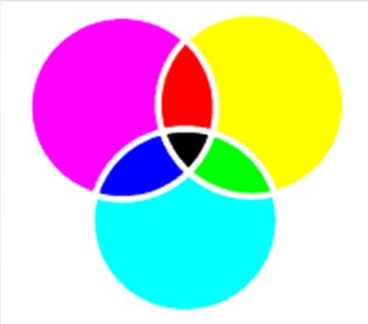
Computer Graphics



CH8：Color

Instructor: Dr. MAO Aihua

ahmao@scut.edu.cn

Color

- To understand how to make realistic images, we need a basic understanding of the physics and physiology of vision.
- Here we step away from the code and math for a bit to talk about basic principles.

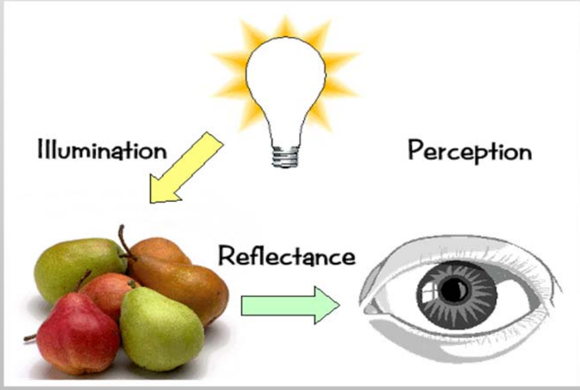
Color

What is color?

- Color is a *sensation* which occurs when light energy, incident on the retina is interpreted by the brain.
- In other words, the perception of color lies in the ability of our visual system to transform light energy into a neural signal.
- The color signal sent to the brain is a function of the surface properties of the object and the spectral composition of its illuminant...

Basics Of Color

Elements of color:



Basics of Color

Physics:

- Illumination
  - *Electromagnetic spectra*
- Reflection
  - *Material properties*
  - *Surface geometry and microgeometry (i.e., polished versus matte versus brushed)*

Perception:

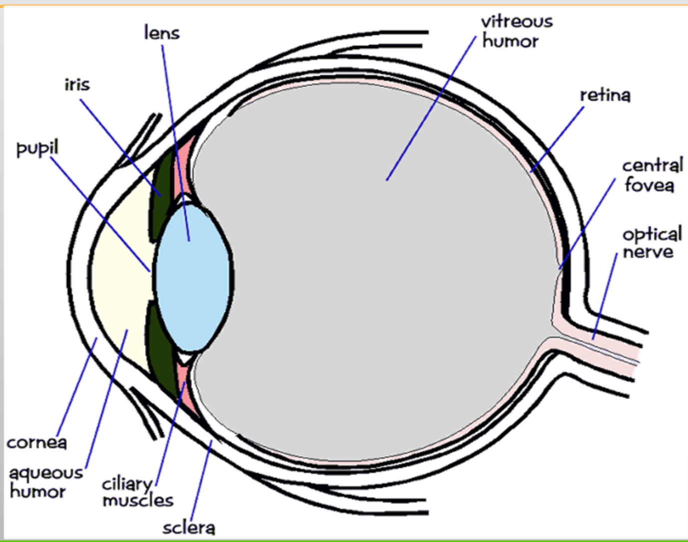
- Physiology and neurophysiology
- Perceptual psychology

Physiology of Vision

The eye:

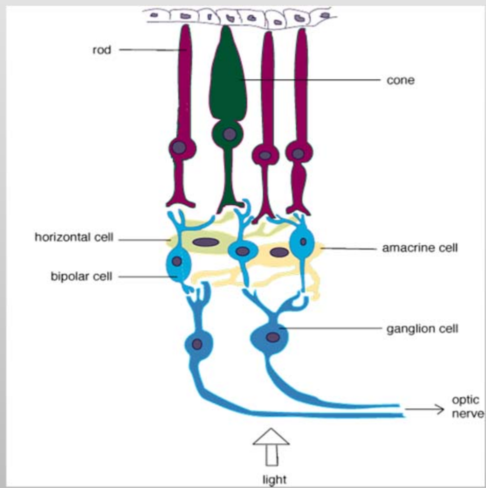
The retina

- Rods
- Cones
  - *Color!*



Physiology of Vision: The Retina

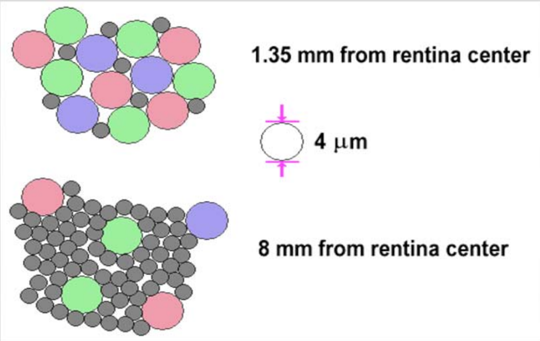
Strangely, rods and cones are at the back of the retina, behind a mostly-transparent neural structure that collects their response.



Physiology of Vision

The center of the retina is a densely packed region called the fovea.

- Cones much denser here than the *periphery*



Psychophysics of Vision

Color is not a physical property but a psychophysical property

- Most of the light we see is reflected
- We see only part of the electromagnetic spectrum—between 400 and 700 nm

Psychophysics of Vision

Photopic: Light intensities that are bright enough to stimulate the cone receptors and bright enough to "saturate" the rod receptors

- Sunlight and bright indoor lighting are both photopic lighting conditions

Scotopic: Light intensities that are bright enough to stimulate the rod receptors but too dim to stimulate the cone receptors

- Moonlight and extremely dim indoor lighting are both scotopic lighting conditions

Trichromacy

Rods are sensitive to scotopic light levels

- All rods contain the same photopigment molecule: Rhodopsin
- All rods have the same sensitivity to various wavelengths of light
- Therefore, rods suffer from the problem of univariance and cannot sense differences in color
- Under scotopic conditions, only rods are active, which is why the world seems drained of color

Trichromacy

SENSATION & PERCEPTION 2e, Figure 5.3

Trichromacy

Cone photoreceptors: Three varieties:

• S-cones: Cones that are preferentially sensitive to short wavelengths (blue cones)

•M-cones: Cones that are preferentially sensitive to middle wavelengths (green cones)

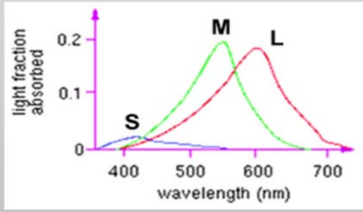
•L-cones: Cones that are preferentially sensitive to long wavelengths (red cones)

With three cone types, we can tell the difference between lights of different wavelengths , be active under photopic conditions

Trichromacy

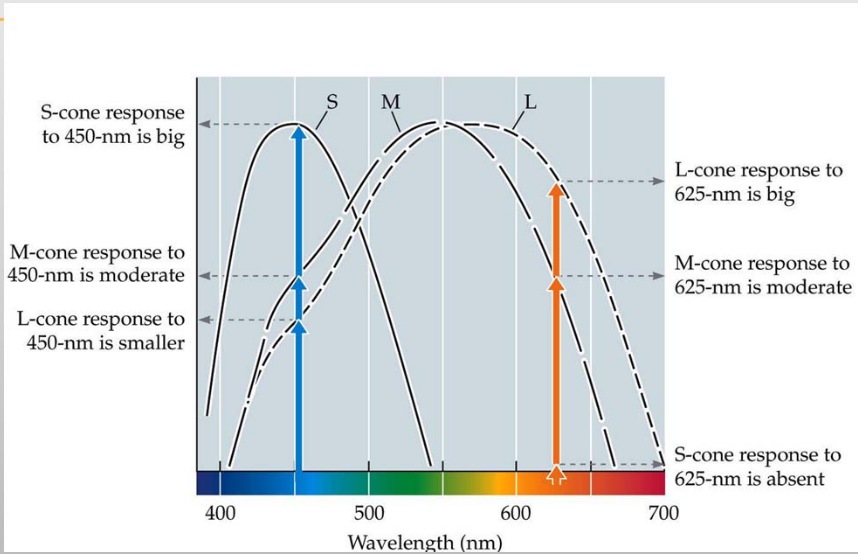
Three types of cones:

