Color Outline

Wavelength encoding (trichromacy)

Three cone types with different spectral sensitivities. Each cone outputs only a single number that depends on how many photons were absorbed. If two physically different lights evoke the same responses in the 3 cones then the two lights will look the same (metamers). Explains when two lights will look the same, not what they will look like.

Color appearance

Color opponency: appearance depends on the differences between cone responses (R-G and B-Y).

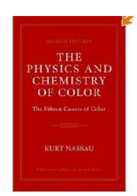
Chromatic adaptation: color appearance also depends on context because the each cone adapts (like light and dark adaptation) to the ambient illumination.

Color constancy: visual system infers surface color, despite changes in illumination.

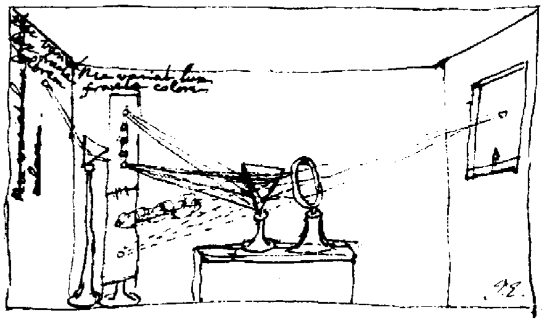
Color, Where does it come from?

Image Formation

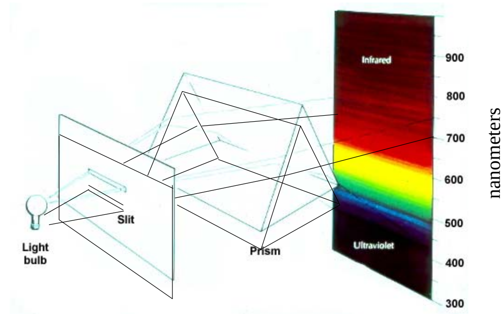
Nassau, K. (2001), The physics and chemistry of color, 2^{nd} Edition. New York: Wiley.