- **L** or **R**, most sensitive to red light (610 nm)
- **M** or **G**, most sensitive to green light (560 nm)
- **S** or **B**, most sensitive to blue light (430 nm)



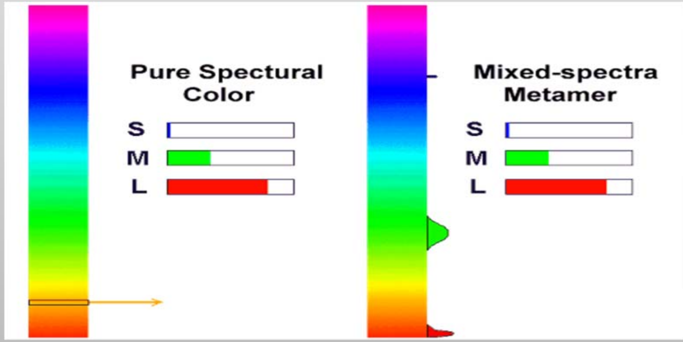
- Color blindness results from missing cone type(s)

Trichromacy



Trichromacy

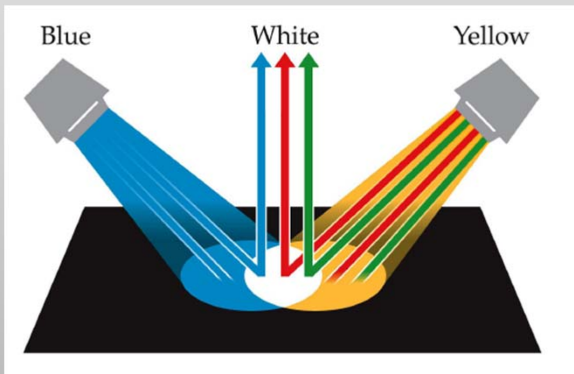
Trichromacy: The theory that the color of any light is defined in our visual system by the relationships of three numbers, the outputs of three receptor types now known to be the three cones



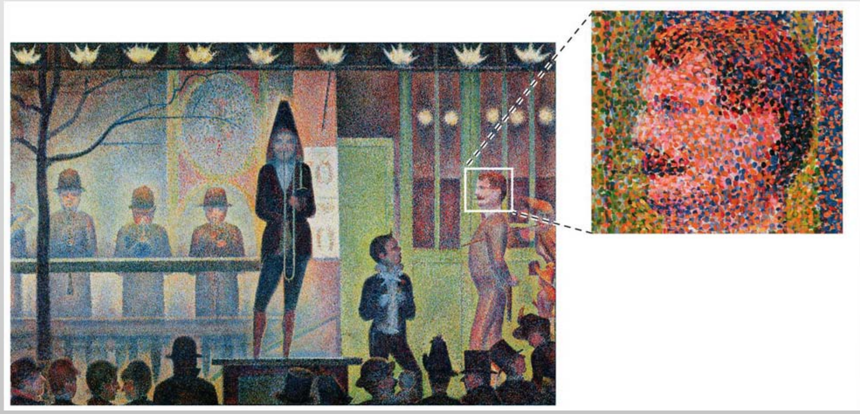
Trichromacy

Additive color mixing: A mixture of lights

- If light A and light B are both reflected from a surface to the eye, in the perception of color the effects of those two lights add together



Trichromacy

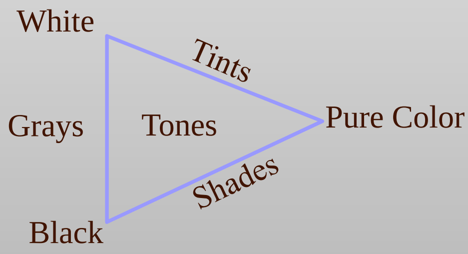


Georges Seurat's painting *La Parade (1887–1888)*
illustrates the effect of additive color mixture with paints

How Do Artists Do It?

Artists often specify color as tints, shades, and tones of saturated (pure) pigments

- Tint: Gotten by adding white to a pure pigment, decreasing saturation
- Shade: Gotten by adding black to a pure pigment, decreasing lightness
- Tone: Gotten by adding white and black to a pure pigment

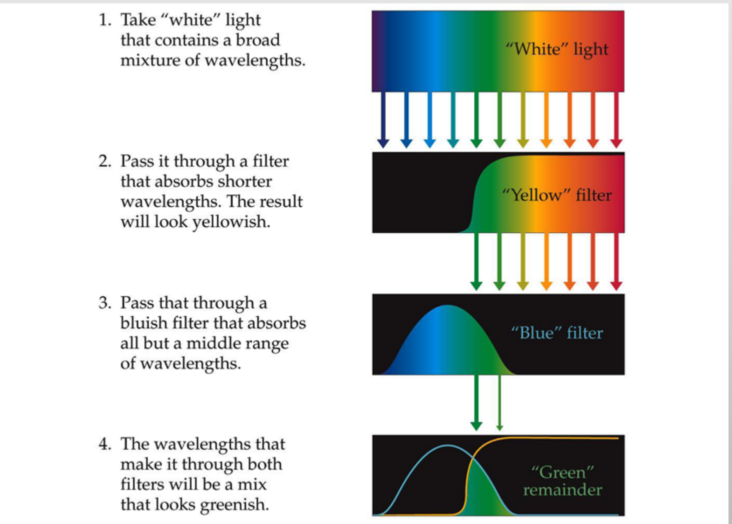


Trichromacy

Subtractive color mixing: A mixture of pigments

•If pigment A and B mix, some of the light shining on the surface will be subtracted by A and some by B. Only the remainder contributes to the perception of color

Trichromacy



In this example of subtractive color mixture, "white" broadband light is passed through two filters

Trichromacy

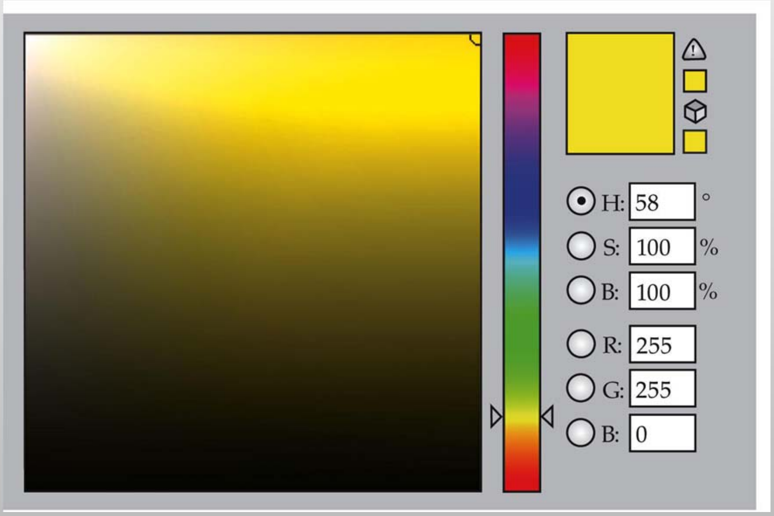
Color space: A three-dimensional space that describes all colors. There are several possible color spaces

• RGB color space: Defined by the outputs of long, medium, and short wavelength lights

•HSB color space: Defined by hue, saturation, and brightness

- Hue: The chromatic (color) aspect of light
- Saturation: The chromatic strength of a hue
- Brightness: The distance from black in color space

Trichromacy



A color picker may offer several ways to specify a color in a three-dimensional color space

The Math of Trichromacy

Write primaries as R, G and B, Many colors can be represented as a mixture of R, G, B:

- M=rR + gG + bB (Additive matching)
- Gives a color description system - two people who agree on R, G, B, need only supply (r, g, b) to describe a color

Some colors can't be matched like this, instead, write:

- M+rR=gG+bB (Subtractive matching)
- Interpret this as (-r, g, b)