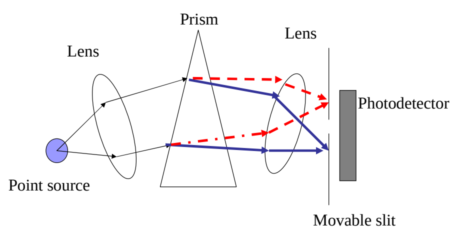
Wavelength and light



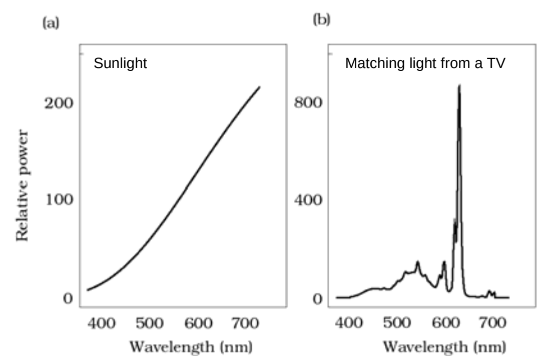
Electromagnetic spectrum



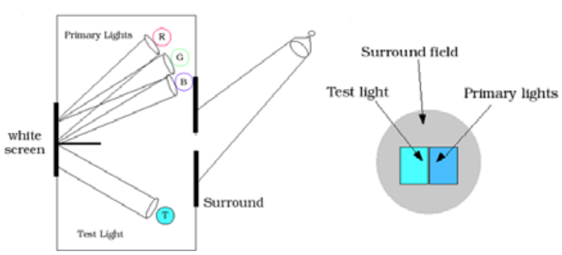
Spectro-radiometer



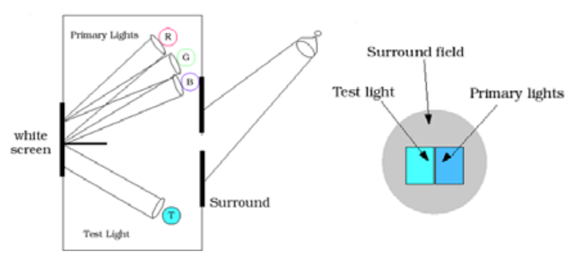
Spectral power distributions



Color matching experiment



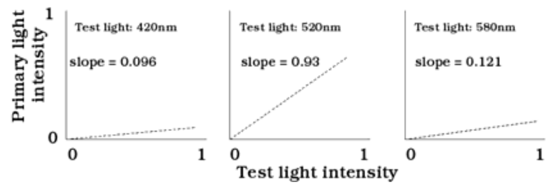
Color matching experiment



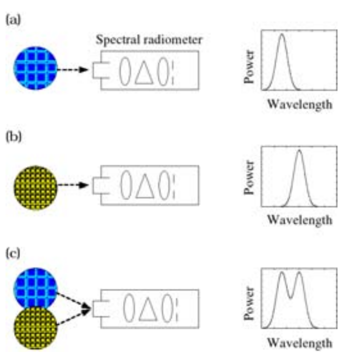
1. Lights that are physically different can look the same (metamers).
2. Three primaries are enough to match any test light.
3. People behave like linear systems in the color matching experiment.

Linear systems

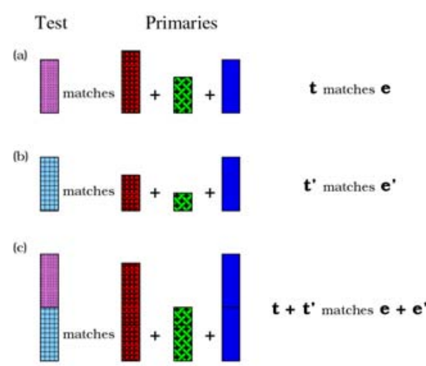
Color matching: scaling



Superposition of light: SPDs add



Color matching: additivity



Color matching as matrix multiplication

Color match settings | Color matching functions | SPD of test light

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} r(\lambda_1) & r(\lambda_2) & \dots & r(\lambda_N) \\ g(\lambda_1) & g(\lambda_2) & \cdots & g(\lambda_N) \\ b(\lambda_1) & b(\lambda_2) & \cdots & b(\lambda_N) \end{pmatrix} \begin{pmatrix} t(\lambda_1) \\ t(\lambda_2) \\ \cdot \\ \cdot \\ \cdot \\ t(\lambda_N) \end{pmatrix}$$

Intensities of the three primary lights

wavelengths: $\lambda_1 = 400$, $\lambda_2 = 401$, etc

Color matching: scaling

Scaling the input by α scales the output by α.

Color match settings | Color matching functions | SPD of test light

$$\begin{pmatrix} \alpha R \\ \alpha G \\ \alpha B \end{pmatrix} = \begin{pmatrix} r(\lambda_1) & r(\lambda_2) & \dots & r(\lambda_N) \\ g(\lambda_1) & g(\lambda_2) & \cdots & g(\lambda_N) \\ b(\lambda_1) & b(\lambda_2) & \cdots & b(\lambda_N) \end{pmatrix} \begin{pmatrix} \alpha\, t(\lambda_1) \\ \alpha\, t(\lambda_2) \\ \cdot \\ \cdot \\ \cdot \\ \alpha\, t(\lambda_N) \end{pmatrix}$$

Color matching: additivity

Adding two the inputs gives the sum of the two outputs.

$$\begin{pmatrix}R_1\\G_1\\B_1\end{pmatrix} = \begin{pmatrix} r(\lambda)\\ g(\lambda)\\ b(\lambda)\end{pmatrix}\begin{pmatrix} t_1(\lambda)\end{pmatrix} \qquad \begin{pmatrix}R_2\\G_2\\B_2\end{pmatrix} = \begin{pmatrix} r(\lambda)\\ g(\lambda)\\ b(\lambda)\end{pmatrix}\begin{pmatrix} t_2(\lambda)\end{pmatrix}$$

$$\begin{pmatrix}R_1+R_2\\G_1+G_2\\B_1+B_2\end{pmatrix} = \begin{pmatrix} r(\lambda)\\ g(\lambda)\\ b(\lambda)\end{pmatrix}\begin{pmatrix} t_1(\lambda)+t_2(\lambda)\end{pmatrix}$$