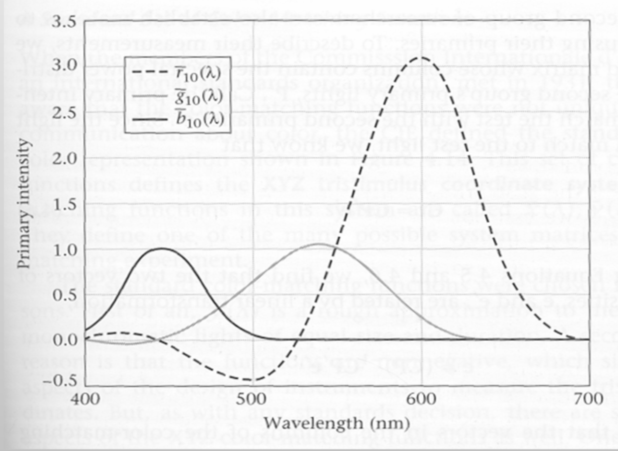
Color Matching

Given a spectrum, how do we determine how much each of R, G and B to use to match it?

First step:

- For a light of unit intensity at each wavelength, ask people to match it with R, G and B primaries
- Result is three functions, r(λ), g(λ) and b(λ), the RGB *color matching functions*

The RGB Color Matching Functions



4.13 THE COLOR-MATCHING FUNCTIONS ARE THE ROWS OF THE COLOR-MATCHING SYSTEM MATRIX. The functions measured by Stiles and Burch (1959) using a 10-degree bipartite field and primary lights at the wavelengths 645.2 nm, 525.3 nm, and 444.4 nm with unit radiant power are shown. The three functions in this figure are called $\bar{r}_{10}(\lambda)$, $\bar{g}_{10}(\lambda)$, and $\bar{b}_{10}(\lambda)$.

Computing the Matching

- The spectrum function that we are trying to match, E(λ), gives the amount of energy at each wavelength
- The RGB matching functions describe how much of each primary is needed to match one unit of energy at each wavelength
- Hence, if the “color” due to E(λ) is E, then the match is:

$$E = rR + gG + bB$$

$$r = \int r(\lambda)E(\lambda)d\lambda$$

$$g = \int g(\lambda)E(\lambda)d\lambda$$

$$b = \int b(\lambda)E(\lambda)d\lambda$$

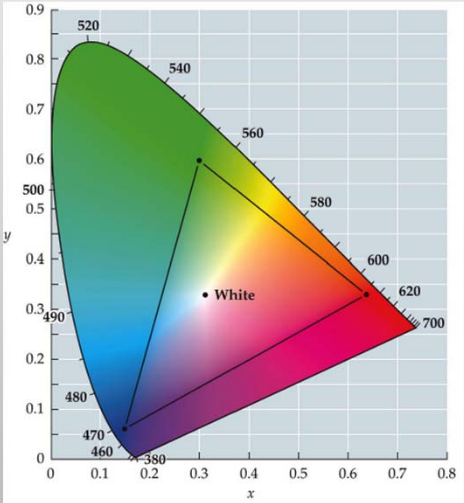
Color Spaces

Taking linear combinations of R, G and B defines the *RGB color space*

- the range of perceptible colors generated by adding some part each of R, G and B

If R, G and B correspond to a monitor's phosphors (monitor RGB), then the space is the range of colors displayable on the monitor

Color Spaces



The curvaceous triangle shown here represents all the colors that can be seen (at one brightness level) by the human visual system

Problems with RGB

Can only a small range of all the colors humans are capable of perceiving (particularly for monitor RGB)

- Have you ever seen magenta on a monitor?

It isn't easy for humans to say how much of RGB to use to make a given color

- How much R, G and B is there in “brown”? (Answer: .64,.16, .16)

Going from RGB to XYZ

These are linear color spaces, related by a linear transformation

$$E = xX + yY + zZ = rR + gG + bB$$

Match each primary, for example:

$$R = x_r X + y_r Y + z_r Z$$

Substitute and equate terms:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} x_r & x_g & x_b \\ y_r & y_g & y_b \\ z_r & z_g & z_b \end{bmatrix} \begin{bmatrix} r \\ g \\ b \end{bmatrix}$$

More linear color spaces

Monitor RGB: primaries are monitor phosphor colors, primaries and color matching functions vary from monitor to monitor:

- Almost all applications assume that RGB is the same as monitor RGB

YIQ: mainly used in television TV in America.