Measuring the color matching functions

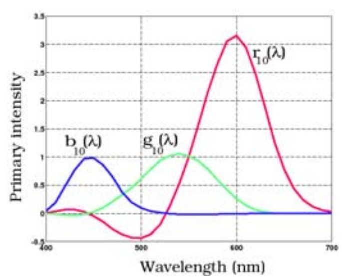
Color match settings — Color matching functions — SPD of test light

$$\begin{pmatrix} r(\lambda_1)\\ g(\lambda_1)\\ b(\lambda_1)\end{pmatrix} = \begin{pmatrix} r(\lambda_1) & r(\lambda_2) & \dots & r(\lambda_N)\\ g(\lambda_1) & g(\lambda_2) & \cdots & g(\lambda_N)\\ b(\lambda_1) & b(\lambda_2) & \cdots & b(\lambda_N)\end{pmatrix}\begin{pmatrix}1\\0\\.\\.\\.\\0\end{pmatrix}$$

monochromatic test light

Repeat with monochromatic test lights of each wavelength, always using the same 3 primary lights.

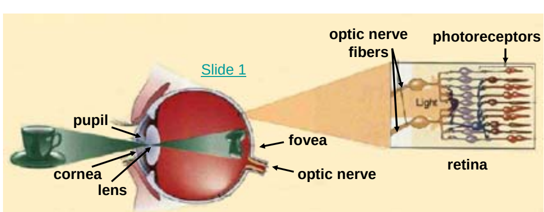
Standardized color matching functions



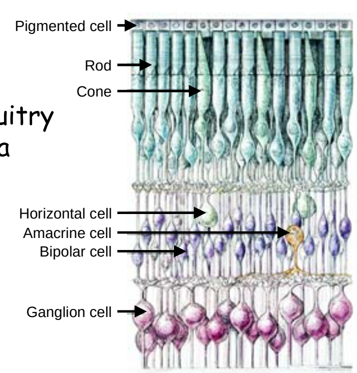
Commission Internationale d'Eclairage (CIE) standard set in 1931 using 3 monochromatic primaries at wavelengths of 435nm, 546nm, and 700nm.

Physiology of color matching

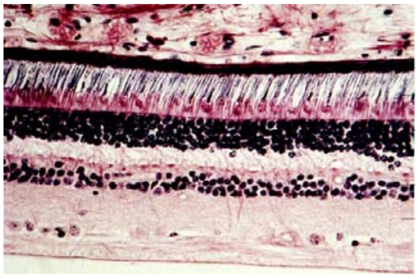
The eye



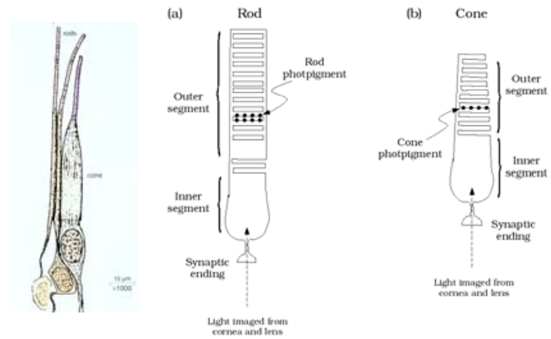
Neural circuitry in the retina

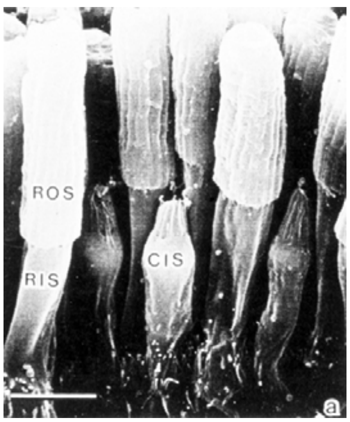


Retina cross-section

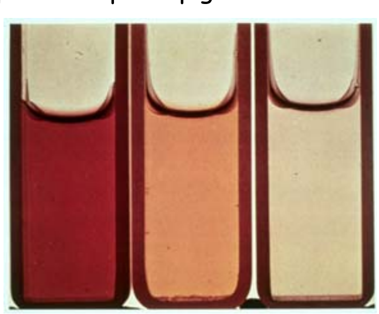


Photoreceptors: rods and cones





Rhodopsin: rod photopigment



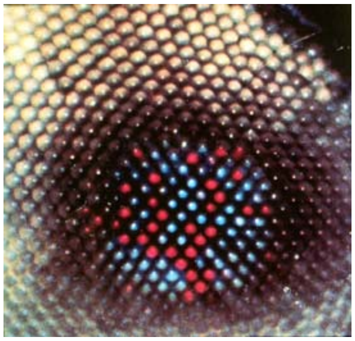
Exposure to light

Bleaching of rhodopsin

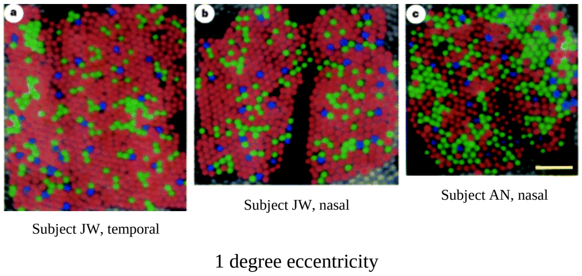
In the dark

Bleached by light

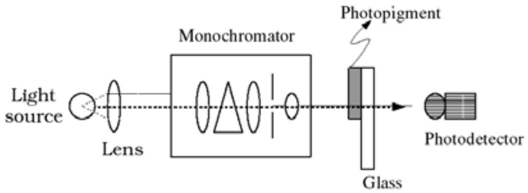
Butterfly eye



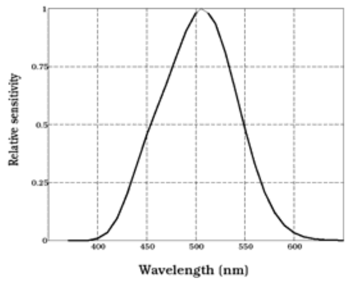
Human cone mosaic



Measuring rod spectral sensitivity
(wavelength-dependence of rhodopsin absorption)



Rod spectral sensitivity



Let's say you have a 500nm light with intensity 10. Can you match it's appearance with a 550nm light? If so, what will be the intensity of the matching light?

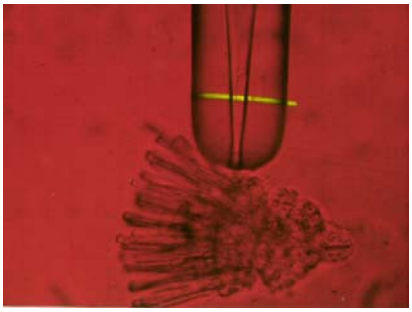
The principle of univariance

The response of a photoreceptor is a function of just one variable (namely, the number of photons absorbed).

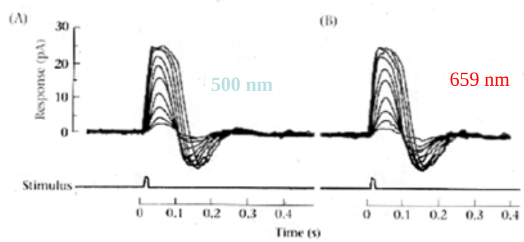
Thus, the response can be identical for:

- a *weak* light at the wavelength of *peak sensitivity*
  - few incident photons, a large fraction of them absorbed
- a *strong* light at a wavelength of *lower sensitivity*
  - many incident photons, a small fraction of them absorbed

Measuring cone photocurrents

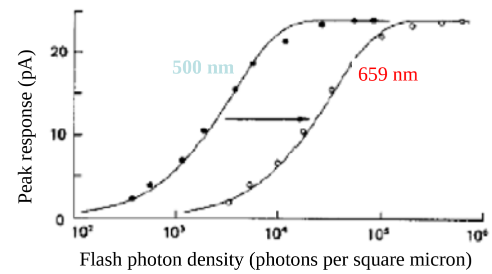


Cone photocurrent

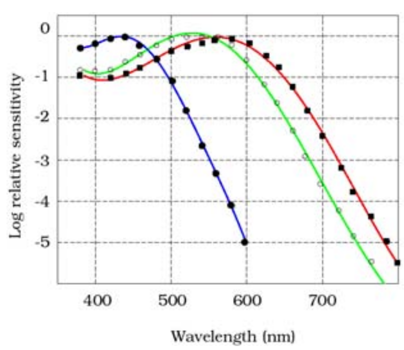


Baylor et al.