- Y is (approximately) intensity, I, Q are chromatic properties
- Linear color space; hence there is a matrix that transforms XYZ coords to YIQ coords, and another to take RGB to YIQ
- I and Q can be transmitted with low bandwidth

Converting Color Spaces

Converting between color models can also be expressed as such a matrix transform:

$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.30 & 0.59 & 0.11 \\ 0.60 & -0.28 & -0.32 \\ 0.21 & -0.52 & 0.31 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Note the relative unimportance of blue in computing the Y

The CMY Color Model

Cyan, magenta, and yellow are the complements of red, green, and blue

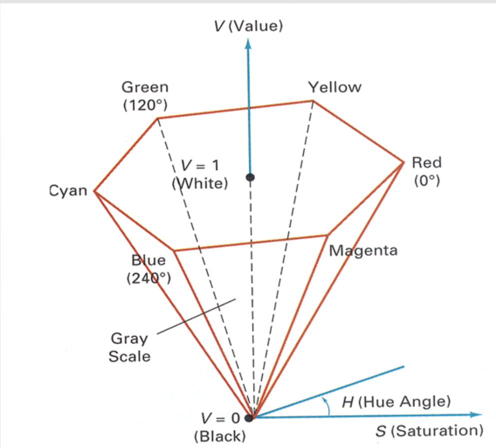
- We can use them as filters to subtract from white
- The space is the same as RGB except the origin is white instead of black

This is useful for hardcopy devices like laser printers

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

- If you put cyan ink on the page, no red light is reflected
- Add black as option (CMYK) to match equal parts CMY

HSV Color Model

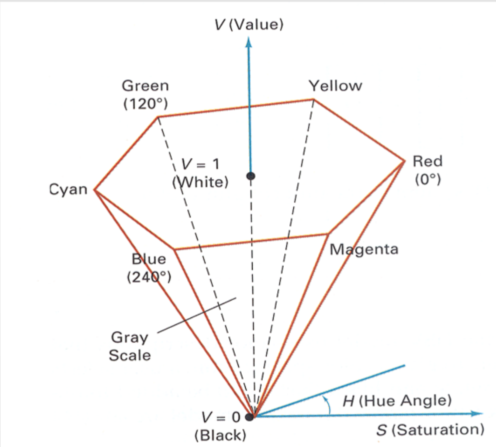


Hue (H) is the angle around the vertical axis

Saturation (S) is a value from 0 to 1 indicating how far from the vertical axis the color lies

Value (V) is the height of the hexcone

HSV Color Model



H	S	V	Color
0	1.0	1.0	Red
120	1.0	1.0	Green
240	1.0	1.0	Blue
*	0.0	1.0	White
*	0.0	0.5	Gray
*	*	0.0	Black
60	1.0	1.0	
270	0.5	1.0	
270	0.0	0.7	

Figure 15.16&15.17 from H&B

How well do we see color?

What color do we see the best?

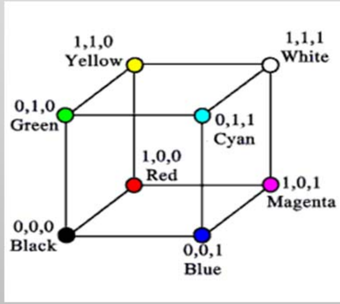
- Yellow-green at 550 nm

What color do we see the worst?

- Blue at 440 nm

RGB Color Space (Color Cube)

Define colors with (r, g, b) amounts of red, green, and blue



Does Everyone See Colors the Same Way?

Does everyone see colors the same way?—*Yes*

- General agreement on colors
- Some variation due to age (lens turns yellow)

Does everyone see colors the same way?—*No*

- About 8% of male population, 0.5% of female population has some form of color vision deficiency: Color blindness

Does Everyone See Colors the Same Way?

Several types of color-blind people:

- Deuteranope: Due to absence of M-cones
- Protanope: Due to absence of L-cones
- Tritanope: Due to absence of S-cones