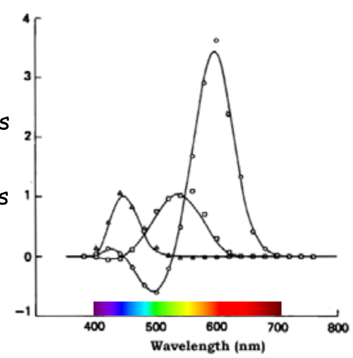
Cone responses are nonlinear
(but can be equated by scaling intensity)



Cone spectral sensitivities



Cone responsivities
(and optical filters)
predict color
matching functions



Baylor et al.

Trichromacy equations

Wavelength encoding equation

Response — Cone responsivity — Input SPD

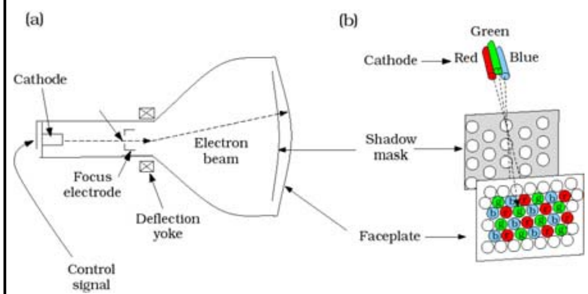
$$\begin{pmatrix} L \\ M \\ S \end{pmatrix} = \begin{pmatrix} \cdots & l(\lambda) & \cdots \\ \cdots & m(\lambda) & \cdots \\ \cdots & s(\lambda) & \cdots \end{pmatrix} \begin{pmatrix} t_1 \\ \vdots \\ t_n \end{pmatrix}$$

Metamers revisited

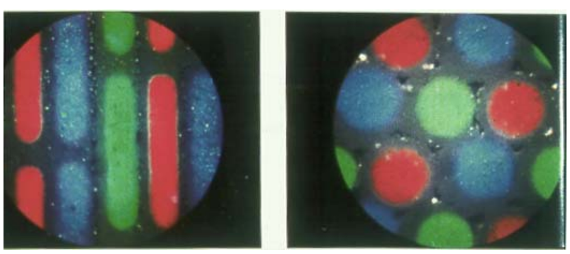
$$\begin{pmatrix} L \\ M \\ S \end{pmatrix} = \begin{pmatrix} \cdots & l(\lambda) & \cdots \\ \cdots & m(\lambda) & \cdots \\ \cdots & s(\lambda) & \cdots \end{pmatrix} \begin{pmatrix} t_1 \\ \vdots \\ t_n \end{pmatrix} = \begin{pmatrix} \cdots & l(\lambda) & \cdots \\ \cdots & m(\lambda) & \cdots \\ \cdots & s(\lambda) & \cdots \end{pmatrix} \begin{pmatrix} s_1 \\ \vdots \\ s_n \end{pmatrix}$$

SPDs of two lights

Displays and color matching



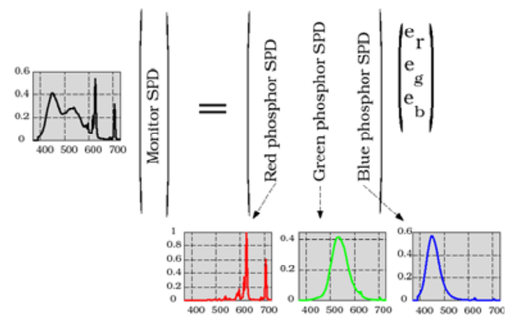
Application: Color TV



Trinitron

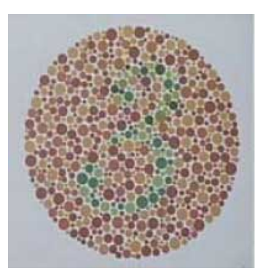
Conventional tri-dot

Color display equation

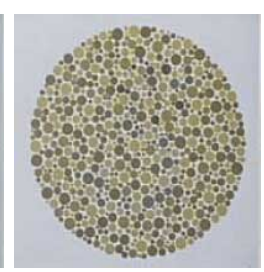


Color blindness

Color blindness



Ishihara plate

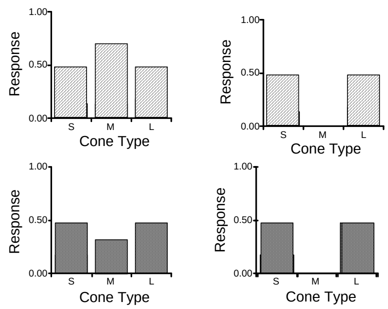


What a red/green color-blind person might see

Trichromat | Dichromat

Light 1

Light 2



Color blindness

normal | red/green color blind | blue-yellow color blind

- Dichromats: missing one of the three photopigment/cone types.
- Can match with 2 primaries in the color matching experiment
- Will accept trichromat's match but trichromat will not always accept dichromats match.

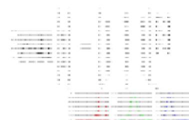
Color blindness

normal | red/green color blind | blue/yellow color blind

People with color deficiencies may have difficulty distinguishing certain colors (e.g., a red/green color deficiency means that reds and greens are more difficult to distinguish). But as this photo demonstrates, many other colors are just as distinguishable to a person with a color deficiency as to someone with normal color vision.

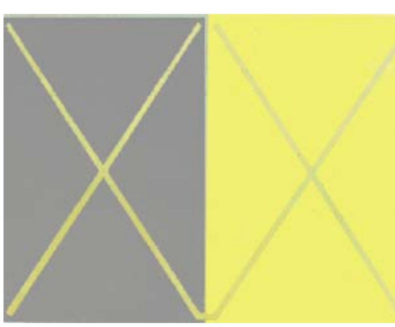
Color matching and trichromacy caveats

1. The 3 primary lights must be linearly independent:



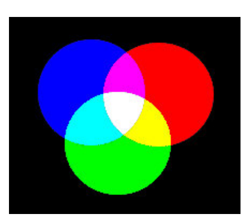
2. For any set of primaries, there are test lights that are out of range such that the primary intensities must be higher than achievable or "negative" (which is physically impossible).
3. Trichromacy determines when two lights look the same, not what they look like.
4. Additive vs "subtractive" color mixtures.

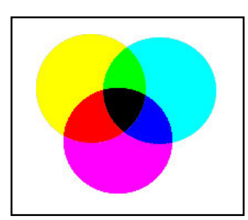
Simultaneous color contrast
(identical lights look different in a different context)



RGB
red, green, blue--used in TVs
Additive mixing of light sources

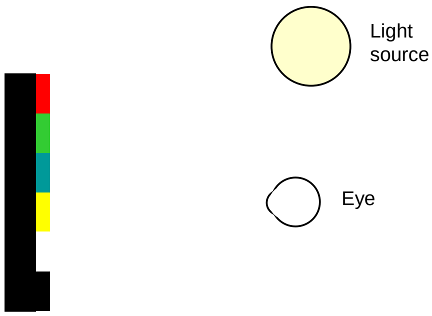
CMYK
cyan, magenta, yellow, black–used in printing
Subtractive mixing of absorbing pigments



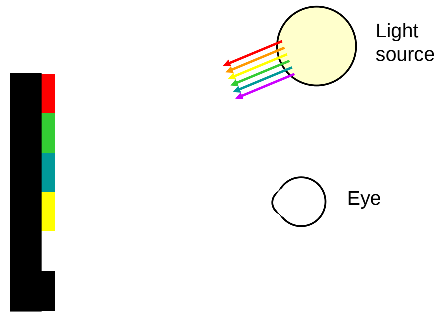


http://www.bbso.njit.edu/Documentations/gimpdoc-html/color.html

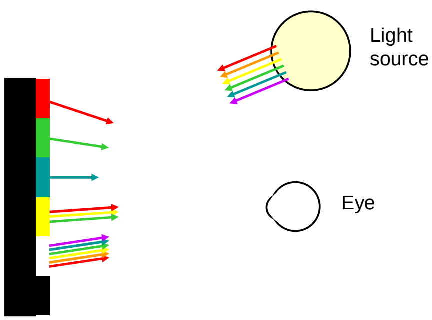
"Subtractive" color mixture: surface reflectance



"Subtractive" color mixture: surface reflectance



"Subtractive" color mixture: surface reflectance



Color calculations in matlab